NBS SPECIAL PUBLICATION 436

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Detection, Diagnosis, and Prognosis

MFPG

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MFPG
Detection, Diagnosis, and Prognosis

t. Special Publication, no. 436

Proceedings of the 22nd Meeting of the
Mechanical Failures Prevention Group,
held at Anaheim, California 92802
April 23-25, 1975

Edited by

T. R. Shives and W. A. Willard

Metallurgy Division
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Washington, D.C. 20234

The 22nd meeting of MFPG and these proceedings were sponsored by the Office of Naval Research, Department of the Navy, Arlington, Va. 22217; the National Aeronautics & Space Administration, Goddard Space Flight Center, Greenbelt, Md. 20771; the Frankford Arsenal, U.S. Army, Philadelphia, Pa. 19137; the Federal Aviation Administration, Department of Transportation, Washington, D.C. 20591; and the Institute for Materials Research of the National Bureau of Standards, Washington, D.C. 20234

U.S. DEPARTMENT OF COMMERCE, Rogers C. B. Morton, *Secretary*

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Issued December 1975

Library of Congress Cataloging in Publication Data

Mechanical Failures Prevention Group.
MFPG--Detection, Diagnosis, and Prognosis.

(NBS Special Publ ; 436)
"Organized by the Detection, Diagnosis, and Prognosis Committee of MFPG."
Supt. of Docs No.: C 13.10:346.
1. Metals--Fracture--Congresses. 2. Metals--Testing--Congresses. I. Shives, T. R. II. Willard, William A. III. United States. Office of Naval Research. IV. Title. V. Series: United States. National Bureau of Standards. Special Publication ; 436. QC100.U57 No. 436 [TA460] 602'.1s 620.1'6'3 75-619365

National Bureau of Standards Special Publication 436

Nat. Bur. Stand. (U.S.), Spec. Publ. 436, 366 pages (Dec. 1975)
CODEN: XNBSAV

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1975

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.10:436). Price $4.25 (Add 25 percent additional for other than U.S. mailing).

FOREWORD

The 22nd meeting of the Mechanical Failures Prevention Group was held April 23-25, 1975, at the Grand Hotel in Anaheim, California. The program was organized by the Detection, Diagnosis, and Prognosis committee of MFPG under the chairmanship of Mr. Raymond Misialek. The DD&P committee, the session chairmen, and especially the speakers are to be commended for the fine program.

The papers are presented in these Proceedings as submitted by the author on camera ready copy, except for some minor editorial changes. In addition to the papers, the Proceedings include the discussions of the talks. The discussions were recorded at the meeting and have been edited to improve readability.

Special appreciation is accorded the Endevco Corporation, and in particular to Mr. Robert M. Whittier of Endevco, for hosting the meeting. They were responsible for the excellent meeting arrangements.

Appreciation should be extended to Mr. T. R. Shives and Mr. W. A. Willard of the NBS Metallurgy Division for their editing, organization, and preparation of the Proceedings, to Mr. H. C. Burnett of the Metallurgy Division for general coordination and registration, to Mr. P. Fleming of the Metallurgy Division for handling financial matters, and to the entire staffs of the Metallurgy Division and the Institute for Materials Research for their assistance in many ways. Special thanks are accorded Mrs. Marian L. Slusser of the Metallurgy Division for her diligent efforts in transcribing the recorded discussions.

ELIO PASSAGLIA
Executive Secretary, MFPG

Chief, Metallurgy Division
National Bureau of Standards

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SESSION IV: COMING REQUIREMENTS

* Indicates speaker when a paper had more than one author.

ABSTRACT

These Proceedings consist of a group of nineteen submitted papers and discussions from the 22nd meeting of the Mechanical Failures Prevention Group which was held at the Grand Hotel in Anaheim, California on April 23-25, 1975. Failure detection, diagnosis and prognosis represent the central theme of the Proceedings. Technology and techniques, ongoing diagnostic programs, and coming requirements in the field of DD&P are discussed. In addition, several case histories are presented.

Key Words: Diagnostic case histories; diagnostic systems; failure detection; failure diagnosis; failure prevention; failure prognosis

UNITS AND SYMBOLS

Customary United States units and symbols appear in many of the papers in these Proceedings. The participants in the 22nd Meeting of the Mechanical Failures Prevention Group have used the established units and symbols commonly employed in their professional fields. However, as an aid to the reader in increasing familiarity with and usage of the metric system of units (SI), the following references are given:

NBS Special Publication, SP330, 1974 Edition, "The International System of Units."
ISO International Standard 1000 (1973 Edition),"SI Units and Recommendations for Use of Their Multiples."
E380-72 ASTM Metric Practice Guide (American National Standard Z210.1).

SESSION I

TECHNOLOGY AND TECHNIQUES

Chairman: R. Hohenberg
Mechanical Technology Inc.

SIGNAL ANALYSIS TECHNIQUES FOR VIBRATION DIAGNOSTICS

Dr. Donald R. Houser, Associate Professor
Ohio State University, Columbus, Ohio 43210

Vibration and sound measurements have been used for the detection of faults in rotating machinery for many years. The classic picture of a mechanic listening to an engine bearing via a stethoscope or screwdriver is a prime example of the basic technique. Because of the apparently large amount of information contained in the vibration signal, investigators have strived to use this signal to automatically determine the condition of mechanical devices. Further still, the ability to isolate specific faults on components in a mechanical system has also been deemed highly desirable.

A schematic of a typical vibration diagnostic system is shown in Figure 1. Here, forces from moving parts such as gears, bearings, or shafts excite their surrounding structures and cause structural vibration. This vibration is then converted to a voltage via a vibration transducer, most often an accelerometer in present day applications. The location of the transducer may be very important since the structural dynamics between the input forces and the transducer may greatly modify the signal. When a single transducer is used to monitor several machine components, the problem of the proper transducer location may become very complex. The transducer signal is then conditioned and further analyzed via a mathematical processor. This processor, which may analyze the data either statistically or deterministically in the time domain or transform the data into the frequency domain, is used to generate discriminants (a statistic or set of statistics) upon which a decision regarding the condition of a system or component within the system is based.

Figure 2 gives a much broader picture of many of the combinations of transducers, signal conditioning, signal processing, and discriminants available for vibration diagnostics. Many of the processing and conditioning techniques such as time summation, Fourier analysis, cepstrum, cross correlation, cross spectral density, and coherence function require relatively complex data processors; whereas special purpose hardware is much more feasible where simple discriminants are ascertained using band pass filtering, peak detection, and rms meters.

By far the most common signal processing technique has been Fourier analysis via either analog hardware or via the fast Fourier transform algorithm on digital processors. The frequency domain presentation of Fourier frequency spectra allows one to relate specific periodic occurrences in a machine member to specific frequencies in the data. Of the time domain processing techniques, time summation and various relatively simple time signal analyses such as crest factors and impact index have been used. Time summation enhances data of a periodic nature and eliminates the effects of random noise and periodic components which are not common to the summation period. However, a very accurate trigger pulse is necessary to perform time summation successfully. Discriminants are commonly selected through one of the following methods:

1. Pattern recognition
2. Mechanical model analysis
3. A combination of modeling and pattern recognition.

The pattern recognition methods of selecting discriminants and their utilization in the detection of faulty components are usually heavily statistics oriented. Often, very little physical insight is used in the selection of discriminants by this method. Because of the purely statistical means of data analysis, these techniques require many samples of data for each failure mode which might be encountered. Also, discriminants selected for one system component may not necessarily be the correct discriminant for a similar component located in another device due to the different dynamic environment. Pattern recognition techniques based on frequency spectra data have been used for the detection of faulty gears and bearings by Butcher et al. [1]* and Kukel et al. [2].

The second approach for the development of vibration diagnostic discriminants is through the use of mechanical modeling to predict changes which will occur in the vibration signal due to typical faults. This approach is quite versatile and allows results for one specific component, a gear for instance, to be applied to many different gear situations. Most of the successful modeling techniques have been applied to rolling element bearing faults, where the ball, cage, and race frequencies may be easily predicted [3]. Methods for predicting high frequency resonances of bearing races have also been developed [4].

In Figure 3 the frequency spectrum from an analog simulation of a discrete bearing fault is shown. Each of the frequency peaks corresponds to a resonance in the system. The smaller peaks are spaced in increments equal to the shaft rotational speed. The vibration frequency spectrum of Figure 4 for an operating bearing having an outer race pit shows the similarity between the model and the actual data. Figure 5 compares time traces for the model and the actual bearing.

Figures 5 and 6 show both model and running data for a gear having a single pitch line pit. The model, which is discussed in reference [5], provides both time domain and frequency domain responses for gears running both with and without faults. Interesting results from the figures are that the gear mesh frequency sidebands were found to be the result of a torque oscillation in the system which was due to coupling misalignment. The fault appears to give a very predominate periodicity at multiples of the shaft frequency. A second less noticeable periodicity occurs at the first torsional natural frequency of the system.

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*Numbers in brackets indicate references cited at the end of this paper.

One possible means of developing a single discriminant for this type of failure mode would be to obtain the cepstrum [6] of the spectra, since the cepstrum is very sensitive to periodicities in the frequency spectrum.

The third and perhaps most logical means of determining discriminants is to combine modeling and pattern recognition, since statistical confidence is still required, even for discriminants determined from physical models. However, this approach is likely to reduce the total amount of data necessary in developing the diagnostic technique.

Through the use of the above-mentioned approaches, many techniques have been developed to detect failures in rotating components, with most of the emphasis being placed on gears and bearings. Listed in Table 1 are techniques which have been attempted or utilized by other investigators. Detailed discussions of these techniques may be found in references [7] and [8]. Many of the techniques listed in Table 1 utilize discriminants and processing methods appearing in Figure 2. Techniques of several different investigators may often be included under one technique class in the table. An example of this is the bearing high frequency "ring" technique which has been employed in various forms by several investigators. The general narrowband technique encompasses a large number of schemes which utilize simple observations of the frequency spectrum. Of the bearing techniques, the high frequency vibration techniques including the shock pulse method have been investigated by many individuals and are presently being employed in operating systems. At this time gear fault detection systems have not shown as much promise as the bearing diagnostic schemes, primarily because transducers can be located closer to the bearings, and bearing mechanics are better defined.

In summary, this paper has presented an overview of the primary methods of utilizing vibration data for diagnostic purposes including signal processing and discriminant determination. A listing of many of the diagnostic schemes which have been investigated or proposed has also been presented.

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Table 1. Summary of Diagnostic Techniques

Technique Name	Faulty Component Detection			Discriminant Conception		
	Bearing	Gear	Other	Model	Pattern Recognition	Combination
Curtiss Wright Sonic Analyzer [9]	√	√	√	√		
Noise-Corrected Spectrum Energy [10]		√				
Correlation Analysis [7]	√	√			√	√
Composite Exceedance [11]	√				√	
Likelihood Analysis [2]	√	√	√		√	
Impact Index (Crest Factor) [12]		√				√
Frequency of Binary Word [13]	√	√	√		√	
Gear Discriminant [14]		√		√		
Gear Wear Discriminant [15,16]		√		√		
General Narrow Band	√	√	√	√	√	√
Test Bed (Hamilton Std) [17]	√	√				√
Test Bed (Northrop) [1]	√	√			√	
Bearing High Frequencies [4]	√			√		
Shock Pulse [18]	√			√		
Optimum-Seeking Classifier [7]	√	√	√		√	√

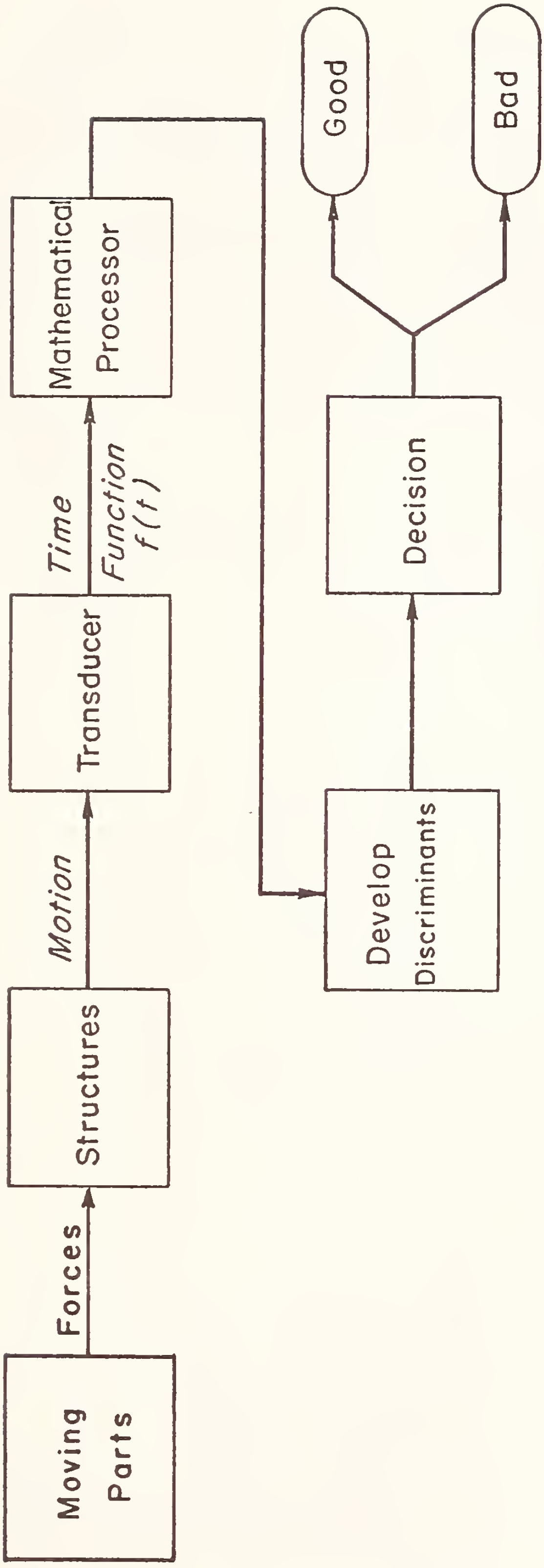

Figure 1. Typical Diagnostic System.

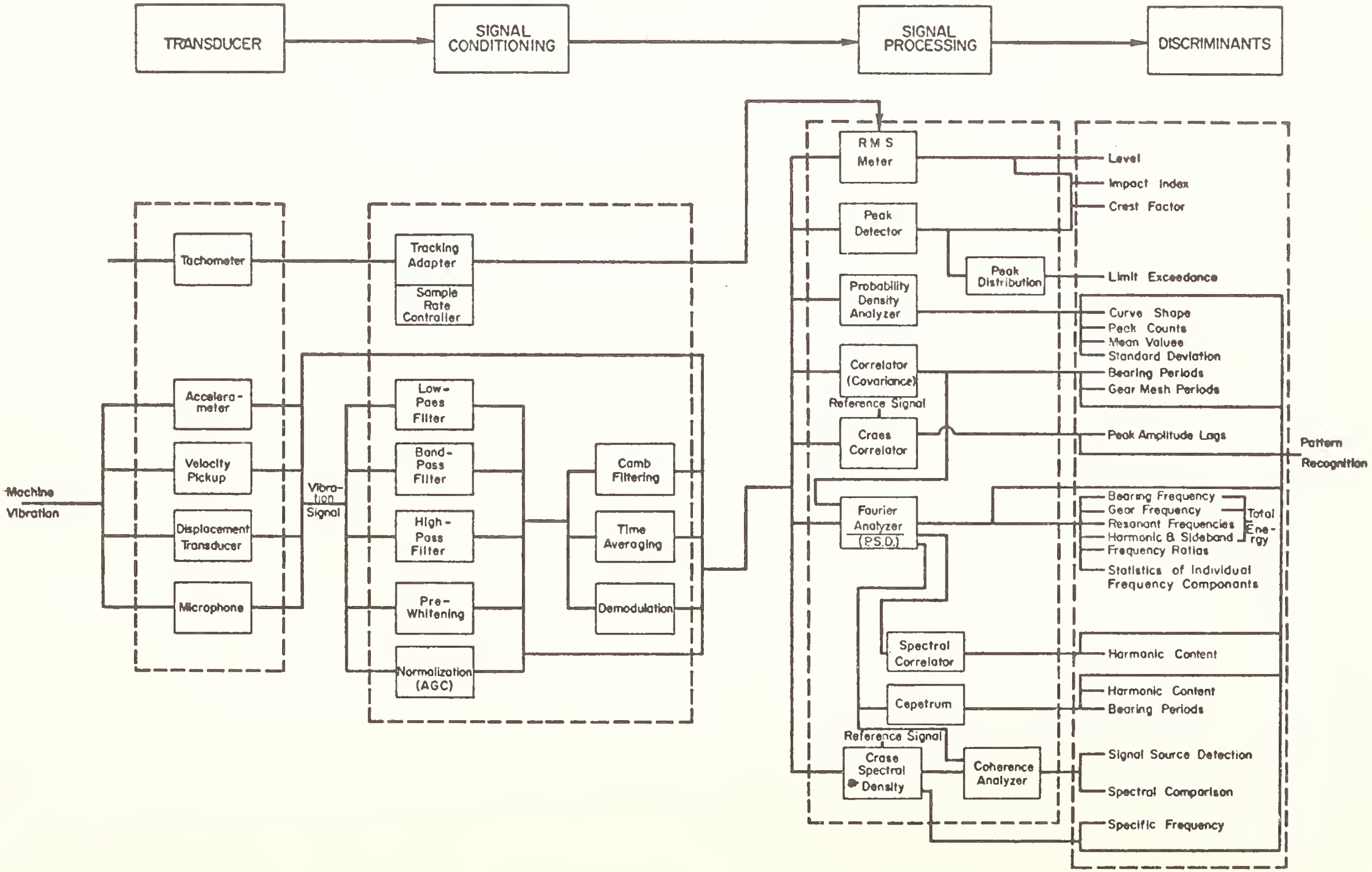

Figure 2. Vibration Signal Analysis for Diagnostics.

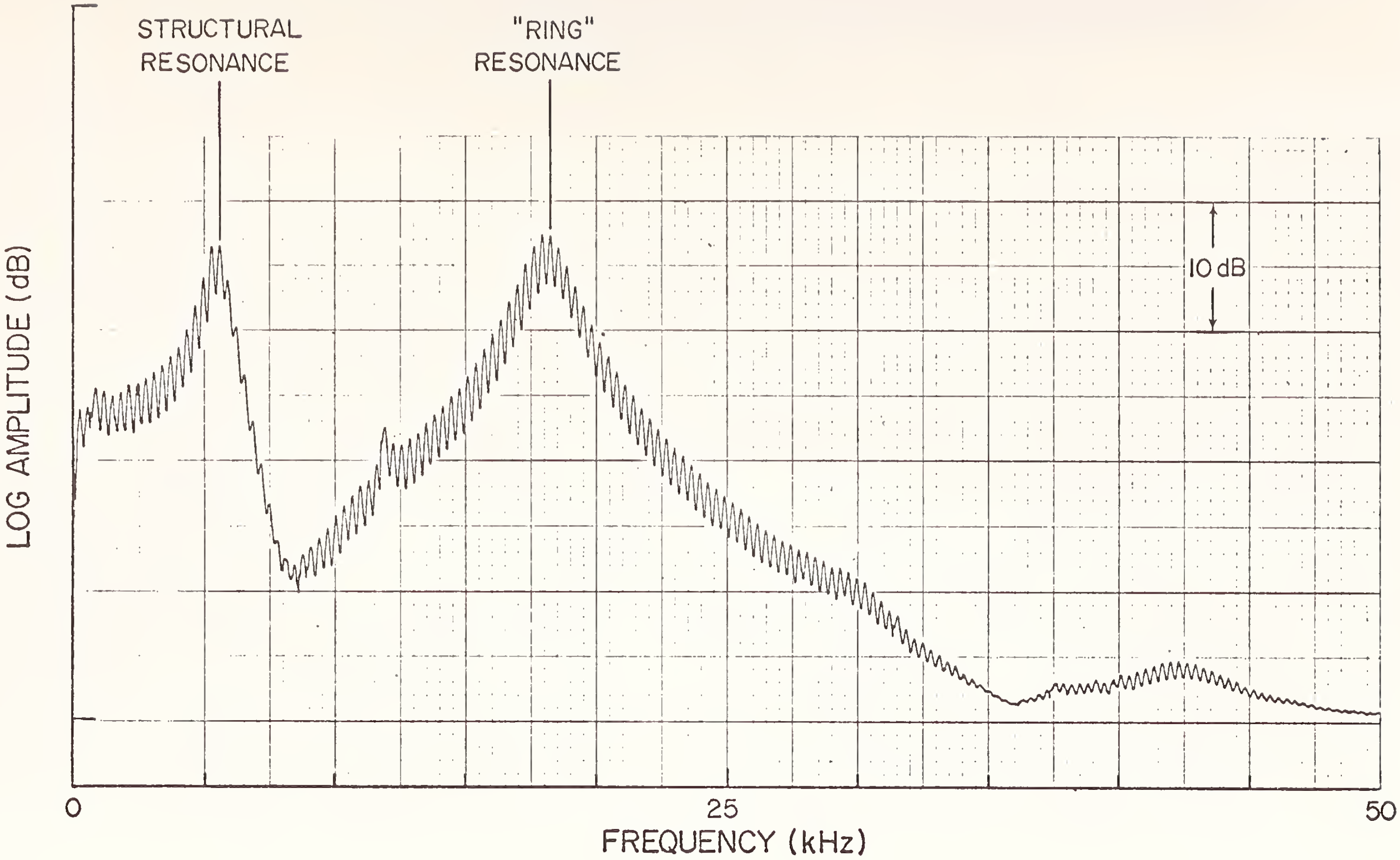

Figure 3. Frequency Spectrum of an Analog Model of a Bearing Containing a Discrete Fault.

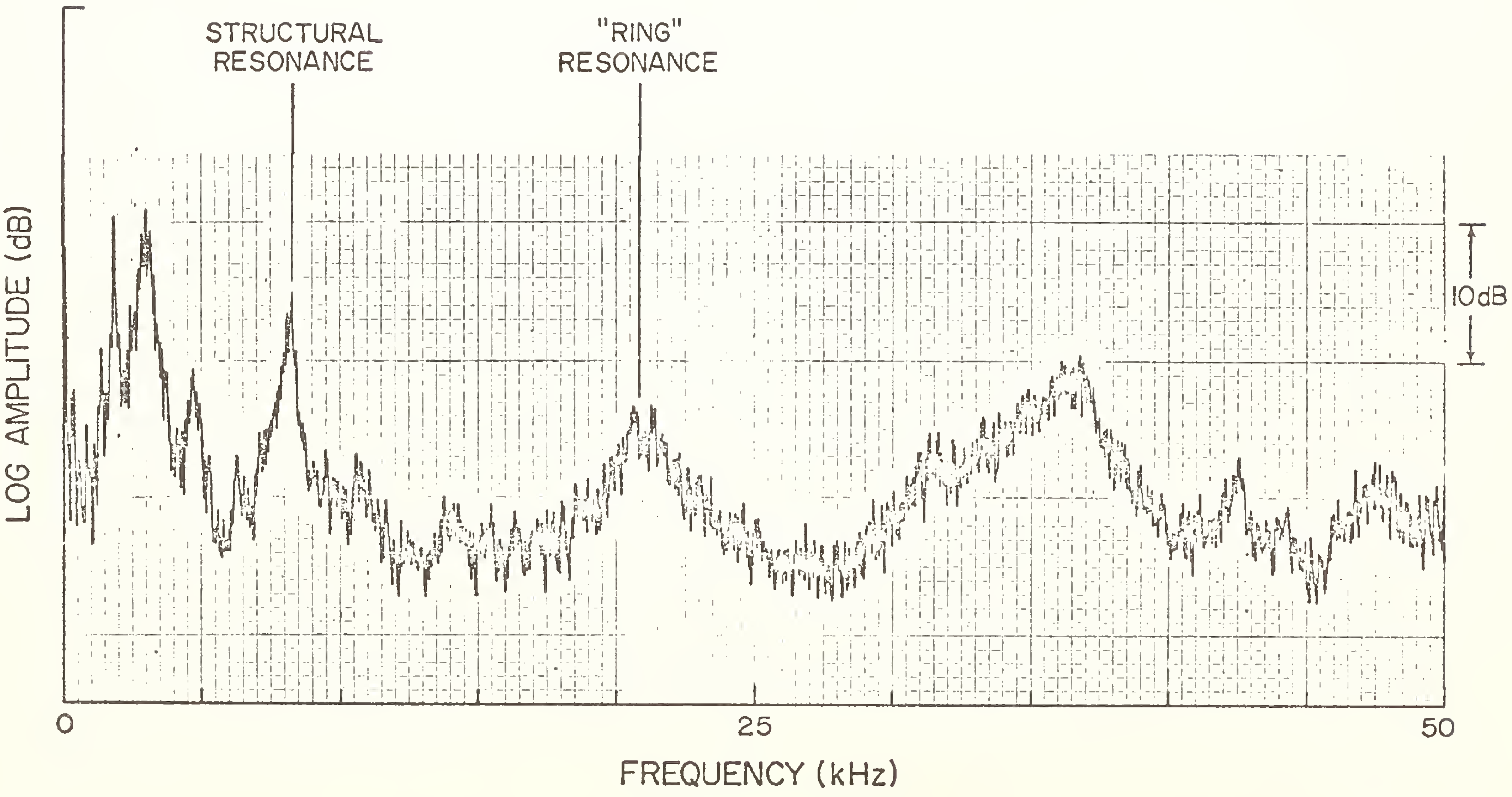

Figure 4. Measured Frequency Spectrum for a Bearing Containing a Discrete Fault.

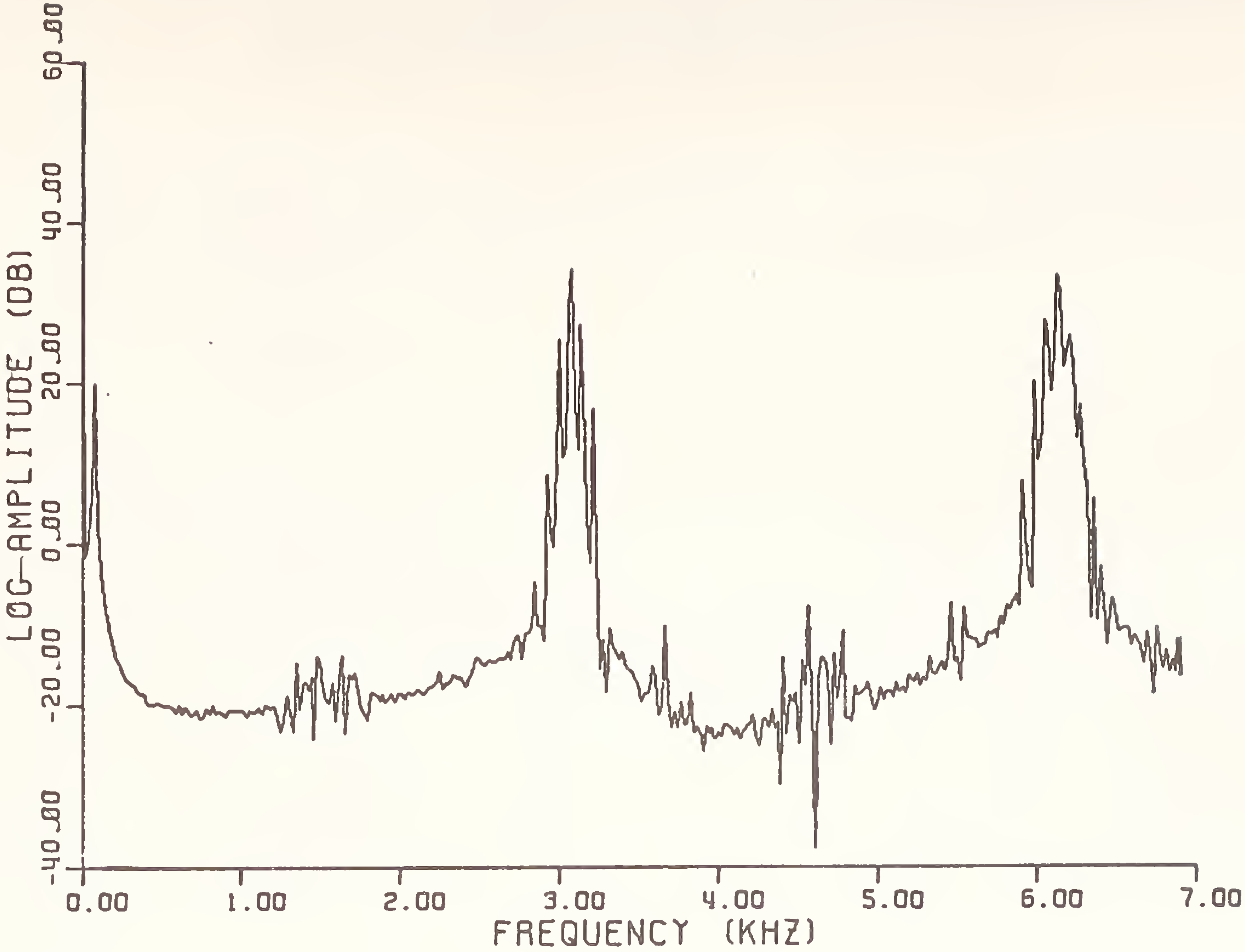

Figure 5a. Dynamic Model Frequency Spectrum (good gear).

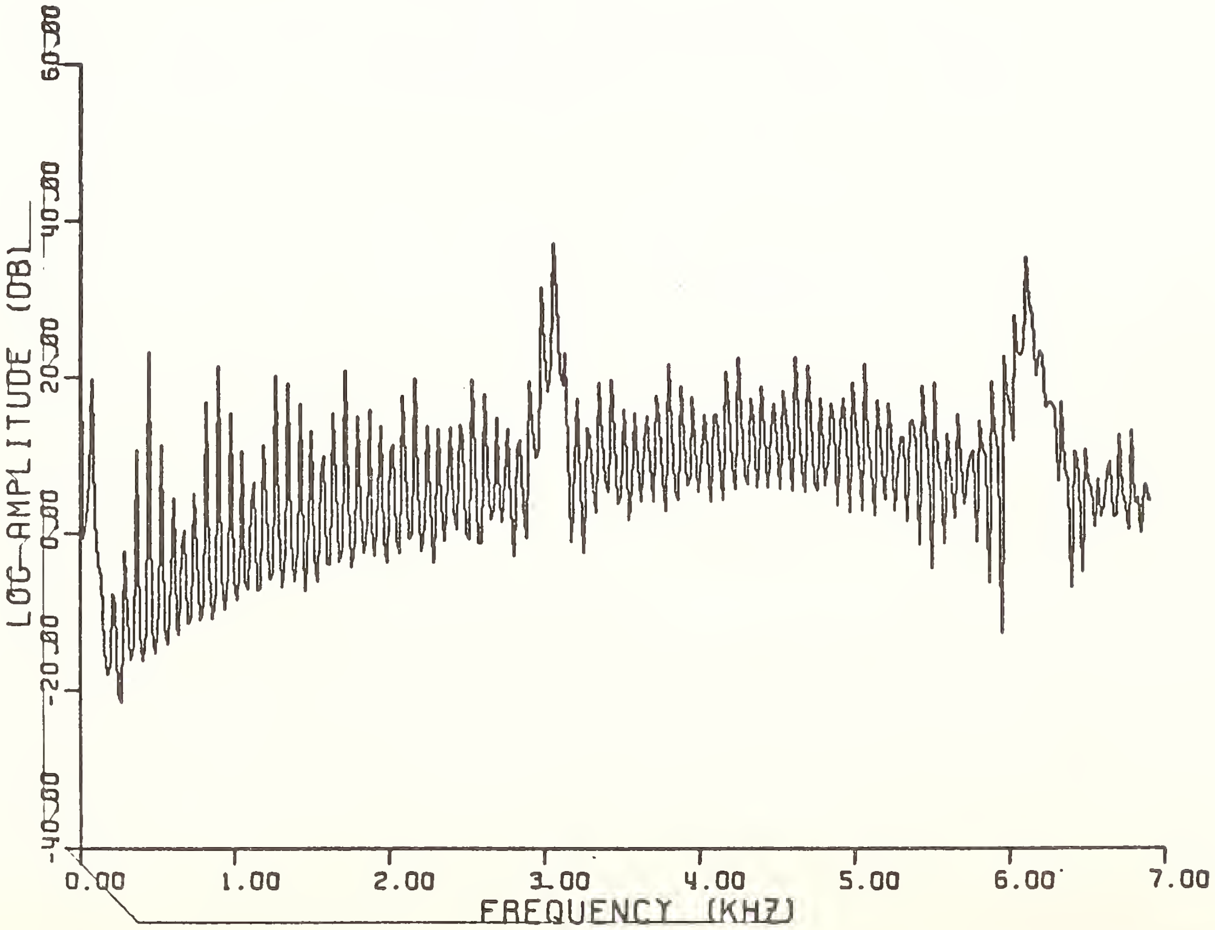

Figure 5b. Dynamic Model Frequency Spectrum (gear with pitch line pitting on a single tooth).

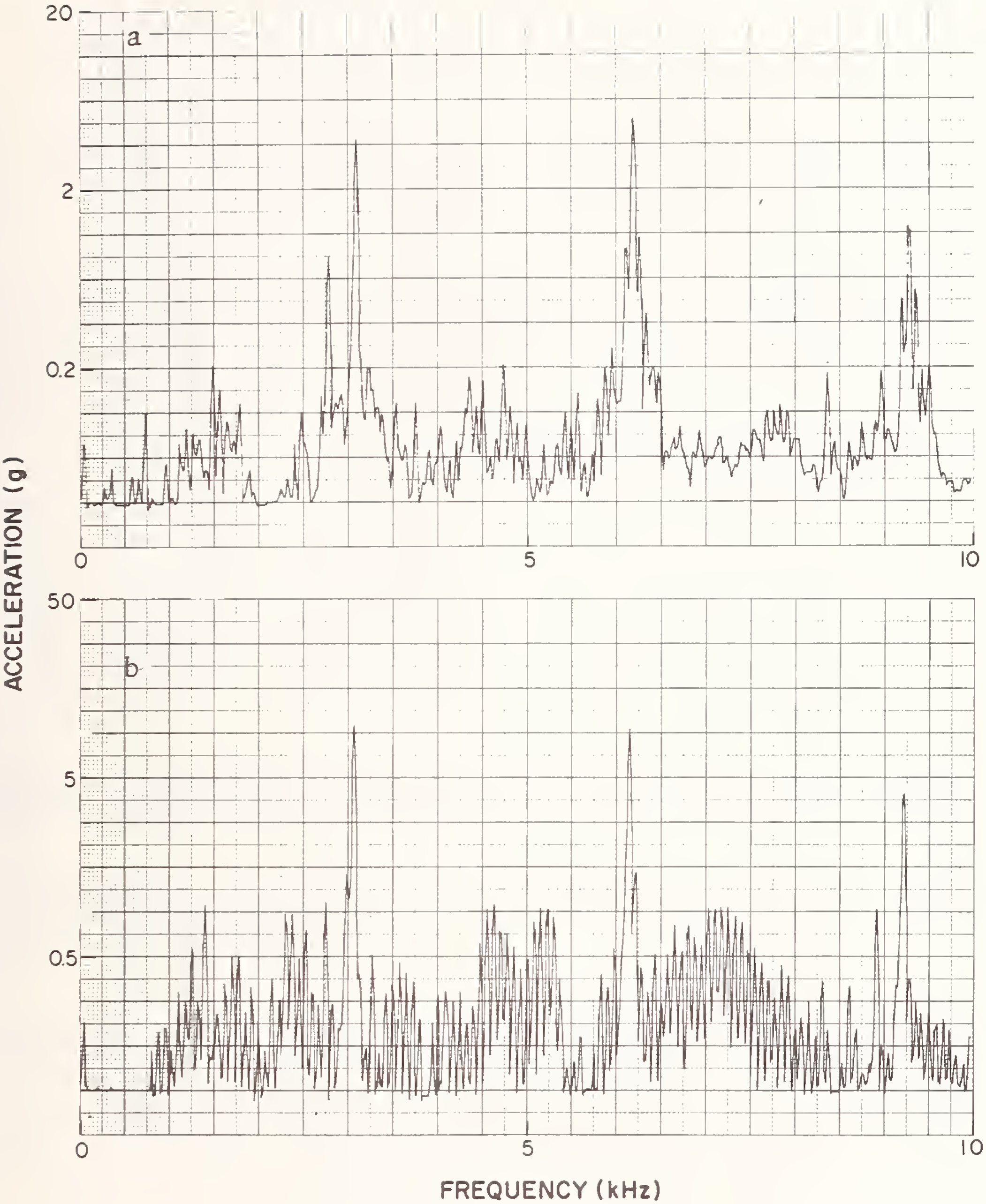

Figure 6. Frequency Spectra for Running Gears.

a) good gear

b) gear with pitch line pit on a single tooth

DISCUSSION

G. deLong, Naval Air Systems Command (Pacific): I wonder whether your bearing analysis has been used for quality control on new bearings?

D. R. Houser: I have not discussed quality control specifically with bearing manufacturers in enough detail to really answer that question. There may be some people here who can answer it.

P. L. Howard, SKF Industries: We at SKF use two basic kinds of tests to check the quality of our bearings. One is three-band vibration, the object of which is to give the customer as quiet a bearing as he is paying for. The second is crest detection, described at earlier MFPG meetings by Kemp Smith and me. In crest detection, the ratio of vibration peaks to the RMS of the vibration is determined. The object is to find assembly damage in the bearing. These techniques can be equally well applied to incoming inspection, in fact, Du Pont in Delaware is doing just that. They are examining incoming bearings using both three-band vibration and crest detection. Another technique called shock pulse was listed on one of Don Houser's charts. That technique is probably better suited for machine or assemble bearing checking than it is for individual incoming bearing inspection because it picks out the bearing source damage in the machine generated noise. So shock pulse doesn't show as strongly as a bearing quality control tool as it does as a machine diagnostic tool.

O. E. Compton, Northrop Corporation, Aircraft Division: Have you employed any analytical models on crossover loading effects in thrust bearings?

D. R. Houser: I have not personally. Most of the bearing loading in bearing models has been quite simple in nature as far as diagnostic type applications are concerned.

D. B. Board, Boeing Vertol Company: I was interested in your model of tooth damage because we have been doing some work in the high frequency regime - a modulated carrier type analysis. On a test stand we damaged a spurgear tooth and we did indeed see the exact type of one per revolution trace that you showed when that tooth comes through the mesh once each time. We got a very large signal change. But our experimental data disagree with your model since we could see nothing changing in gear mesh at all.

D. R. Houser: I didn't say that the gear mesh changed significantly; in fact, our model only shows that through the 3 db increase in amplitude with the gear mesh.

D. B. Board: I thought you said there were side band changes.

D. R. Houser: The only time we got side band changes was when we put a torque oscillation in the system. There was a torque fluctuation, but this was not due to the pit in the tooth.

D. B. Board: We did another test where there was a small crack in the gear starting at the tooth and propagating through the web down to the bolt hole where it is mounted. We again got very large one per revolution signal changes. I believe that there was a torsional stiffness change. We didn't see any change in the gear mesh.

D. R. Houser: The gear mesh frequency stiffness is so great relative to the rest of the system that I would doubt very much if you affected the overall stiffness changes in a once per revolution fashion enough to produce the effect that we are talking about. We are talking about a fluctuation of 20 to 30% of mean torque.

W. R. McWhirter, Jr., Naval Ship Research and Development Center: Where were you placing the sensor in your experimental analysis?

D. R. Houser: For our bearing work, we normally placed the sensor reasonably close to the bearing. On our rig, there were two shafts driving a gear, and there were two sets of small bearings about a foot apart. We tried moving the sensor to various positions on the rig.

W. R. McWhirter: To get an idea of the mechanical impedance?

D. R. Houser: To see how the signal travels. There was definitely a reduction in the high frequency oscillations as the sensor was moved farther away from the bearing; however, we still did pick it up.

W. R. McWhirter: In one of the reports you did for Fort Eustis on the gear trains for helicopters, didn't you place sensors on the bearing housings or on the gear housings?

D. R. Houser: We didn't really place sensors there. Most of the data analyzed for helicopter transmissions was obtained from AVSCOM. They chose the transducer locations. In our gear work, we located transducers as close as we could to the bearings. The gear box we used was an offset gear box from a UH-1 main transmission. We did try mounting transducers right on the flexible parts of the housing, but we definitely got a reduction in usable information.

E. DuBack, General Dynamics, Electric Boat: The bulk of your presentation dealt with frequency domain results. What about other domains?

D. R. Houser: For gears, we did only frequency domain work. We have done some correlation work on some of our bearing rigs, but you just don't get that much information relative to that from the frequency domain.

A NEW TECHNOLOGY FOR BEARING PERFORMANCE MONITORING

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Annapolis, Maryland 21402

Ball bearing rings are of relatively thin cross section. These rings deform when the bearing is loaded. Under a pure thrust load the rings expand equally at each ball position as indicated in figure 1. As shown in figure 2, the contouring of these expansions are seen with the aid of holographic interferometry. In this case a 3½" diameter bearing is shown which has been loaded with 600 lb thrust. The peak displacement was measured as 80 microinches. During bearing operation, the ball complement rotates. This causes the surface expansions to travel about the periphery of the bearing rings. There is, then, a traveling wave of sizable magnitude on the bearing rings.

A new approach towards monitoring bearing performance has evolved since the first observation of these waves. An important element of this new technology is the fiber optics probe, shown in figure 3, which is used to monitor the bearing ring displacements. This probe can be inserted into a bearing housing perpendicular to the bearing outer ring (see figure 4). The output of the probe, when displayed on an oscilloscope, generally produces a characteristic pattern very similar to a half-sine wave, figure 5. Since this wave is generated by the passage of balls past the probe, it provides an exact measure of the ball-passage frequency. By additionally measuring the shaft rotational frequency, and taking the speed ratio of shaft revolutions to ball train revolutions, the measurement can be converted to an operating contact angle. If the initial geometries and clearances of the bearing are known, bearing loads can be calculated. This capability to monitor the speed ratio can be useful in several ways: checks for improper machinery assemblies can be made since bearings stuck or misaligned in their housings and fits which are too tight are detectable; bearing performance during thermal transients can be observed and thermal lockup prevented.

For example, figure 6 shows speed ratio measurements of the "floating" bearing in a vertically mounted 75 hp motor whose bearings were properly installed. After passing through a brief thermal transient, the speed ratio settled to a value very close to the calculated or design value which was based on a 780 lb bearing thrust load. When the same motor was assembled with bearings which were too tight in their housings, the speed ratio varied as seen in figure 7, and did not settle close to the design value. Bearing loads varied from 120 to 950 lb in this case as the motor passed through the thermal transient following a startup. The final load value corresponding to the equilibrium speed ratio was 250 lb as opposed to the desired design value of 780 lb.

The fiber optics instrumentation system described above can not only be used as a tool for correct bearing installation monitoring but also as a tool for the detection of bearing faults. In this capacity, it is extremely sensitive for it has been observed that bearing defects can be positively identified from their inception with this system. This is so because the probe is sensing bearing vibrations directly. Therefore, the signal is not confounded by extraneous frequencies and resonances in the machine structure. As explained earlier, a good bearing generates a smooth waveform. If a bearing has defects they will first appear as discontinuities in that otherwise smooth waveform. If a bearing has a flaw on its outer race, discontinuities will be created as shown in figure 8a; i.e., one per wave as each ball impacts the flaw. An inner race defect would produce the disruptions shown in figure 8b; i.e., discontinuities on every wave but spaced closer than the main wave. Figure 8c illustrates the signal when a single ball has a defect; i.e., the discontinuities are centered about one wave only and the spacing is equal to the ball spin frequency.

A case study of a bearing with a defect illustrates the high sensitivity of the fiber optics system. Photographs, figure 9, of bearing displacement waves indicated the presence of a defect on one ball of a brand new bearing. This defect was observed after 15 hours of operation in an electric motor. After 381 hours, the bearing failed. (Failure mode was extremely high audible and structure-borne noise.) Concurrent vibration spectra recorded using an accelerometer stud-mounted to the motor, figure 10, gave no forewarning of the failure. Subsequent disassembly and inspection confirmed predictions of the fiber optics probe. A single ball, figure 11, was found which had a set of ring shaped grooves cut into it. The figure shows a photograph of the intersection of a 100-microinch deep groove with the wear track of that ball.

The accumulation of experience with this new application of fiber optics is continuing.

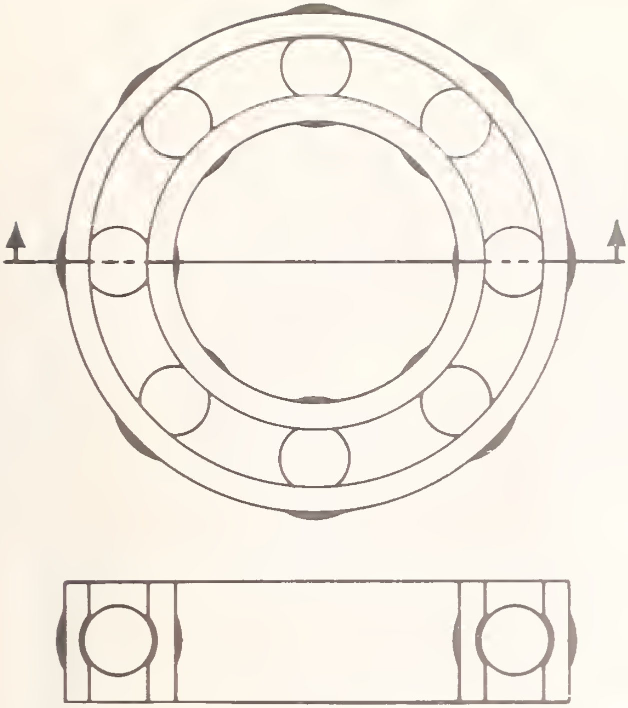


Figure 1
Local Ring Deformations

Figure 2
Holographic Interferogram
Showing Contours of
Local Deformations

Figure 3
Fiber Optics Probe

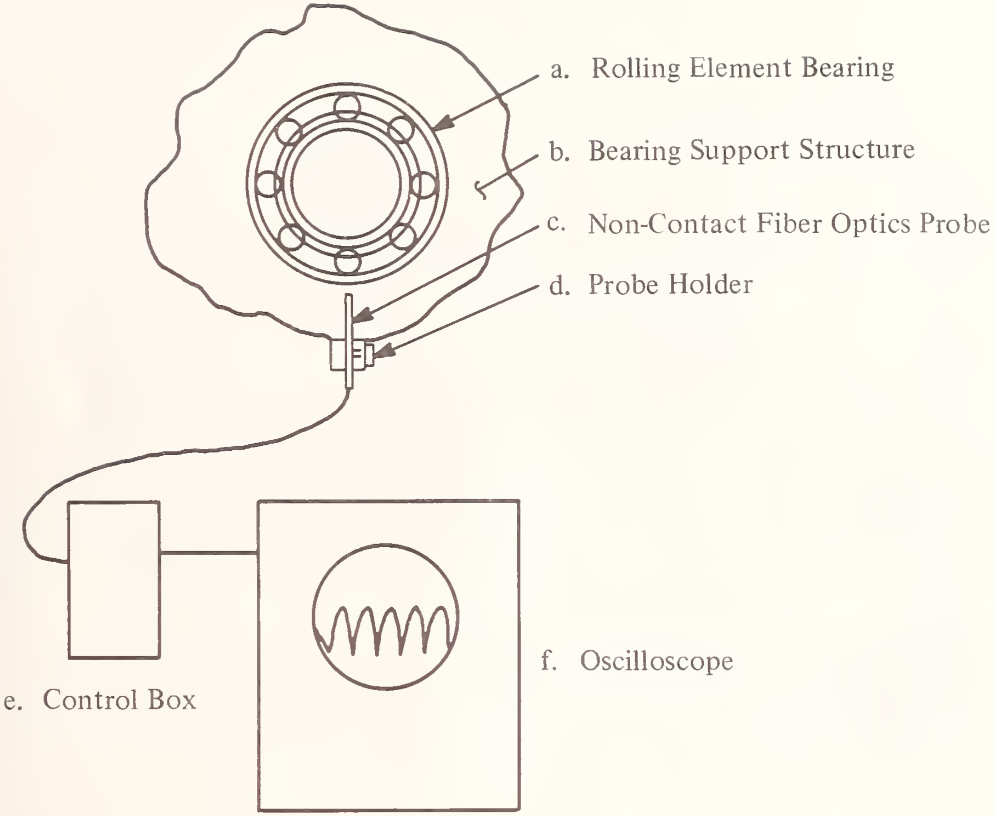


Figure 4
Probe Installation

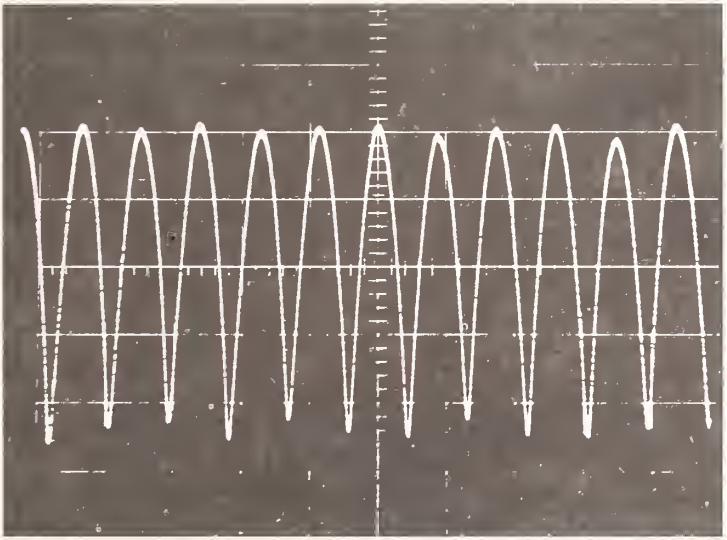


Figure 5
Characteristic Displacement Wave
Form of a Good Ball Bearing

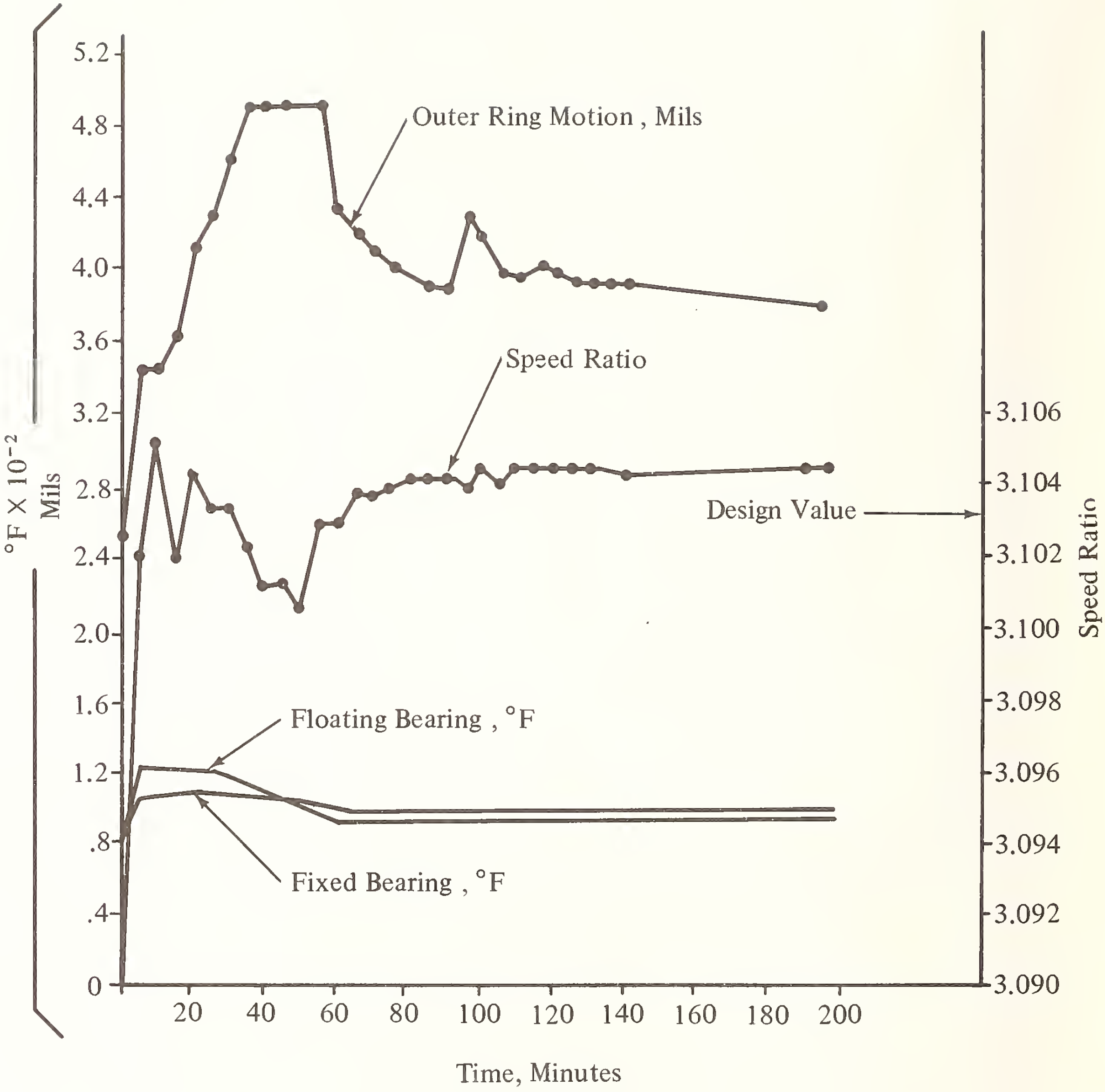


Figure 6
Speed Ratio: Loose Bearing-Housing Fit

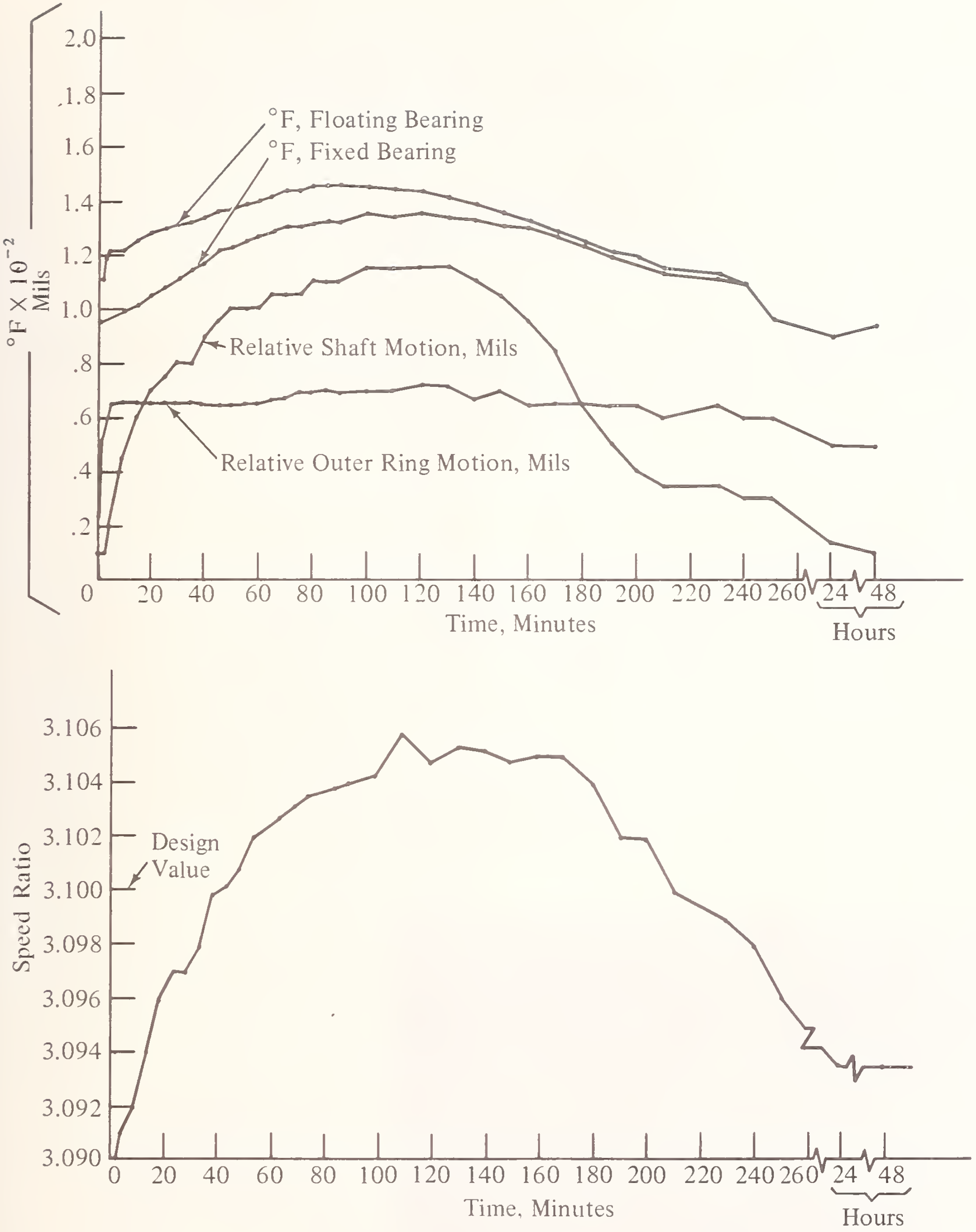
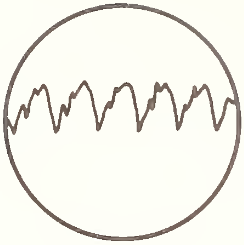
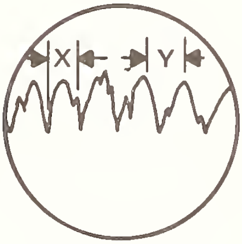


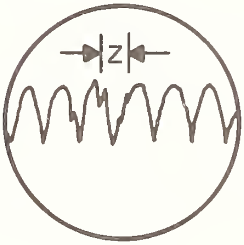
Figure 7
Speed Ratio:
Tight Bearing – Housing Fit



a. Outer Raceway Fault – One Discontinuity Per Wave



b. Inner Raceway Fault – Discontinuities on Every Wave, Spacing (x) Uniform but Less Than Main Waveform (y).



c. Ball Defect – Discontinuities Clustered About
1 Wave Only and Spaced (z)
at Ball Spin Frequency

Figure 8
Bearing Fault Analysis

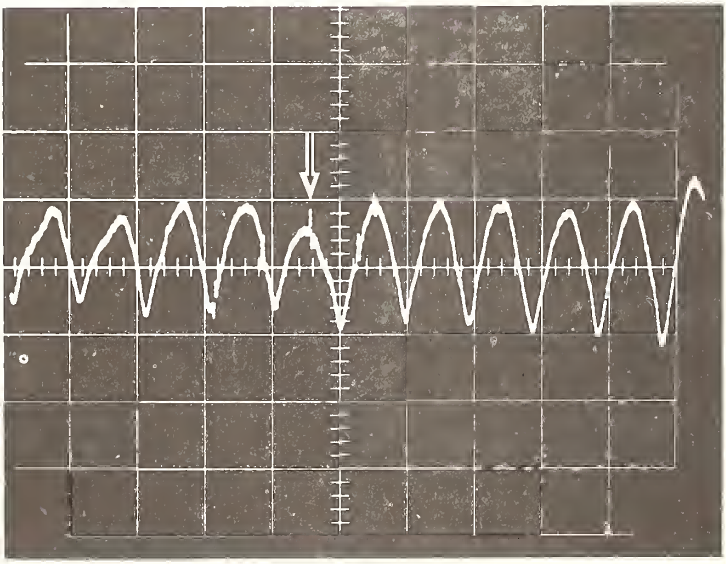


Figure 9
Bearing Wave Form
Showing Presence of
One Defective Ball

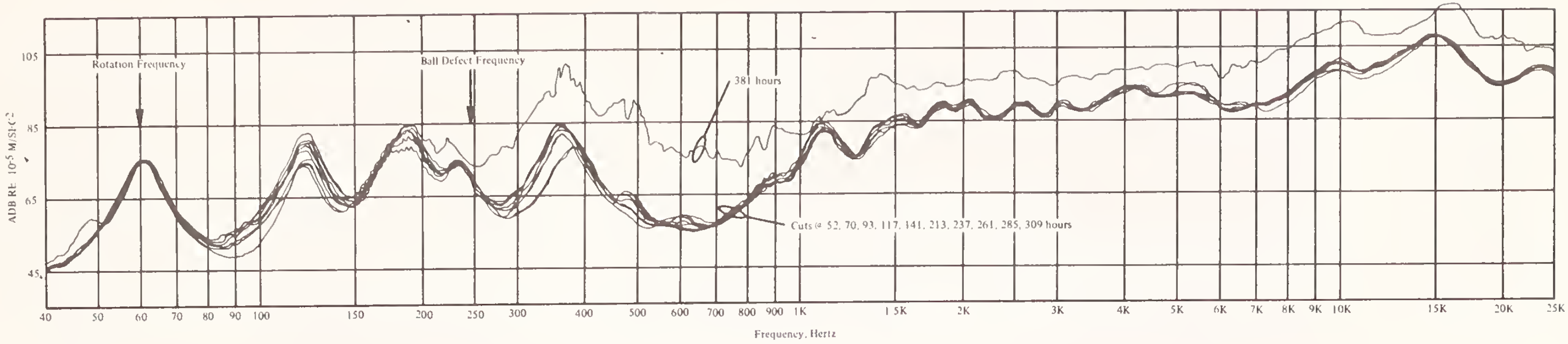


Figure 10
Motor Vibration
with Defective Bearing

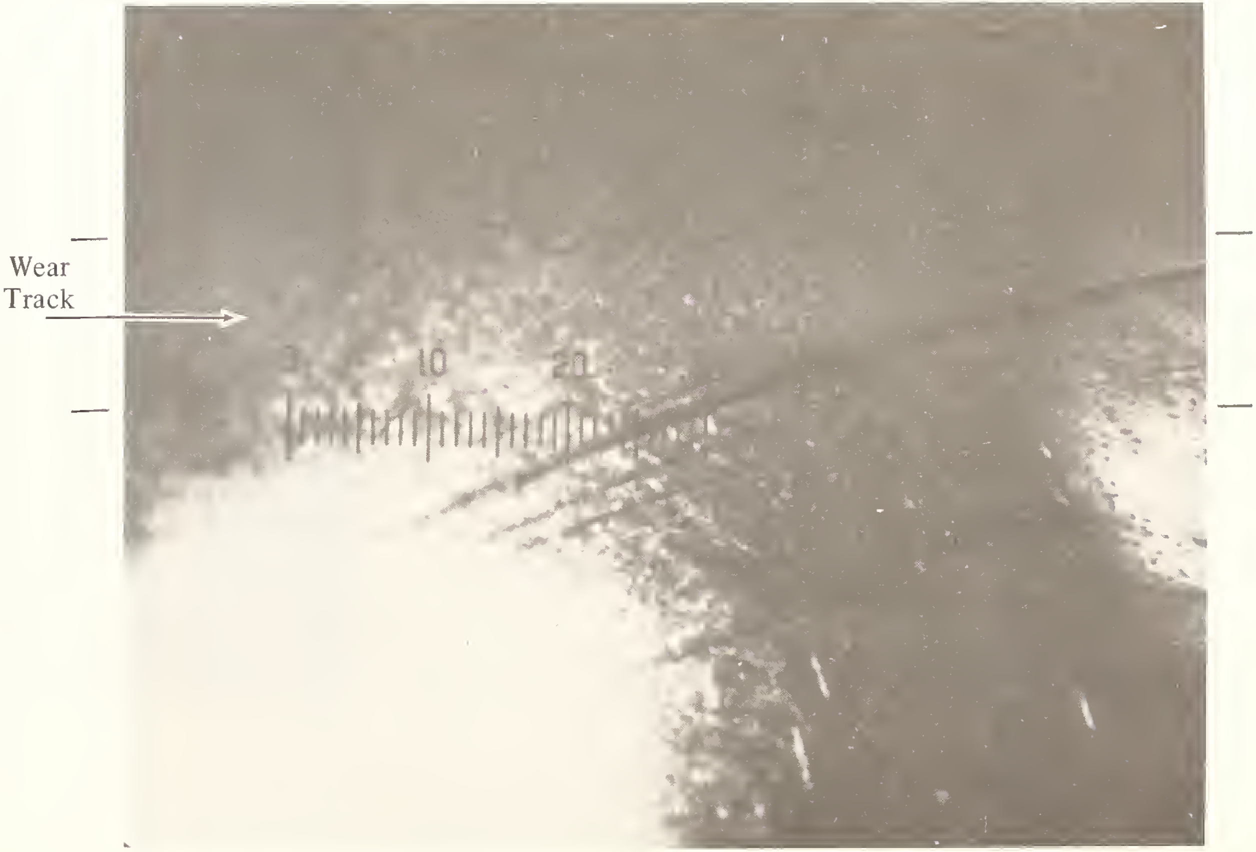


Figure 11
Defect on Ball
(At Intersection With Wear Track)

DISCUSSION

J. L. Frarey, Shaker Research Corporation: You showed the vibration spectra going into the high frequency region. Did you filter or demodulate any of the high frequencies as Dr. Houser mentioned?

G. J. Philips: No.

J. L. Frarey: I can see how you could get little spikes from bad balls in ball bearings by looking at the outer race at one point, but how can you see outer race defects 180° away from the location of the probe?

G. J. Philips: That's one of the development areas that I want to look at. Hopefully, the rigid body motion of the ring itself will be sufficient to enable us to pick up the signal. It may turn out we will need more than one sensor.

D. N. Schuh, Beta Machinery Analysis, Limited: What are the amplitudes of the motion that you are observing?

G. J. Philips: In one particular case that I mentioned earlier, 80 μin was the peak-to-valley displacement for that size bearing with 600 lbs. load. Generally, the amplitudes are less than 100 μin. Some bearing defects produced spikes corresponding to a displacement of 10 μin.

D. N. Schuh: And this occurs even though the bearing might be tight in the housing?

G. J. Philips: Yes.

D. N. Schuh: Do you feel this is going to be a practical technique for field type measurements? It seems that very high accuracy is required.

G. J. Philips: Yes, that is what we are shooting for. The big thing we have going for us here is that the signal itself is so simple. We are planning this year to look at a large quantity of bearings to try to develop some statistical confidence in what we are doing. As I mentioned we are going to be inspecting brand new bearings and looking at failures that have been returned to us from the fleet. We will also be looking at the assembly of electric motors. We are trying to get as much experience with this technique as we can.

D. M. O'Dea, Exxon Research and Engineering Company: Why did you use fiber optics in preference to strain gauges to monitor the outer race?

G. J. Philips: We started this work about four or five years ago and I don't remember what governed my selection of the transducer. I'm not saying this can be done only with fiber optics, but since I have been using that transducer I found it very convenient. It is very easy to work with. You need only a hole about one-eighth inch in diameter to provide access to the bearing. A strain gauge must be wired to the bearing, which is very awkward. Fiber optics is non-contact, it does not interfere with the operation of the bearing.

R. M. Whittier, Endevco Corporation: Errors might be due to two things. One would be the mechanical effects of the oil in the gap between the outer race and the casing. The second would be the reflectivity of the optic gauge on the race because of the presence of oil.

G. J. Philips: The displacement wave is a purely mechanical function. It depends on the geometries involved and the applied load. The reflectivity of the probe itself is affected by any kind of fluids between the surfaces. I haven't done any correlation with exact amplitudes. Right now, it's a go, no go type of gauge. Either the wave form is smooth and has no spikes or it contains spikes.

C. E. Horten, Naval Ship Engineering Center: We are presently monitoring some 50 pieces of rotating machinery at deployed sites with a real-time analyzer. We have been doing it for about five years and we recommend bearing removal and replacement based on the sound cuts. We send these bearings back to Annapolis for analysis. Very often the acceptance tests that are run on bearings using an andarometer show the bearings to be OK because a laboratory test stand is used. Are you going to tie in your work on this new technique with the signatures of bearings installed in the fleet?

G. J. Philips: When I checked the bearing that I showed with the ball defect on our andarometer it ran smooth and quiet, like a noise-tested bearing. When I mounted the probe on the andarometer head and looked at the bearing vibration, I could again see spikes. The andarometer is a three-band vibration measuring instrument. It measures an RMS average of vibration over a very broad frequency range. It's a rough quality control instrument. This fiber optics probe goes beyond that. It discriminates bearing faults whereas the andarometer can't. At Annapolis this year, we will be looking at thousands of bearings from current Navy stocks with this technique.

D. W. Long, Pacific Fruit Express Company: Have you done any work on cylindrical or tapered roller bearings and would you expect this technique to be useful in the diagnosis of these bearings?

G. J. Philips: I haven't done much work myself with the roller bearings because ball bearings are used to such a wide extent in the fleet, but the theory of defects is the same for both roller bearings and ball bearings; it is just a matter of the magnitudes. There is so much more contact area in a roller bearing that it might be possible to straddle a fault and not detect it.

BEARING CONTACT RESISTANCE AS A DIAGNOSTIC AID

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The technique described below can be used to determine the relative "health" of an operating bearing by measuring its contact resistance. The approach described is not presented as a "beat--all" bearing monitoring system but rather an alternative for certain bearing applications. Use of the technique described, requires a small D.C. voltage (normally less than 100 millivolts) to be placed across the bearing during the time of fault detection. Most of the data shown on the figures below are taken from an analysis of several freight car roller bearings used in the railroad industry.

When two solid surfaces are put together, "asperity contact" occurs. The degree of metallic interaction or asperity contact between bearing components is determined by the lubricant film thickness within the bearing. Lubricants used to minimize asperity contact in bearings attempt to maximize this film through boundary or hydrodynamic means.

Variations in electrical resistivity as a result of asperity interaction were for many years (1)* observed with the oscilloscope. Photographs similar to that shown in Figure 1 revealed the degree of asperity interaction within an operating bearing. A time varying contact signal can be obtained from a rolling element bearing with the aid of the circuitry and test arrangement shown in Figures 2 and 3.

Properly-lubricated bearings operate with a minimum of metal contact between rolling elements. Best designs operate with fluid films which are at least four times the average component surface finish. Since most lubricants are organic hydrocarbons, a high average resistance is maintained between the inner and outer race of a well-lubricated bearing. Experience has shown that average bearing operating resistances may range from one ohm in the case of the freight car bearing, to over a million ohms in a fully flooded instrument bearing.

Bearing average operating resistance is a function of operating film thickness. Typical film thicknesses (2) calculated for a railcar roller bearing are shown in Figure 4. This type of bearing has a surface roughness normally greater than four micro-inches. The analytical film thickness shown assumes fully flooded oil lubricated conditions (3). The railcar bearing operates on a grease film and is likely to have a

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* Numbers in parentheses indicate references listed at the end of the paper.

true operating film which is reduced (4) from the values shown. Freight train bearings operate for most of their lives in the boundary lubricated regime as a result of their low average speed, which is reportedly 20 MPH (5). Boundary lubrication implies a high percentage of asperity contact.

Figure 5 is a qualitative functional display of contact resistance and the nominal film thickness generated between the rolling elements of a bearing.

Although functional dependence of resistance and films on unlubricated solids with oxide layers is understood (6) for some metals; the dynamic conditions of lubricated contacts present an extremely difficult analytical problem. Thus, prediction of the exact level of the mean resistance for a given operating bearing, to date, has not been attempted to the author's knowledge.

An experimental display of how the "average" resistance changes when the amount of oil in the bearing is altered and when the viscosity of the lubricant is lowered is shown in Figure 6. The average here is based electronically upon the percentage of time the contact resistance signal is below the selected center-scale-resistance. An effective bearing monitor would make use of this simple resistance level change. Once a nominal operating range has been established, a level sensing circuit could be used to automatically indicate when operation has gone "bad".

Another experimental display of resistance level change is shown in Figure 7. Displayed is the common variation in percent contact for a 202 size bearing while increasing load and keeping the speed fixed. Three constant speeds of 280, 395, and 725 RPM are shown in the same figure. As is well known, the average film thickness of a hydrodynamically lubricated bearing is relatively insensitive to load (inverse 1/11 power dependence). The average electrical contact resistance in the same bearing, however, can change over several decade levels.

Asperity count rate level can also vary with improperly operating bearing components. Figure 8 shows a bearing with a cage which affected the electrical contact rate during each rotational cycle. Bearing components which were forced into sliding as a result of the out-of-round-cage could be one explanation for the observed data.

A.C. as well as D.C. level changes in the asperity contact signal can also be used to establish bearing "component health". A look at the time varying asperity signal on the oscilloscope reveals what appears at first glance to be a random signal filled with "white noise". The real time spectral analyzer, however, reveals singular spikes in those bearings which have inherent defects.

A comparison reference spectrum of a "new" bearing of the same size as four defective bearings whose spectra follow is shown in Figure 9. For ease in comparing each of the following spectra shown, all electronic controls of the spectrum and electronic contact analyzer, except one were held fixed during the experiment. The center scale resistance (see Figure 2) was adjusted in order that the A.C. signal variation of the asperity contacts were not suppressed by high or low level clipping.

Figures 10 through 13 display the spectra along with a photo of the inherent defect in each bearing used during the tests. The defects shown were

1. Figure 10, a roller with a split seam line,
2. Figure 11, a bearing with surface corrosion,
3. Figure 12, a dented roller, and
4. Figure 13, a slightly spalled roller.

Sharp edged defects such as that displayed in Figure 10 result in many harmonic "spikes" being present in the electrical contact spectra. An extreme example of this is shown in Figure 14 from a ball bearing. Harmonics to 10,000 hertz at multiples of twice the ball passing frequency are displayed. A ball with a "flat spot" causes this.

A comparison of two bearing diagnostic techniques is displayed in Table I. A ranking of twelve bearings which had inherent defects is shown. Some bearings screened by each technique were found to have signals indiscernable from that of the "good" reference bearing. It should be noted that each of the bearings had previously been found "faulty" for at least one or more of nine reasons without electronic means.

Bearing "L" is found to be "good" with the high frequency diagnostics scheme and ranks as third to the worst with the electrical contact technique.

An opposite ranking for bearing "H" appears to hold. The point here is that neither detection scheme appears to catch "all defects" and those bearings found to be "good" comprised a mutually exclusive set from each technique. It is reasonable that some critical bearing applications could use the complementary aspects of electrical contact analysis.

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4. Chiu, Y.P., "An Analysis and Prediction of Lubricant Film Starvation in Rolling Contact Systems", ASLE Preprint Number 73AM-3B-4, April 1973.

5. "Yearbook of Railroad Facts", AAR Publication, 1974.

6. Gupta, P.K. and Cook, N.H., "Statistical Analysis of Mechanical Interaction of Rough Surfaces", J. Lub. Tech., ASME Trans. Vol. 94F, 19-25, Jan. 1972.

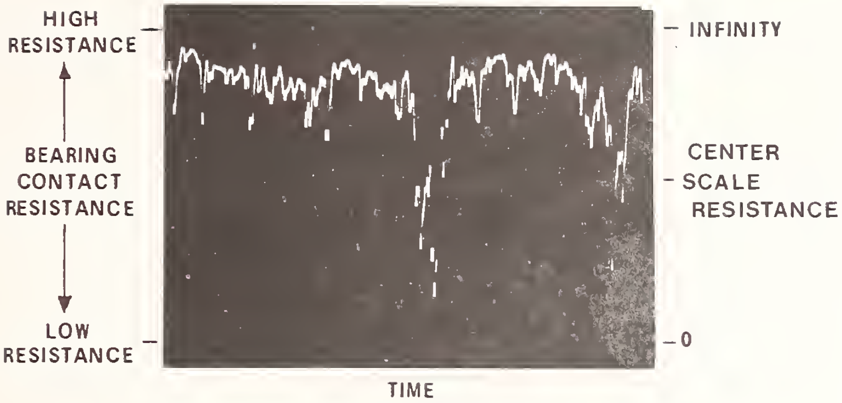

Figure 1. Typical Bearing Contact Resistance Signal.

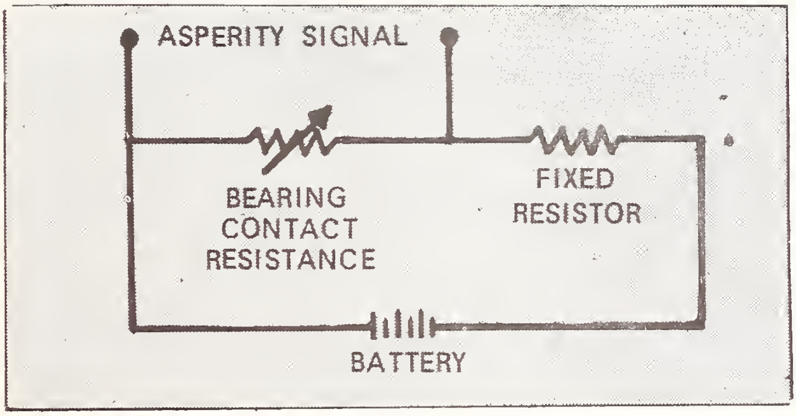

Figure 2. Electrical Contact Diagram.

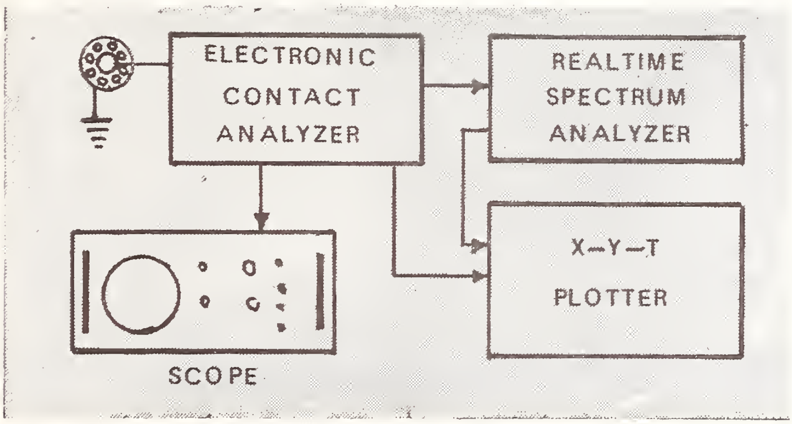

Figure 3. Typical Test Instrumentation Set-up.

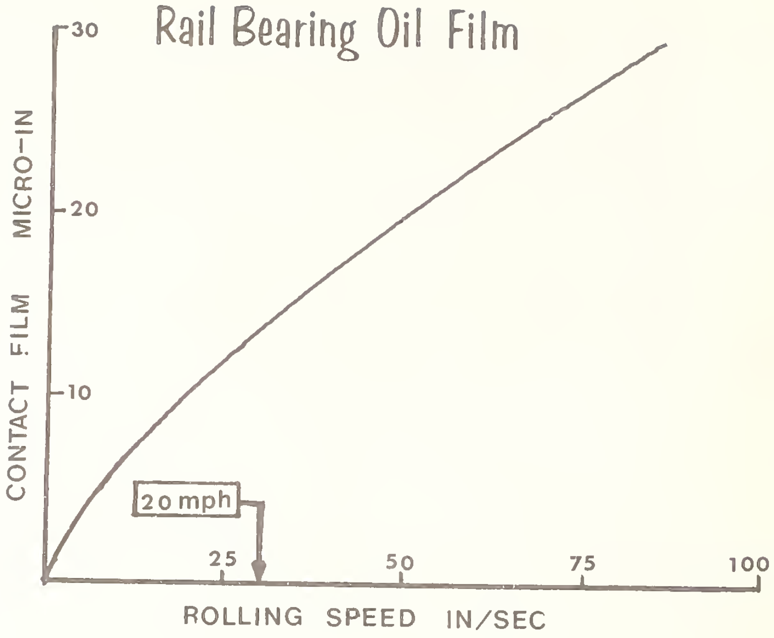

Figure 4. Calculated Railcar Roller Bearing Operating Film Thicknesses.

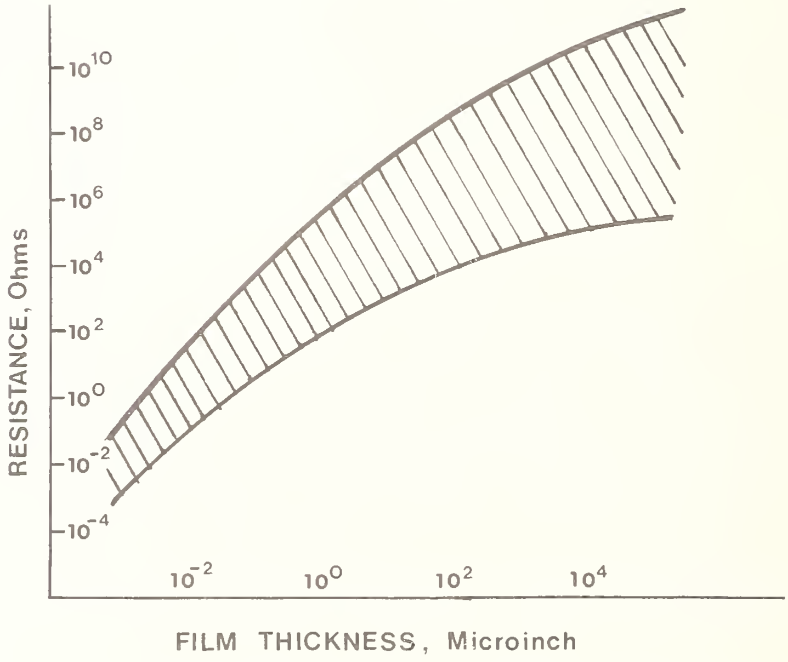

Figure 5. Contact Resistance and Nominal Operating Fluid Film Thickness.

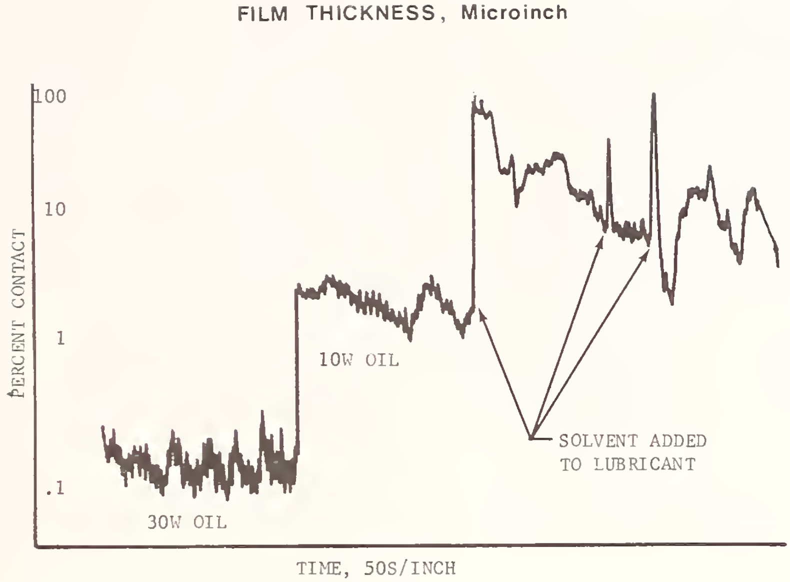

Figure 6. Percent Contact and Fluid Viscosity.

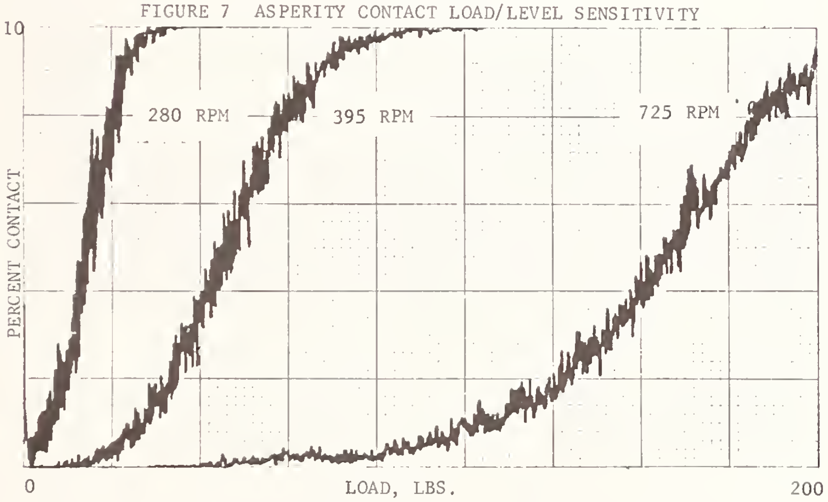

Figure 7. Asperity Contact Load/Level Sensitivity.

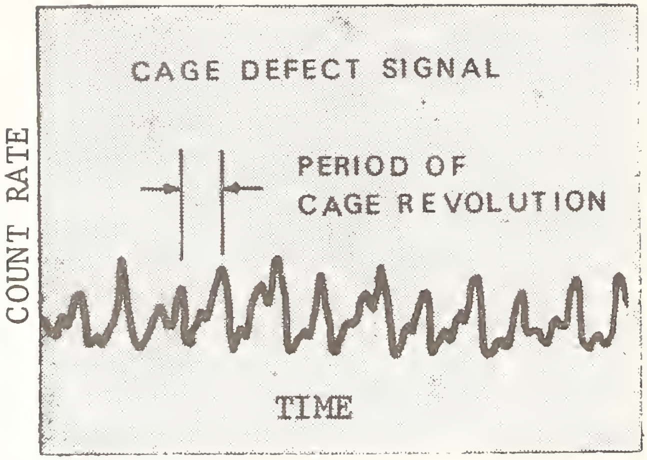

Figure 8. Cage Defect Signal.

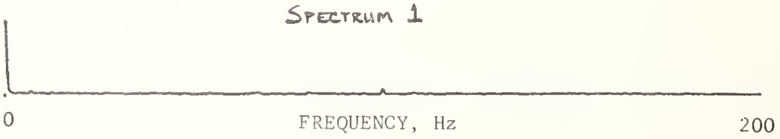

Figure 9. Reference Spectrum From New Bearing.

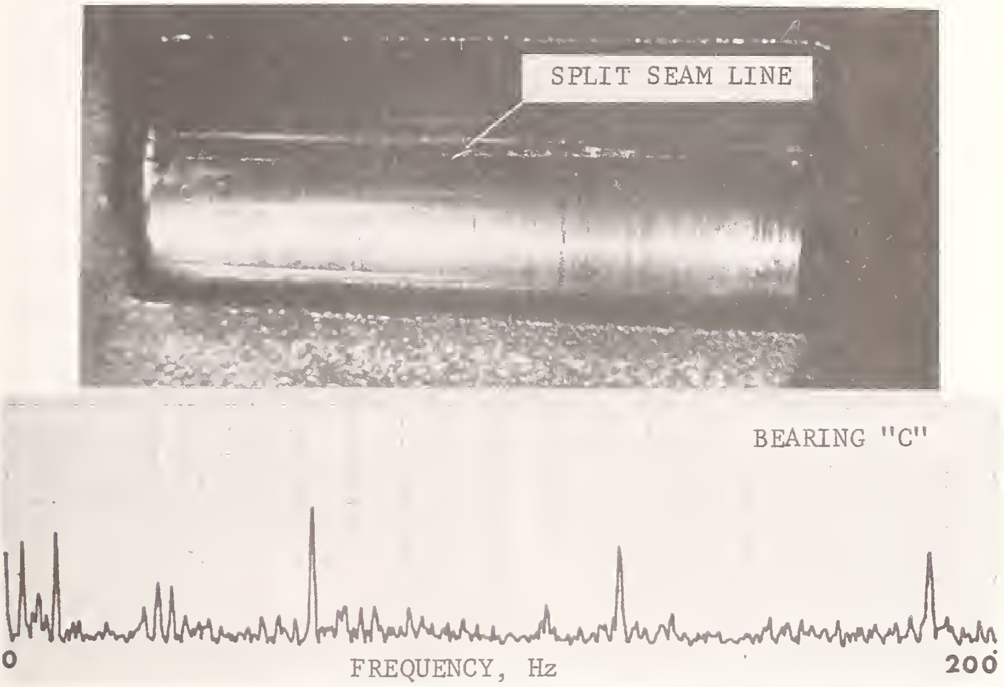

Figure 10. Split Seamed Roller with Spectrum.

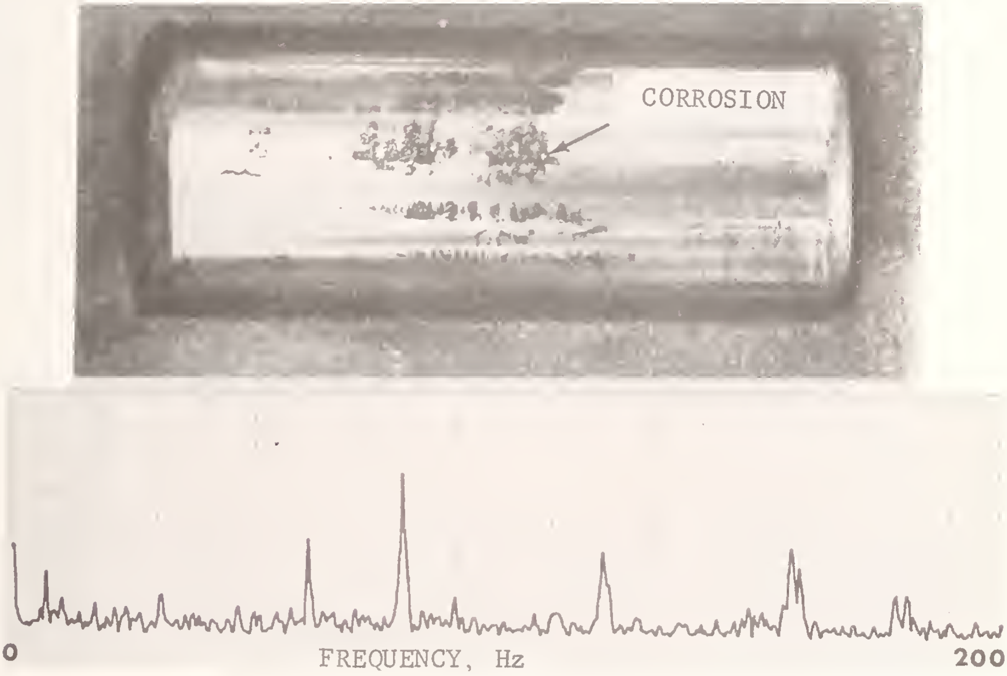

Figure 11. Corroded Roller Bearing with Spectrum.

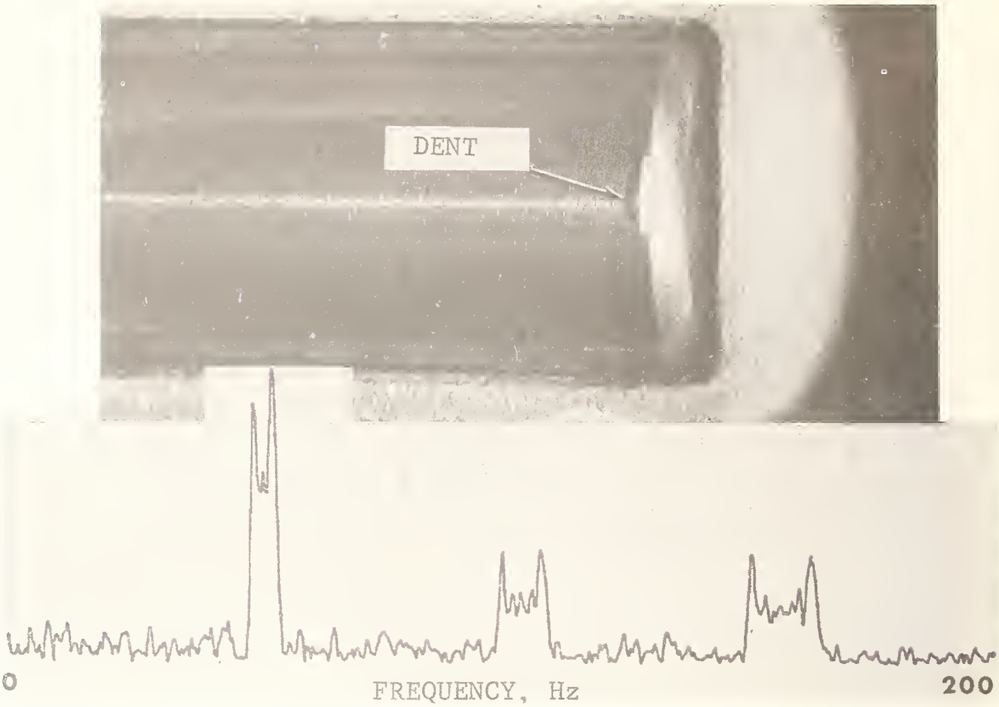

Figure 12. Dented Roller Bearing with Spectrum.

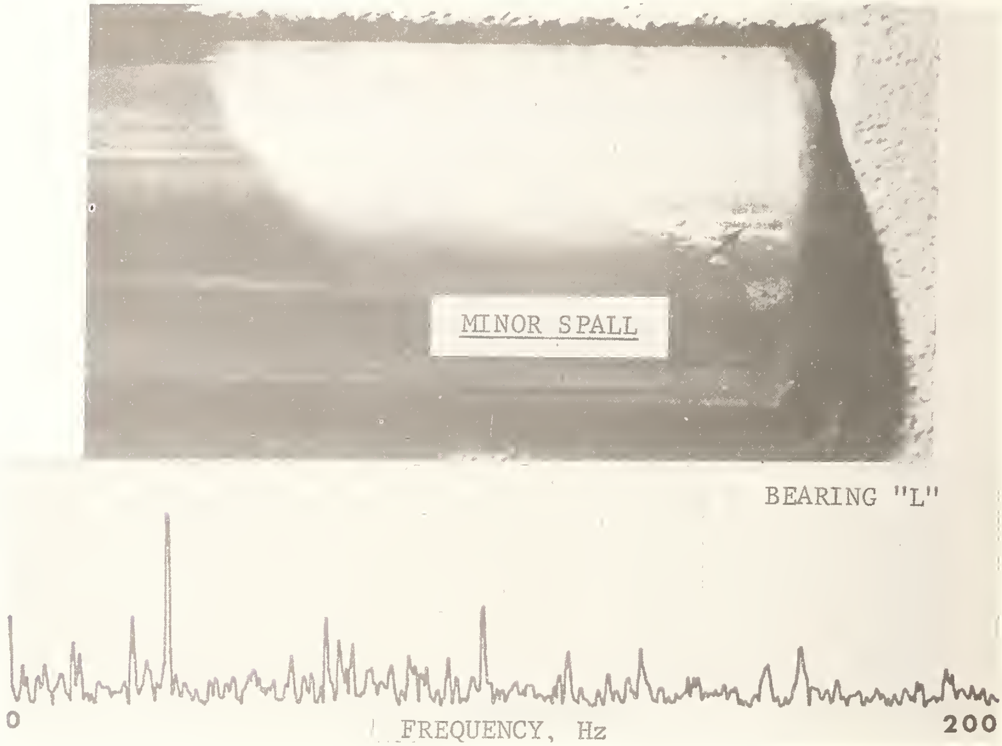

Figure 13. Spalled Roller Bearing with Spectrum.

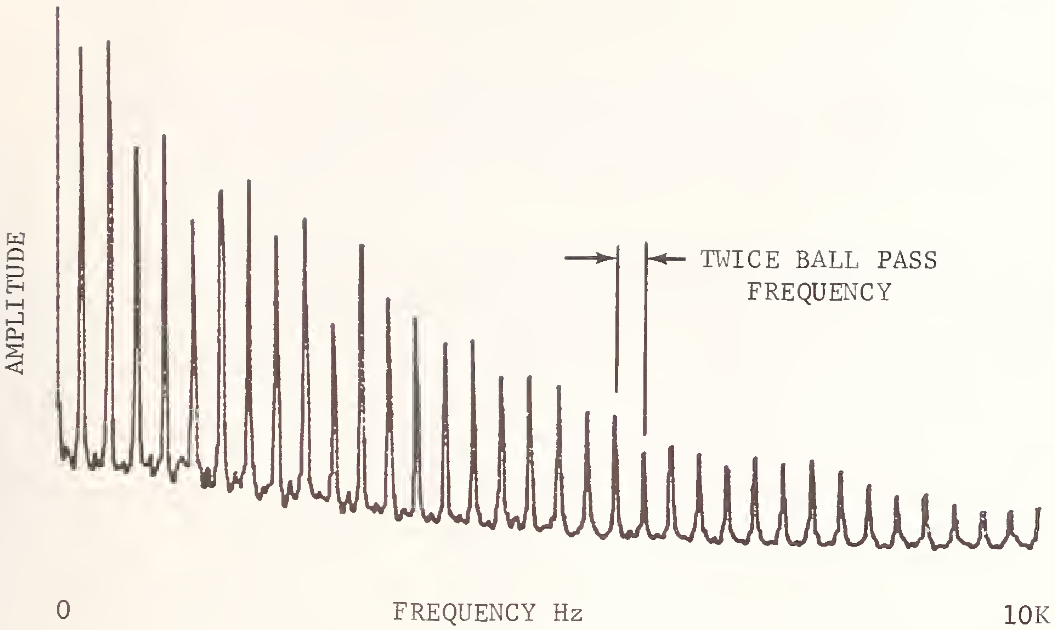

Figure 14. Spectrum of Faulty Ball Bearing.

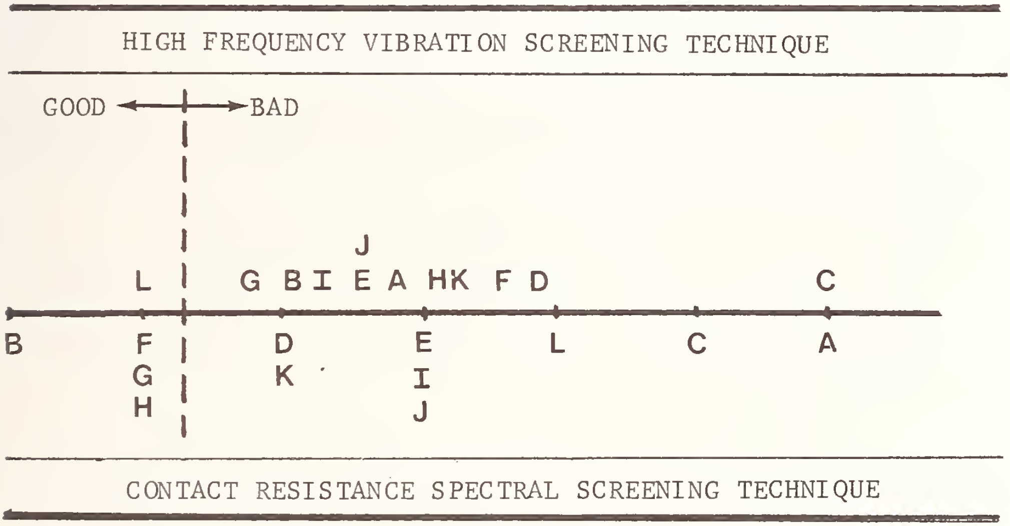

Figure 15. Comparison of Tabulated Bearing Fault Results.

DISCUSSION

P. L. Howard, SKF Industries: How do you control the effect of tunneling through the lubricant and what effect does dirt in the lubricant have on your measurements? I noticed you were changing resistance scales which changes the potential across the bearing quite drastically.

R. L. Smith: I don't really control the tunneling. It occurs when the lubricant film thins to one μin. When it occurs, the resistance must be changed. I am not really controlling tunneling but I do use it. The applied voltage, though, is small enough so that the percent contact is not changed significantly, at least in the regions where I have been looking. In other words, during an experiment the voltage can be changed either by changing the center scale resistance or changing the voltage in the system. If the applied voltage and applied current are limited, then there really isn't a change in percent contact until you have reached a certain specific voltage. In one case I found the voltage to be 0.86 volt applied across the bearing. Other people have found it to be as high as 3 volts. Tunneling or discharge will occur across the lubricant film when the film gets thin enough. When a particle goes through the contact zone, the film gets very thin and, of course, there is a large change in resistance.

P. L. Howard: This is one reason people use capacitance variation.

R. L. Smith: Yes, my experience indicates that capacitance change can be used but it doesn't have that decade level change that resistance offers. The percentage variation due to capacitance changes is always masked by the large capacitance due to the geometry of the bearing itself - the inner and outer races provide a large capacitance and the small variations due to film thickness changes are a small percentage of that large variation.

P. L. Howard: It becomes very valuable at low film level.

NONDESTRUCTIVE TIRE INSPECTION

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NHTSA in 1971 initiated a research effort in the area of nondestructive testing which would apply to inspection and test of motor vehicle tires. This research task was assigned to the Transportation Systems Center (TSC), Cambridge, Massachusetts which had previously been a research arm of NASA and was known as the Electronics Research Center.

The prime objective of this program was to determine the feasibility and practicality of utilizing NDT techniques to inspect and predict dynamic tire performance. The techniques that were investigated were:

X-Ray - (FIGURE 1)
Utilized by the industry in the tire development phase. It could detect broken cords, ply overlap and belt doglegs.

Infrared Imagery - (FIGURE 2)
Not true NDT because the technique required some exercising, although minor, of the tire to obtain its thermal profile. Signal interpretation was very difficult.

Holographic Imagery - (FIGURE 3)
Through double exposure holograms and the resulting fringe patterns, anomaly (separation) detection was fairly precise.

Ultrasonics - (FIGURES 4a and 4b)
Both the reflection and transmission techniques were investigated. This technique proved to be the most cost-effective for new and recycled tires respectively.

Resonance - (FIGURE 5)
This technique relies on exciting the tire to its resonant frequency at the tread center and utilizing symmetrically placed receiving transducers on the sidewalls to detect imbalances in the output signals.

The latter NDT technique, because of its simplicity, ease of operation and maintenance, direct application to mounted tires, short test time, and low equipment cost was selected for motor vehicle inspection (MVI) use. The MVI of tires is the principal theme of this paper and the following will outline the effort that has carried the system to the prototype validation phase.

The first known active use of resonant vibration as a technique for determining mounted tire integrity was published in Mr. James Weigl's masters thesis (Ref. 1) in 1967 at M.I.T. The equipment used by Weigl in his research and the laboratory system evaluated by Dr. D. Wilson and S. Loebl also from M.I.T. did not validate the technique for identifying defects or anomalies within tires. The Transportation Systems Center in 1973, convinced that the resonance technique could, with modifications, be utilized to sense and position abnormalities within tires, undertook an in-house research effort to advance the S. A. Loebl and D. G. Wilson system (Ref. 2). FIGURE 6 depicts a block diagram of the M.I.T. developed system and its function and FIGURE 7 is a photograph of the developed system.

The TSC developed system also utilized the vibrating resonance properties of the tire but differs from the M.I.T system in that the sensing technique for abnormalities is somewhat different. The system difference can be seen in the TSC block diagram shown in FIGURE 8 where the vibration source is placed at the center of the tire tread area and the receiver transducers are positioned in the same radial plane equidistant from the source (Ref. 3). The TSC advanced prototype (Ref. 4) system is shown in FIGURE 9 (Mechanical Design)and FIGURES 10 and 11 (Photographs).

To comprehend how the resonance technique senses anomalies or flaws in the tire it will be necessary to understand and interpret the manner in how a tire vibrates when excited sinusoidally.

The type of resonant mode pattern that is obtained in a tire is dependent on the direction of the applied force and the position at which it is applied. In the TSC developmental system the force transducer was positioned at the center of the tread area. The vibrating force transducer when in contact with the tire tread will induce within the cross section a circumferential response (see FIGURE 12a) and simultaneously a tangential mode along the entire circumference (see FIGURE 12b). The combination of these two modes generates a two dimensional mode pattern within the tire carcass. The resultant mode patterns have been observed in tires by G. Potts (Ref. 5) through time-average holography. Pictorial representation of resonant vibration patterns from the Potts investigation are shown in FIGURES 13 and 14.

With an oscillating transducer applied to the tire tread center line, the tire can be made to oscillate in a manner shown by the displacement envelope of the cross section indicated by the dotted lines in FIGURE 15. The beads and the "X" marked points are the nodal points. By placing receiver transducers in the same radial plane, at equal distances from the source transducer (FIGURE 15), the vibrating properties of the tire and the vibrating symmetry of the radial cross section can be measured. Rotating the tire about its axis and holding the oscillating and receiver transducers stationary, the vibrating properties and radial symmetry for the entire tire carcass can be measured. The oscillating transducer, through electronic control, will maintain its resonance condition even if the properties of the vibrating tire carcass change.

The tire defects of greatest interest to motor vehicle safety are those which may lead to or result in the tire failure; these include cuts, tread chunking, uneven wear, broken cords and separations. In all cases, these defects will, in general, upset the symmetry of the tire and therefore affect the resonant vibration properties of the tire.

The tire symmetry under inspection is that obtained in comparing the two halves separated by a plane perpendicular to and through the center of the tread area. The TSC system configuration for inducing oscillations in the tire tread area and obtaining wave-forms off the sidewalls will produce the comparative symmetry needed to determine tire integrity. The system requires simultaneous circumference readings of the two individual sensing transducers (designated A & B) and the algebraic sum of the A + B readings to determine defect content and placement. Full tire inspection is accomplished by rotating the tire at a rate that will give a good signal to noise ratio.

Mechanical or electronic expertise will be required for maintenance or trouble shooting, but system operation can be accomplished by personnel without prior technical training. In fact, the tire inspection process is fairly effortless except for the selection of the applicable resonant frequency at which to perform the inspection. The operator must be indoctrinated in the basic understanding of the whys and how a tire carcass vibrates when excited sinusoidally. The selected resonance frequency depends primarily on the tire size and construction. For instance, FIGURES 16 and 17 holographically show that the second mode of vibration is the most applicable for use with the TSC technique. The resonant frequency for an H78-15 bias ply tire and for an HR78-15 radial ply tire turned out to be 168 Hz and 80 Hz respectively. The lower mode would be less sensitive and the higher modes tend to "break-up" and become unresolvable.

During laboratory evaluation the tires to be inspected were mounted on standard automotive wheels, inflated to normal operating pressure, and placed on the tire tester hub. The exciting transducer input roller was mechanically placed in contact with the tire at the center of the tread. Using the exciter armature bias control, the input roller to tire contact force was adjusted to approximately 3 pounds. The receiver transducers were then positioned perpendicular to the tire sidewall surface at equal distances from the input roller contact point. The optimum position was determined to be between 70° and 90° from the roller input point (See FIGURE 18). The receiver transducer to tire surface contact force was readjusted to approximately 2 pounds.

Having performed the mechanical requisites the electrical system is then energized. The oscillator and the exciter amplifier are adjusted to produce an energy level input that will give desired signal outputs. The oscilloscope presentation of the receiver transducer response is then used to tune the exciter to the desired resonant tire mode and the exciter is readjusted, if necessary, to the desired input energy level. The operator now has the option of operating the system at a constant frequency or using the automatic frequency tracking system.

The tire is rotated at about 1 rev/min. so as to minimize accelerometer response from sidewall lettering or other tire surface anomalies, by means of the wheel shaft drive or the roller drum. The sensing transducer signals are viewed visually in real-time with an oscilloscope and/or are recorded on an X-Y recorder (See FIGURE 19). When using the X-Y recorder, a shaft encoder insures a point to point correlation between the tire circumference position and the data recording. Hard copy recordings (X-Y) were made of each transducer response (A & B) and of the algebraic sum (A + B) of the two output signals which is accomplished electronically.

System evaluation was based on numerous tests for which data recordings similar to those of FIGURES 20, 21, and 22 were obtained and the tire was destructively analyzed to confirm the system's detection capability. Excellent detection capability was obtained for the flaw types listed in Table A.

The location of the tire flaws is determined by the signal amplitude variance corresponding to a receiver transducer and its placement along the developed circumference for the tire. A defect located in the center of the tread area will be detected by both receivers but will cancel out on the A + B trace. FIGURES 20, 21, and 22 are receiver amplitude responses taken of tires containing known defects. The system's response to the defects are obvious and are labeled as to type, location and size on the recordings.

The resonance vibration technique is a valid process by which in-service automobile tires may be inspected quickly and inexpensively. The tires can be inspected while mounted on the vehicle because the weight of the automobile on the tire has no effect on system performance. Based on the research and development effort conducted at the Transportation Systems Center, NHTSA concluded that the technique was valid and an automatic prototype system should be developed to confirm its practicality and usefulness. To this end NHTSA awarded Southwest Research Institute (SWRI) a contract (DOT-HS-5-01066 "Passenger Vehicle Tire Inspection Equipment Development") which has as its primary objective the design, construction and validation of a prototype system which will be less complex than the TSC system, eventhough it will have a triple inspection function, and will incorporate a go, no-go indicator to eliminate inspector subjectivity. The three function system (FIGURE 23) will include the automatic capability of simultaneously evaluating tire structural soundness, measuring tread depth and inflation pressure. The contractual effort was initiated in January 1975, and the progress to date has not gone beyond basic system layout as shown in FIGURES 24, 25, and 26 and preparation of appropriate specifications. This research and development effort is scheduled for completion in June 1977.

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6. Potts, G., Tire Vibration Studies - The State-of-the-Art, Akron Rubber Group Winter Meeting, January 1974.

7. J.E. Johnson, "Passenger Vehicle Tire Inspection Equipment Development" (Briefing) February 19, 1975.

DEFECT	SIZE	LOCATION	DETECTABILITY
Separations	1″ and smaller	Sidewall, tread	Very good
Separations	smaller than 1″	Sidewall, tread	Good - poor
Separations	1″ and smaller	Shoulder area	Poor
Cut (into ply)	2″ and larger	Sidewall	Good
	2″ and larger	Shoulder	Poor
Scuff (severe)	2″ and larger	Sidewall	Good - poor
Chunk Out	2″ and larger	Tread area	Good
Patches & Plugs		Tread area	None

Defect which were symmetrical about the circumference of the tire were not detectable such as a circumferential break in the belt

TABLE I - Defect Detectability

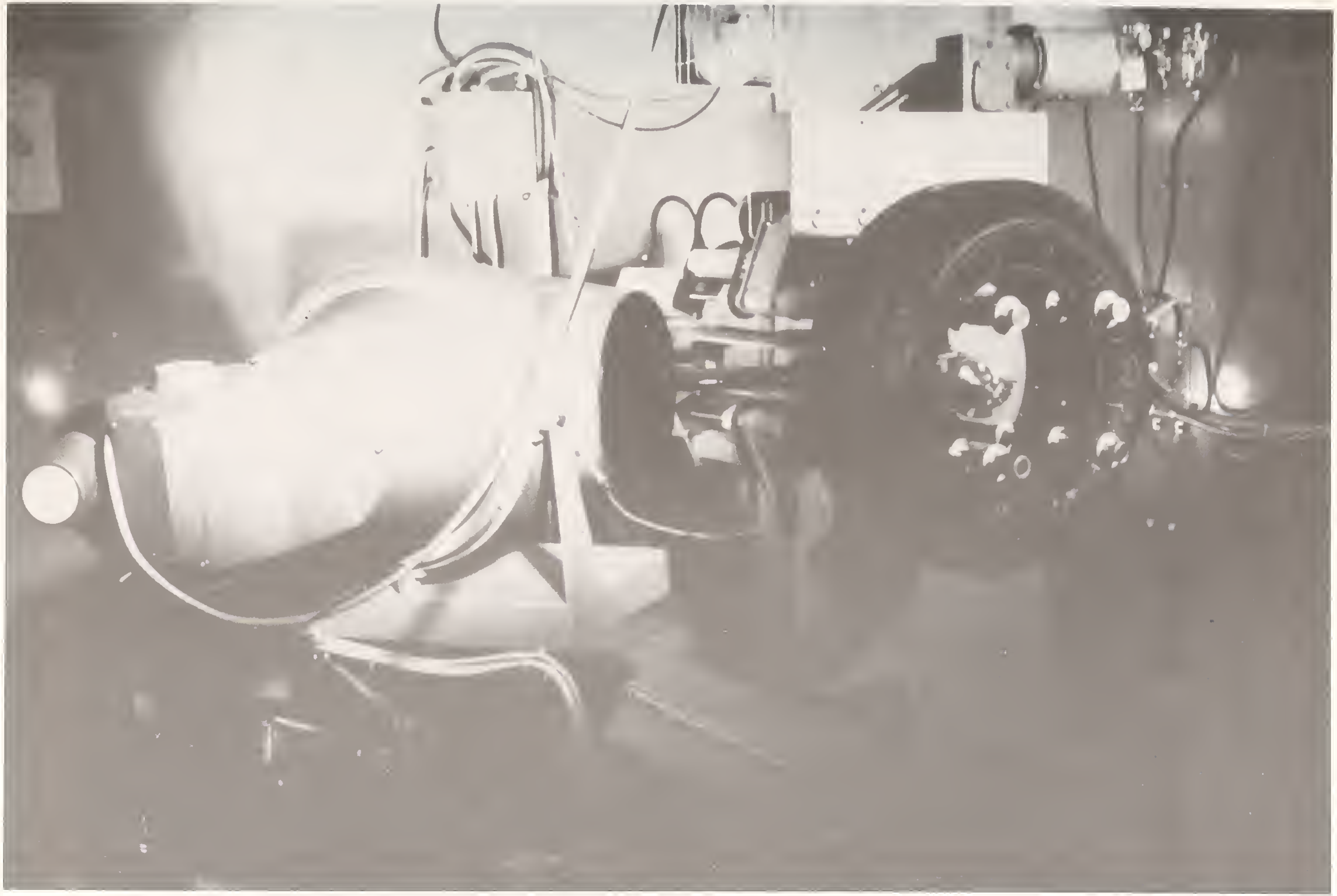


FIGURE 1 - Closed Circuit Television X-Ray Inspection System

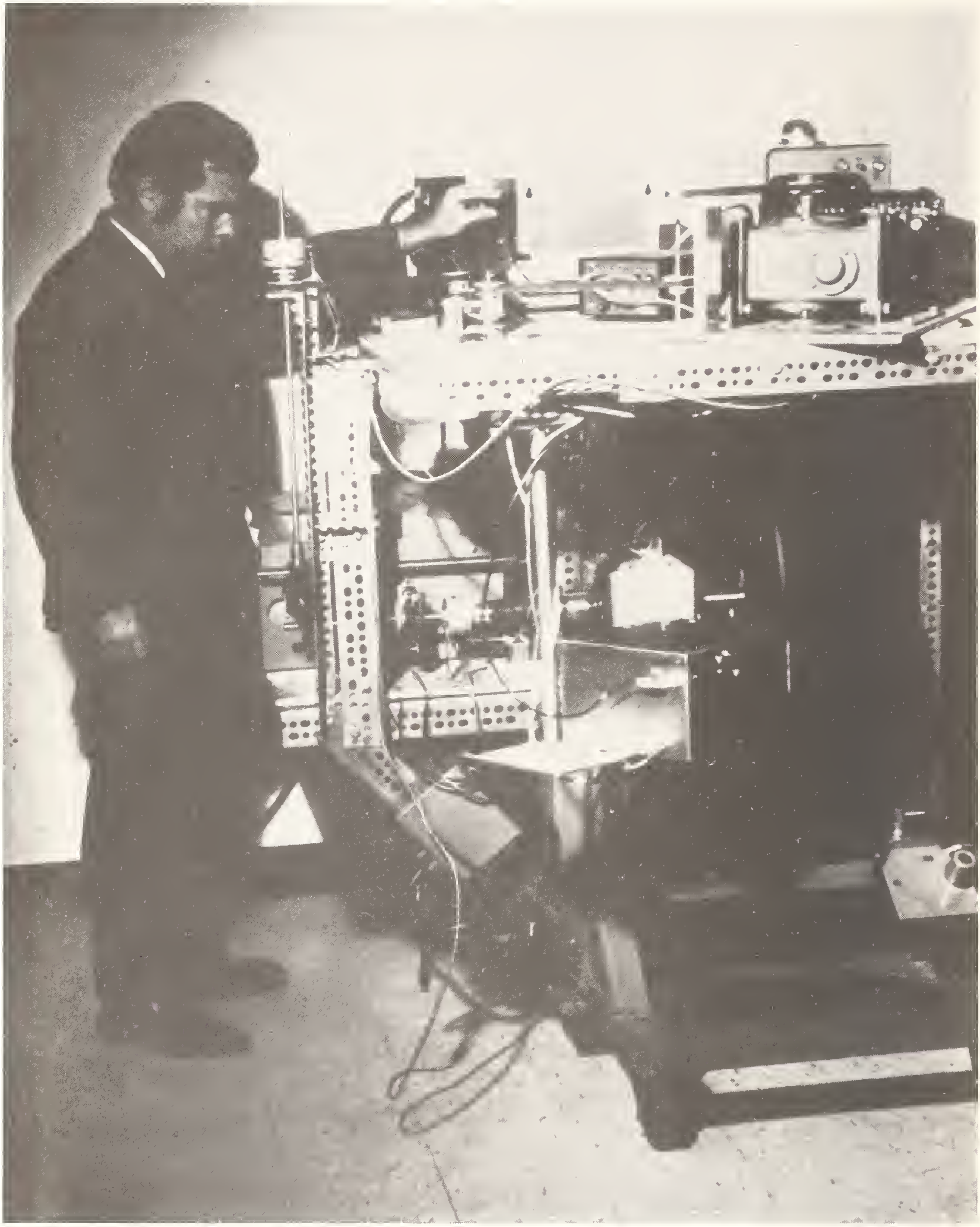


FIGURE 2 - Infrared Inspection System

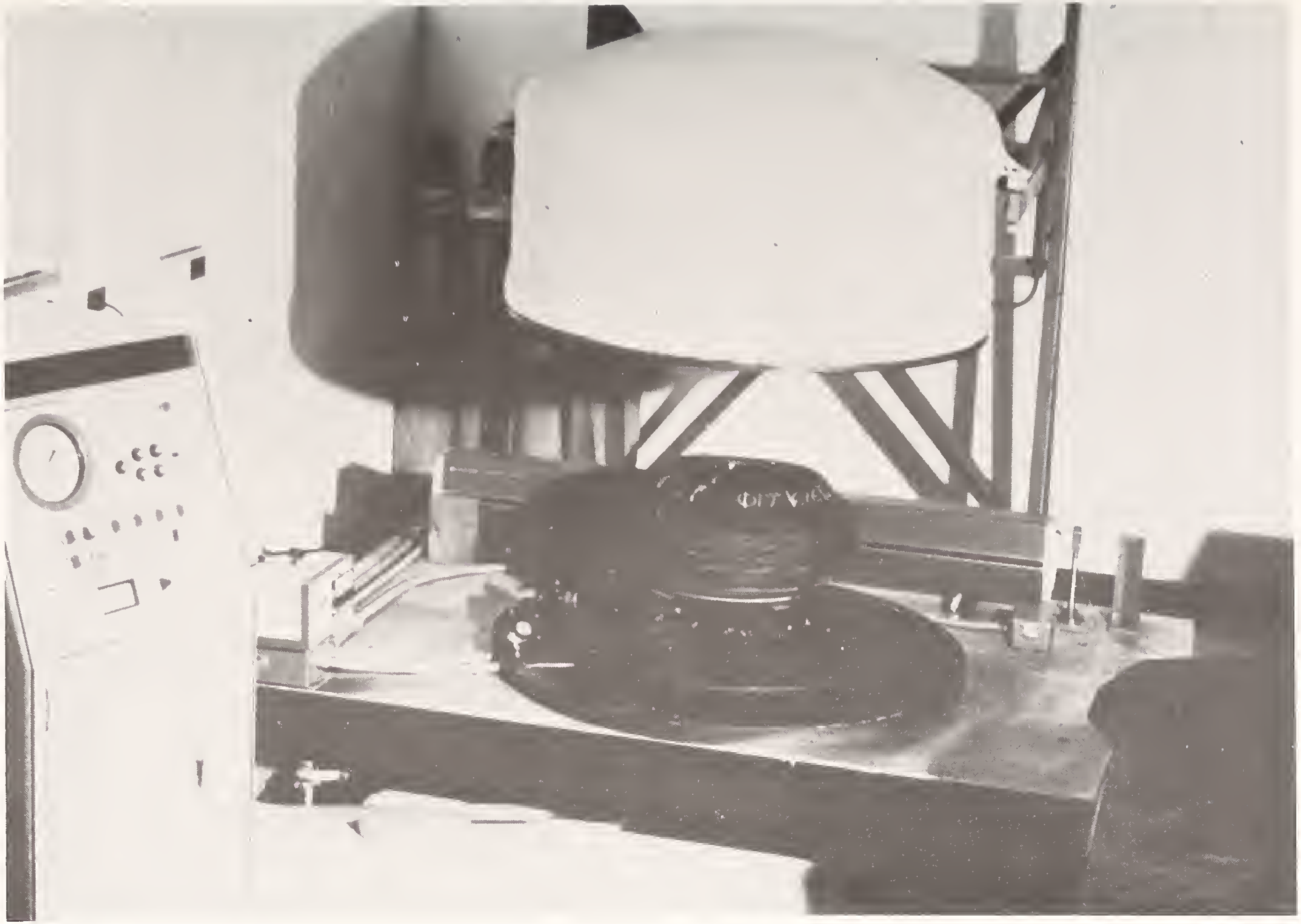


FIGURE 3 - Holographic Inspection System

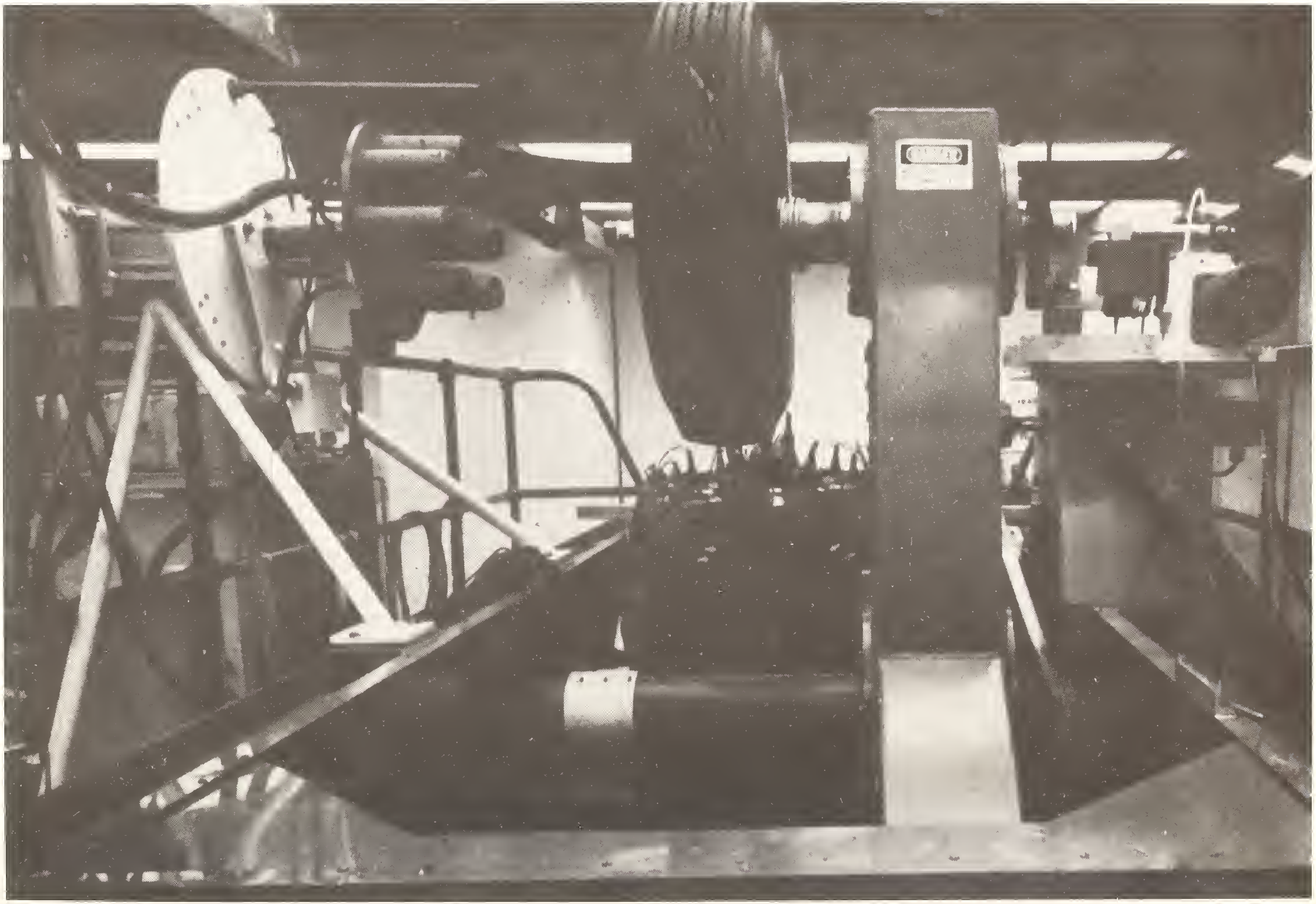


FIGURE 4a - Reflection Ultrasonic Inspection System

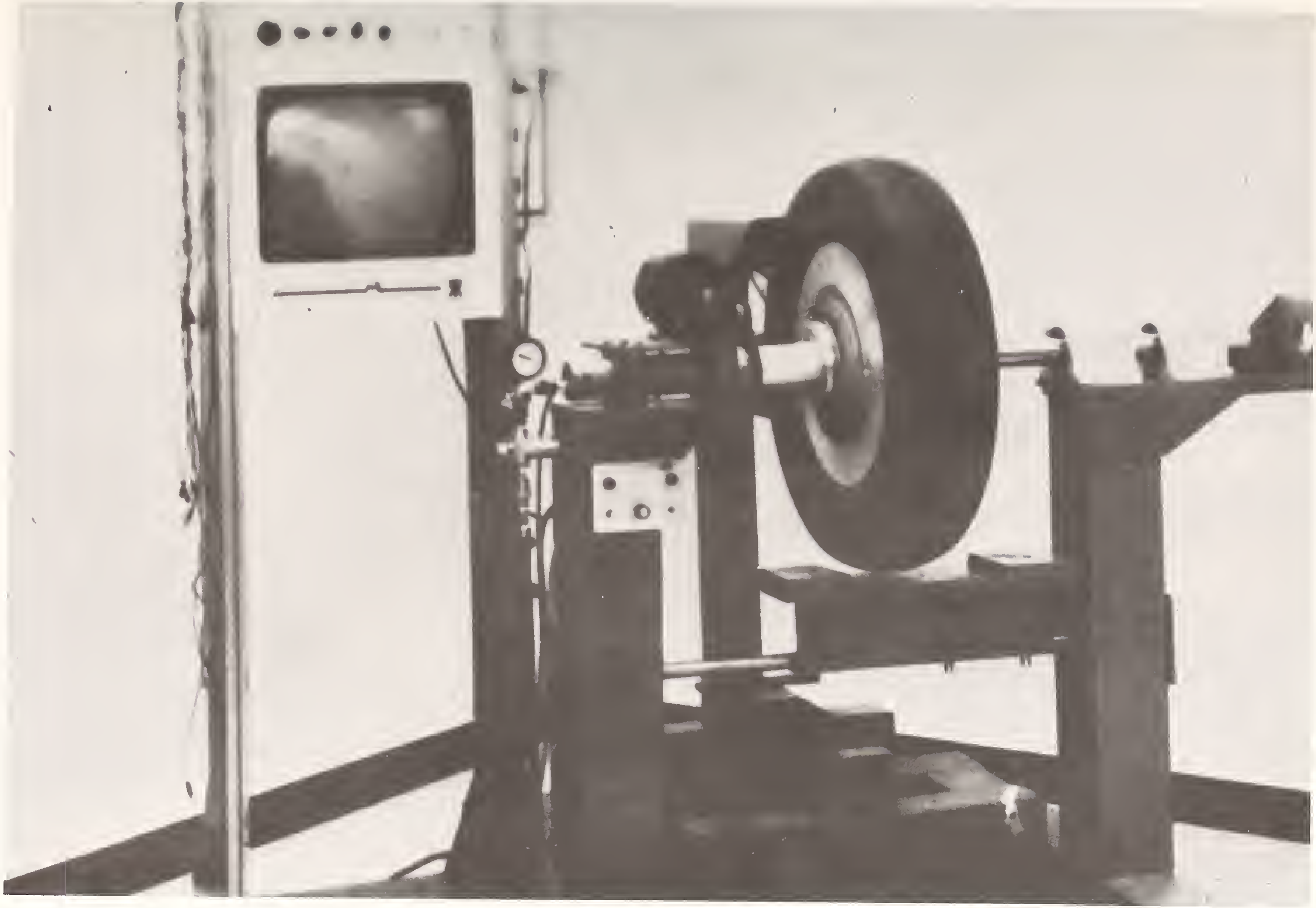


FIGURE 4b - Transmission Ultrasonic Inspection System

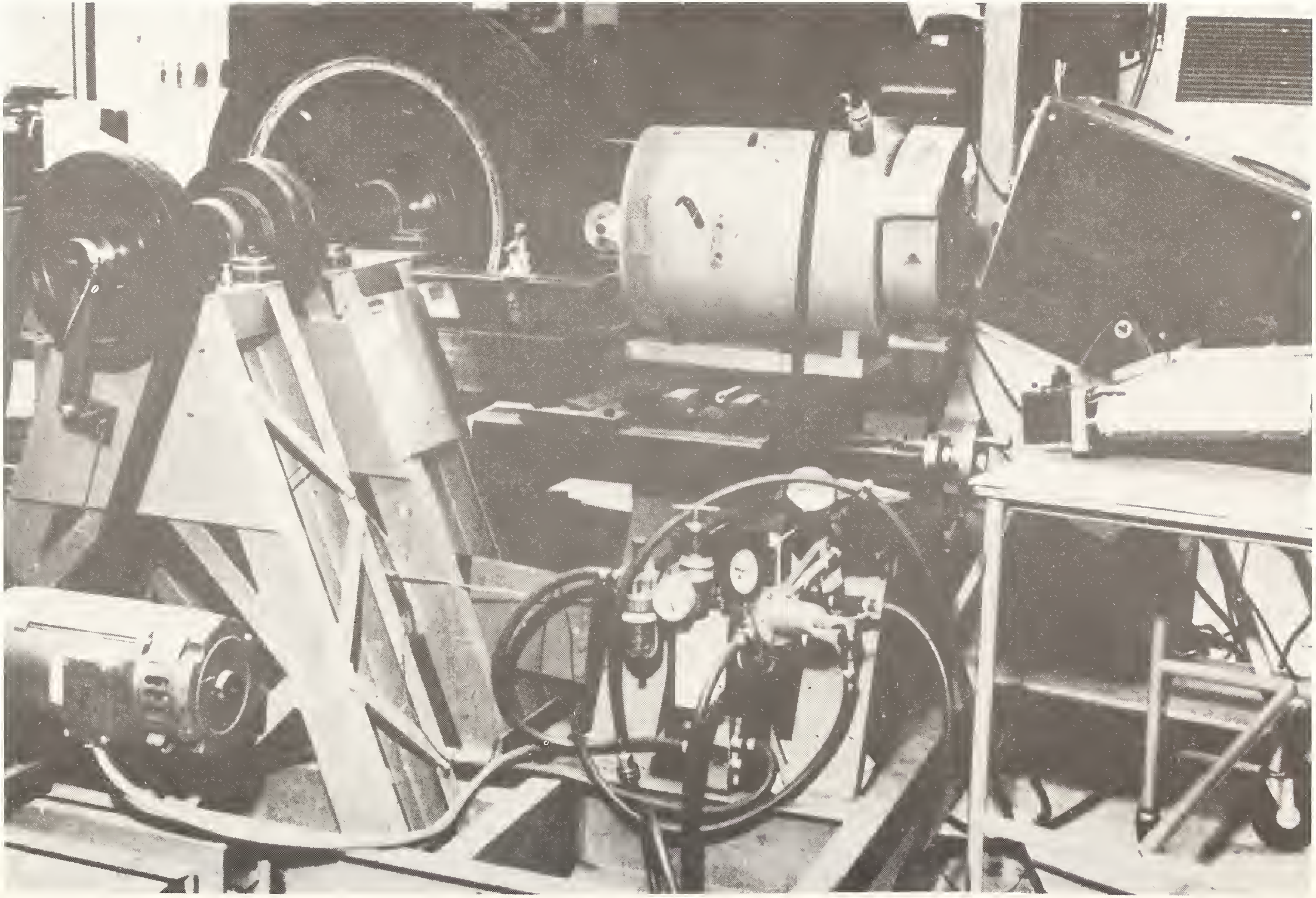


FIGURE 5 - TSC Resonance Inspection System

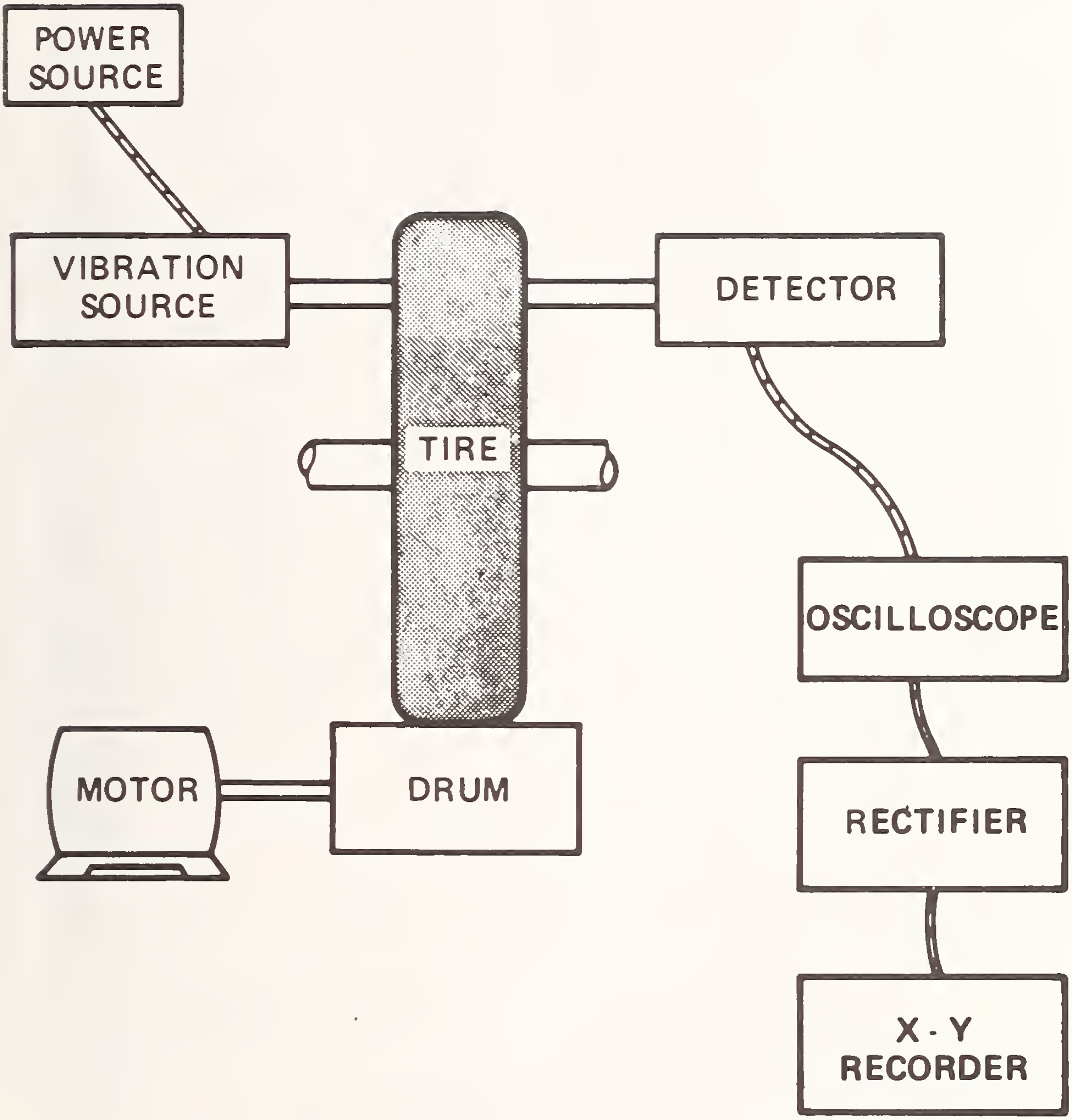


FIGURE 6 - MIT Resonance System Block Diagram

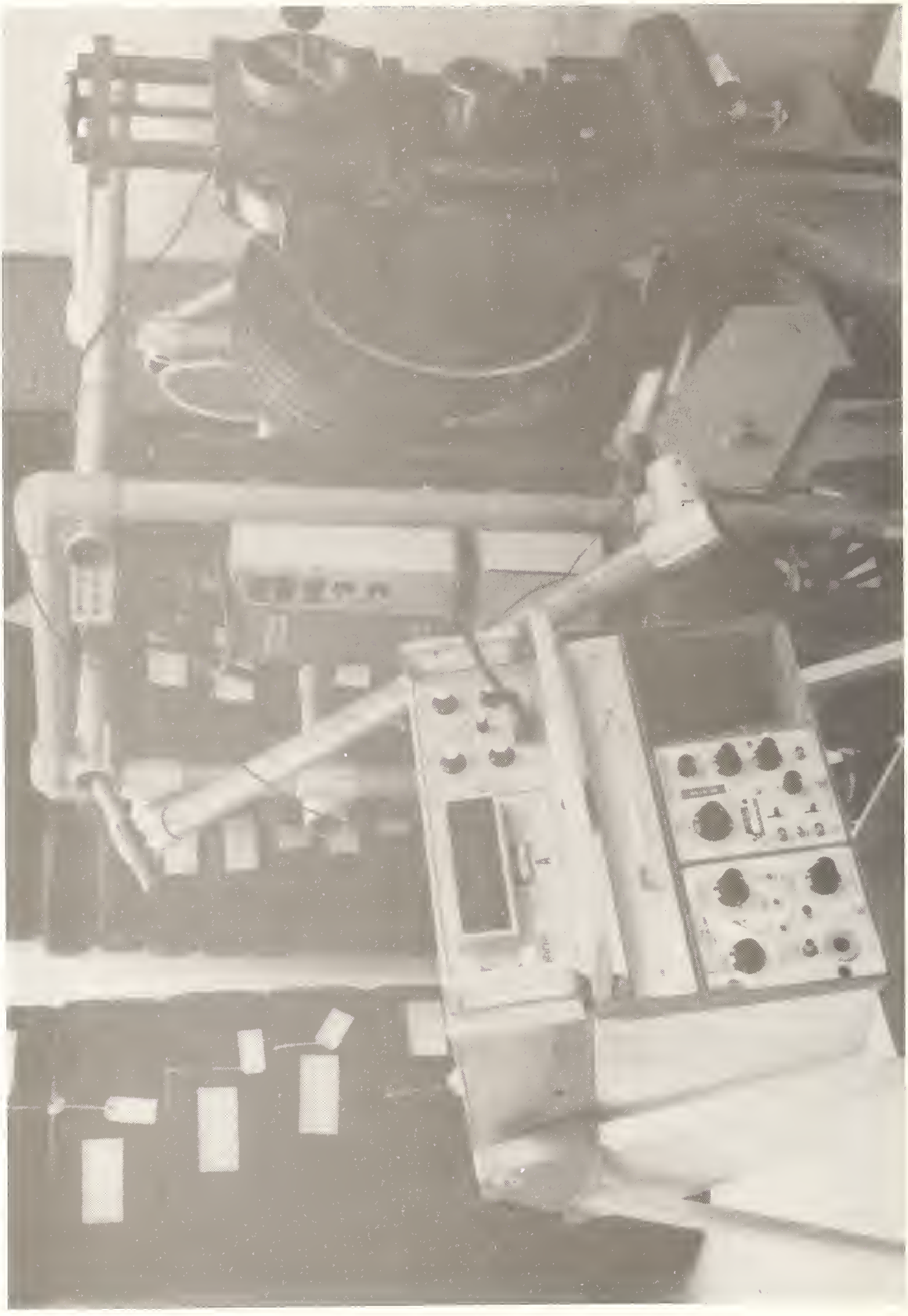


FIGURE 7 - MIT Developed Resonance Inspection System

SCHEME FOR MEASUREMENT

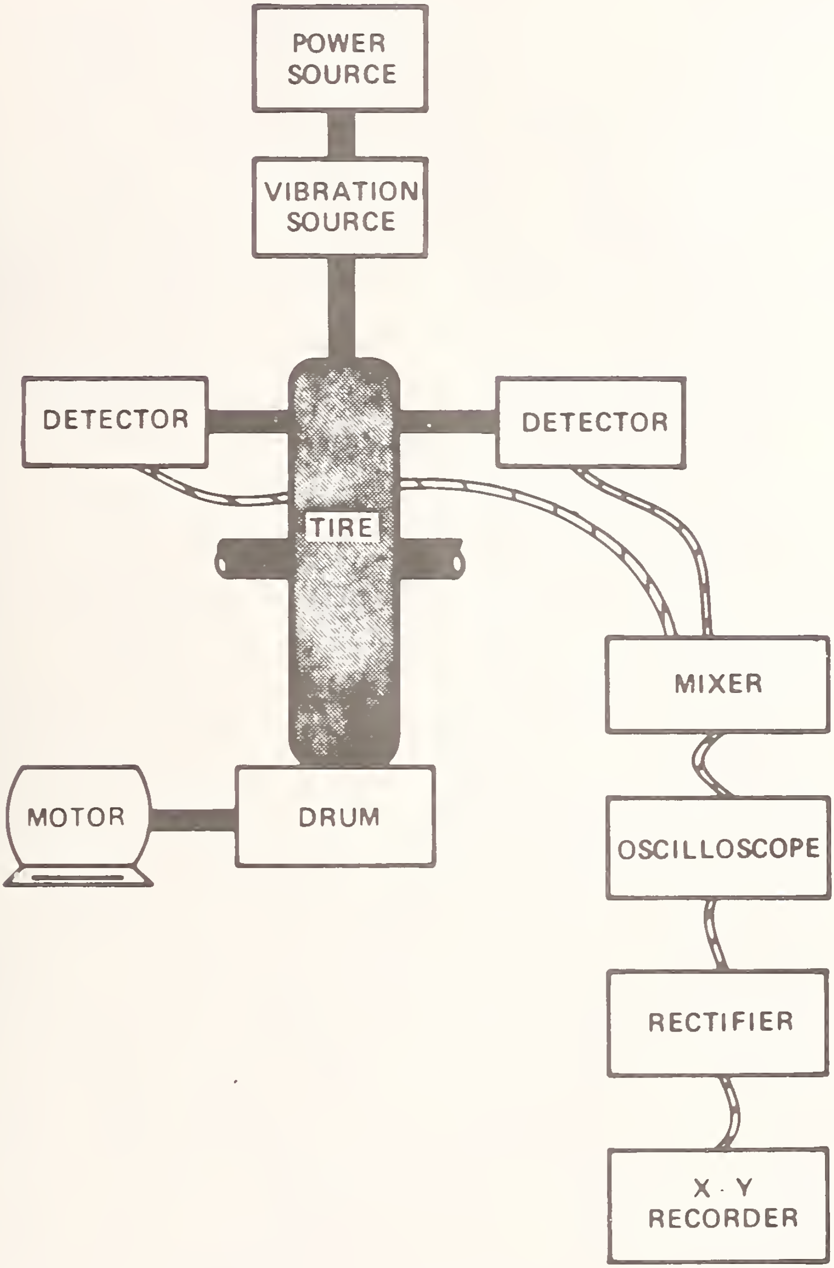


FIGURE 8 - TSC Resonance System Block Diagram

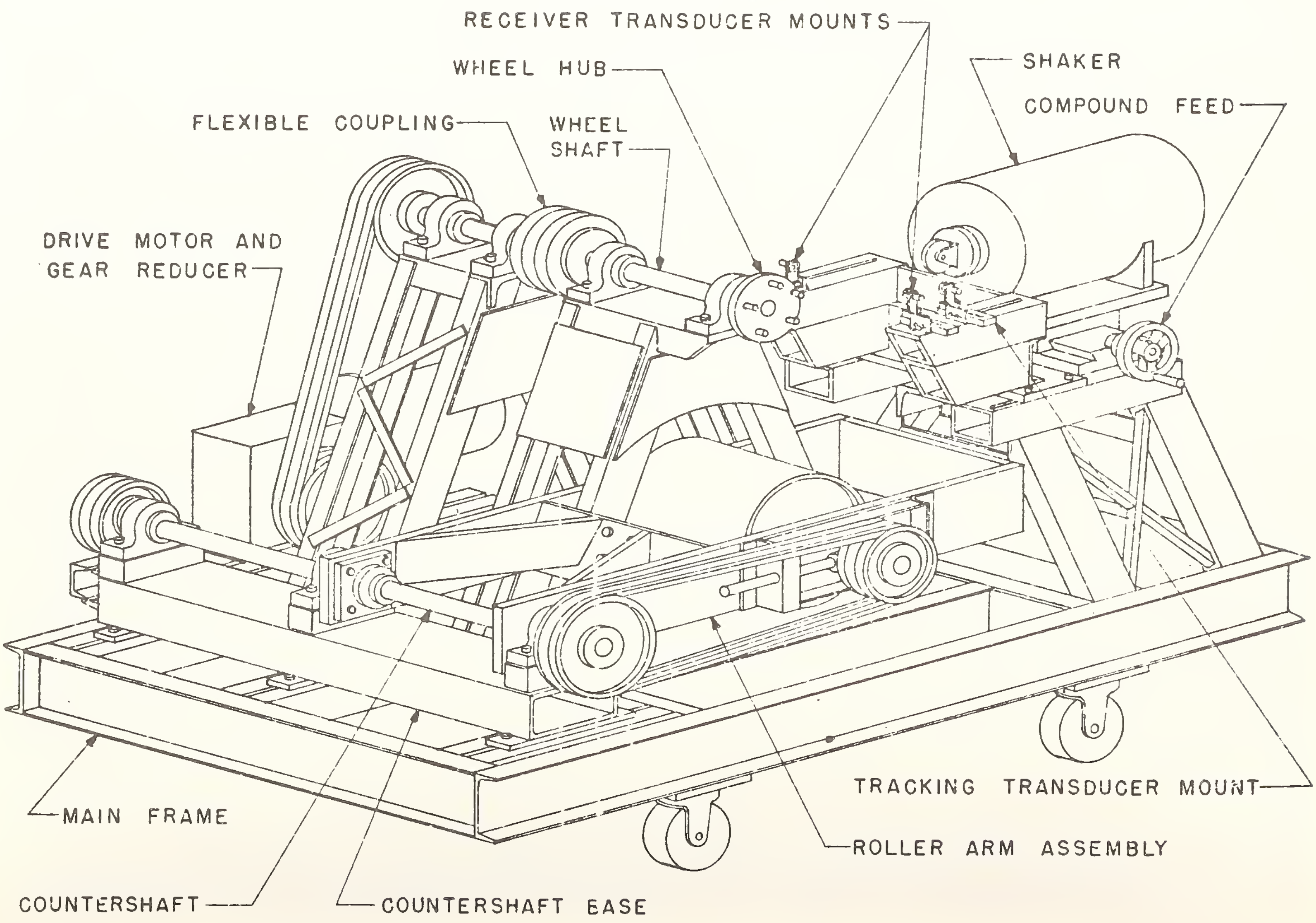


FIGURE 9 - Tire Tester Assembly

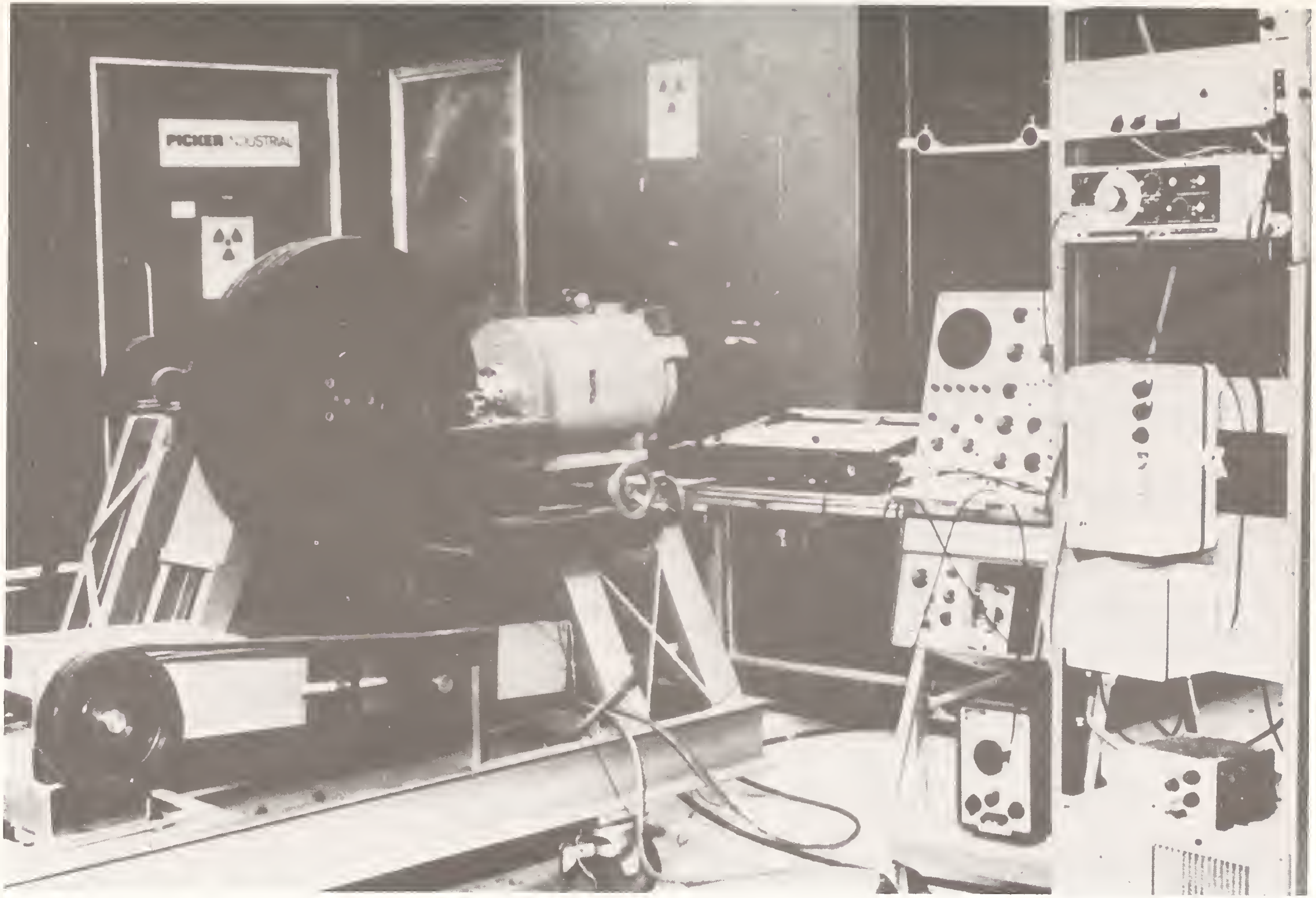


FIGURE 10 - TSC Developed Resonance Inspection System

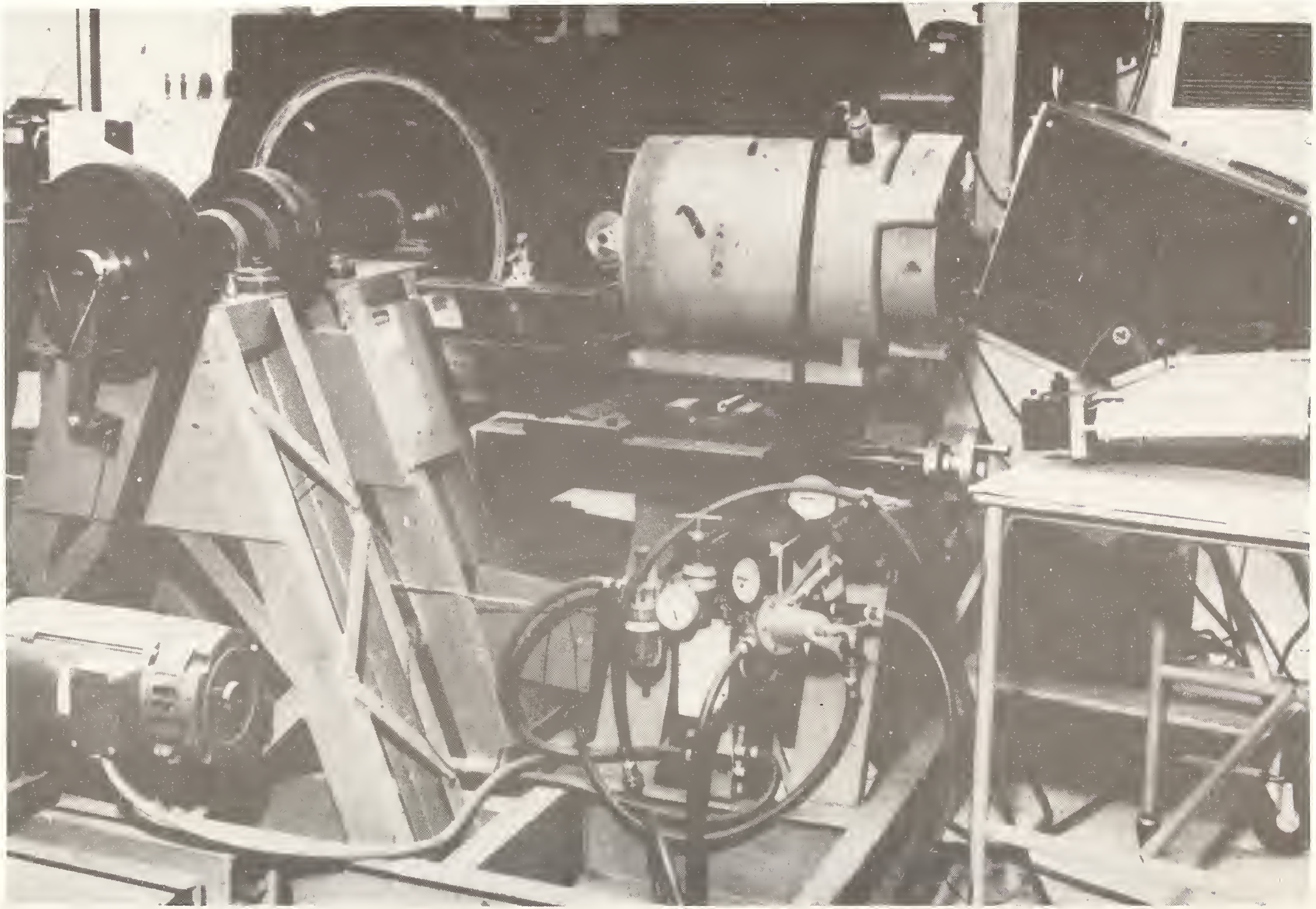
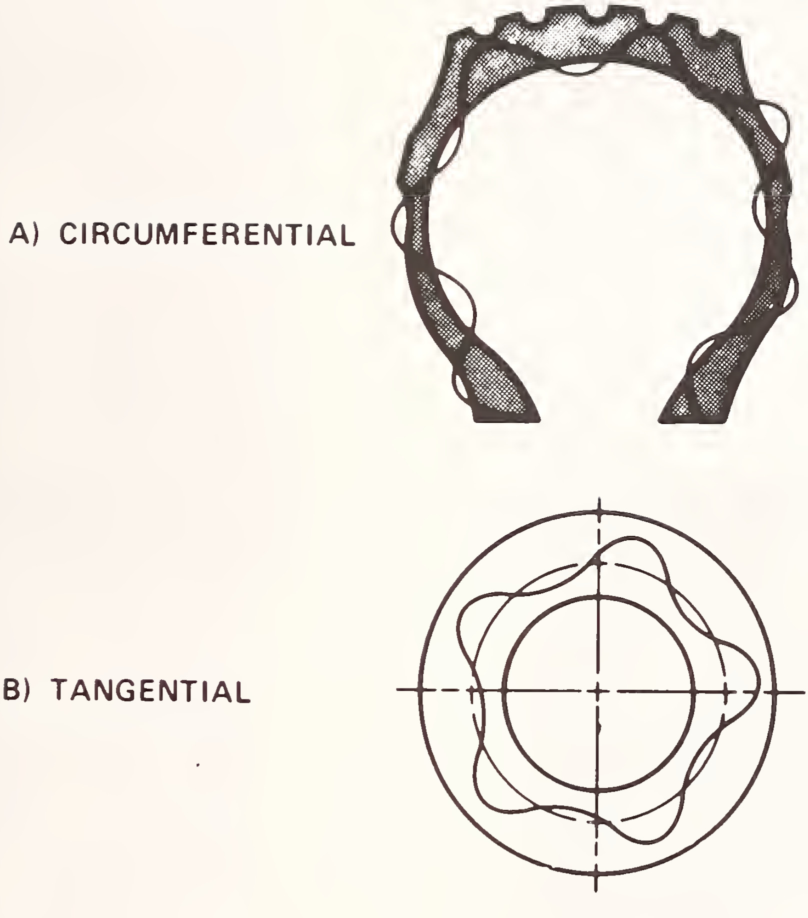


FIGURE 11 - TSC Developed Resonance Inspection System (Transducer Close-up)



A) CIRCUMFERENTIAL

B) TANGENTIAL

FIGURE 12 - Vibration Modes and Displacement of a Tire

FIGURE 13 - RESONANT VIBRATION PATTERNS

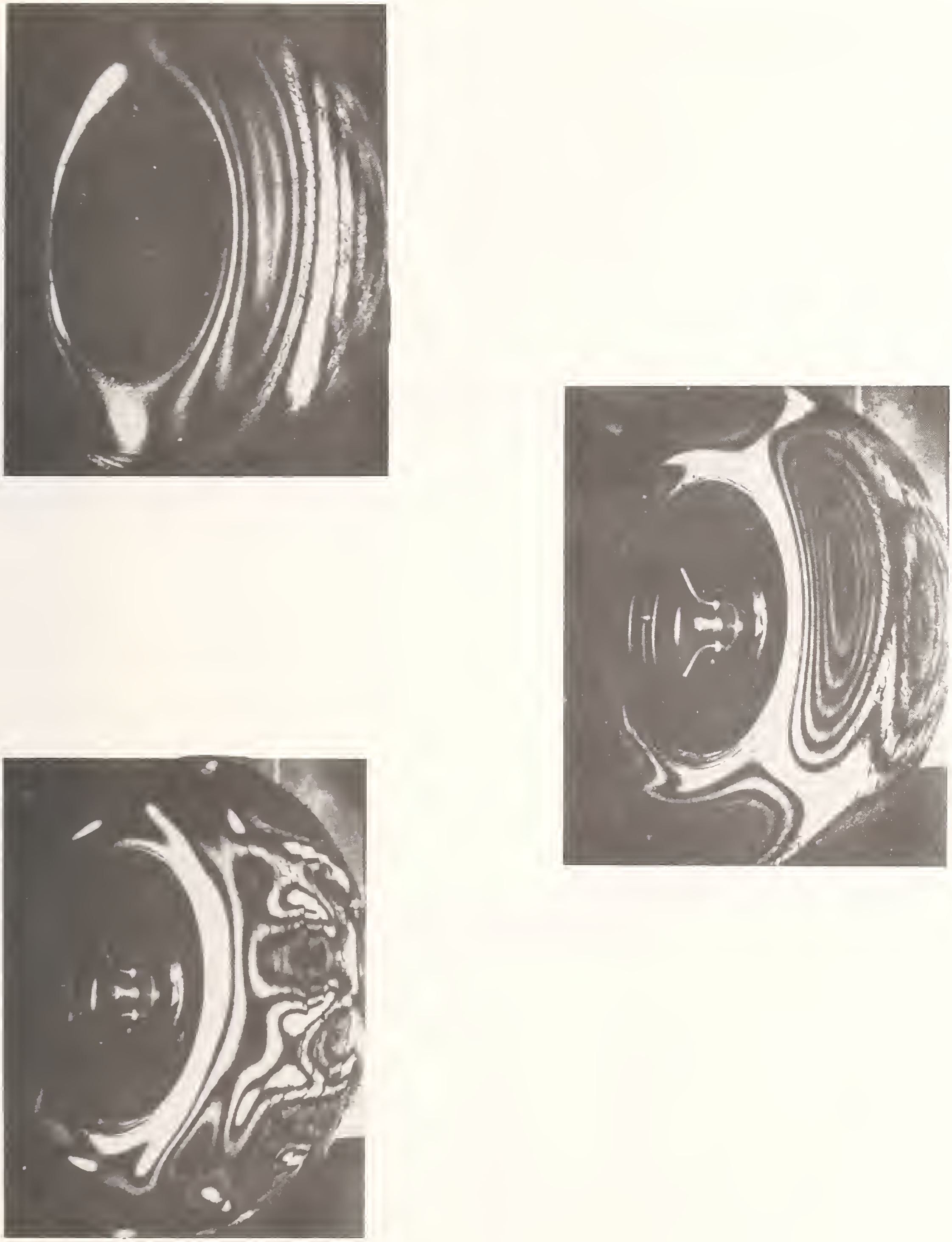


FIGURE 14 - RESONANT VIBRATION PATTERNS

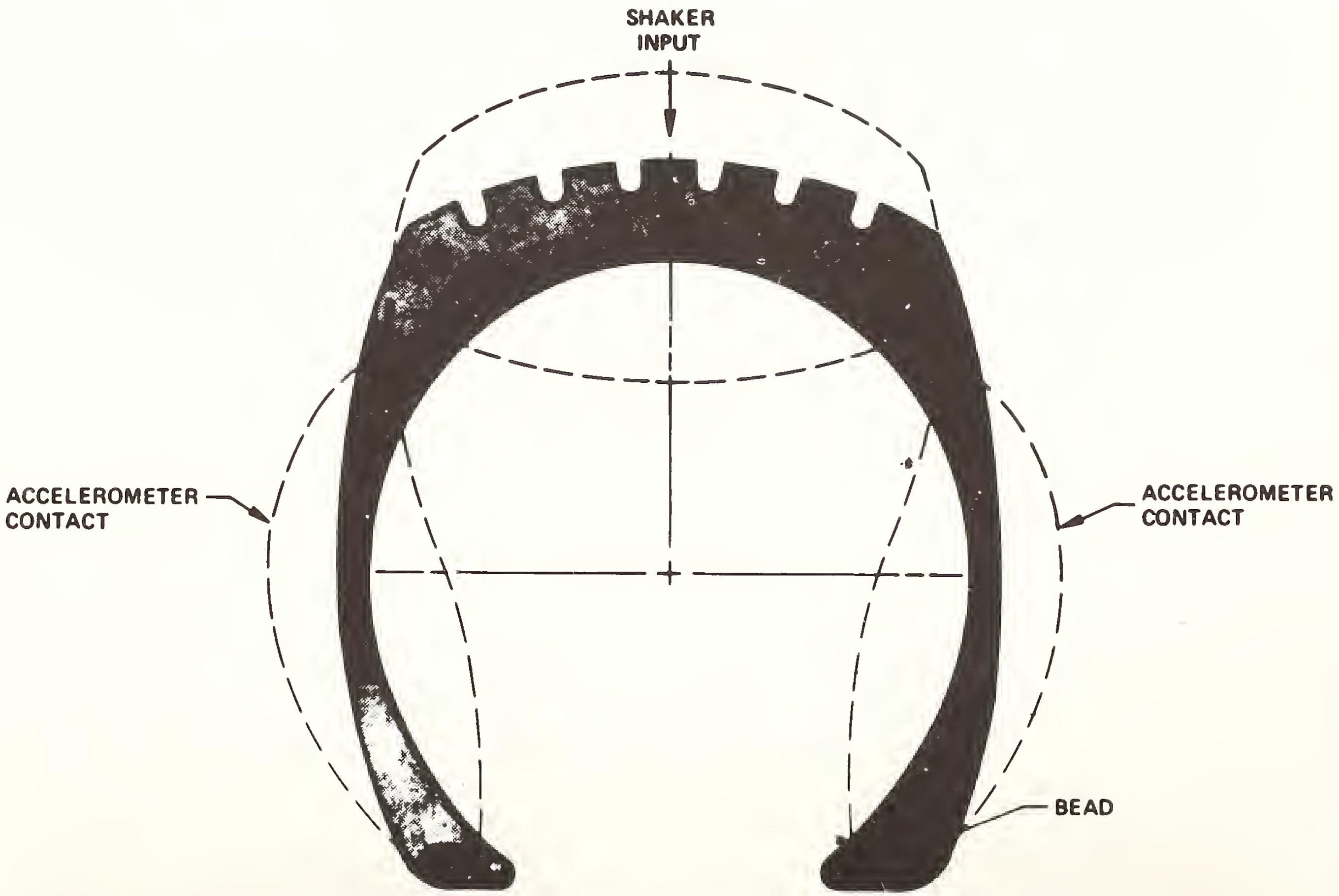
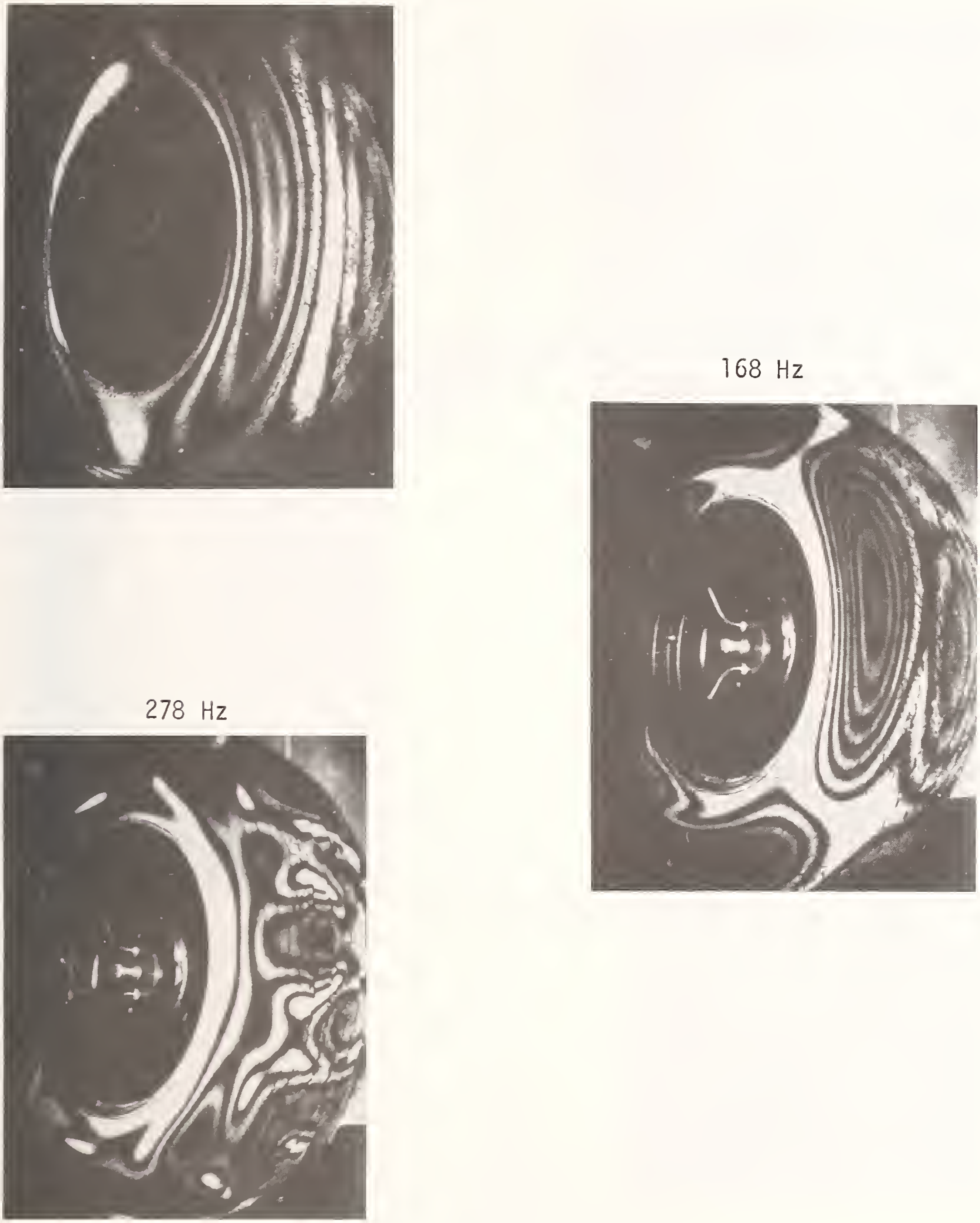


FIGURE 15 - Vibrating Cross Section of a Tire

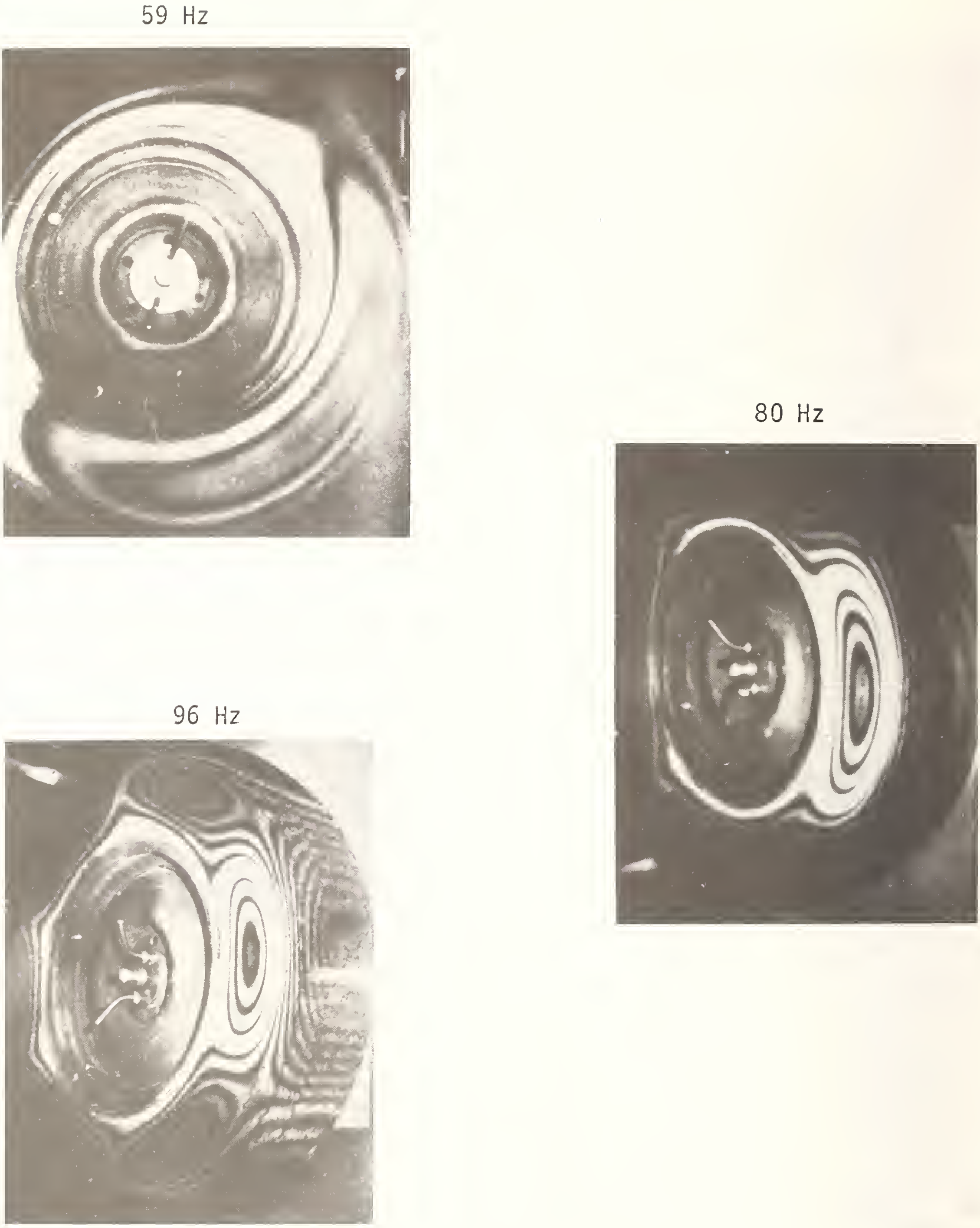


140 Hz

168 Hz

278 Hz

FIGURE 16 - First, Second and Third Mode Radial Vibration Resonances for H78-15 Bias Ply Tire; 140, 168 and 278 Hz, Respectively



59 Hz

80 Hz

96 Hz

FIGURE 17 - First, Second, and Third Mode Radial Vibration Resonances for HR78-15 Radial Ply Tire; 59, 80 and 96 Hz, Respectively

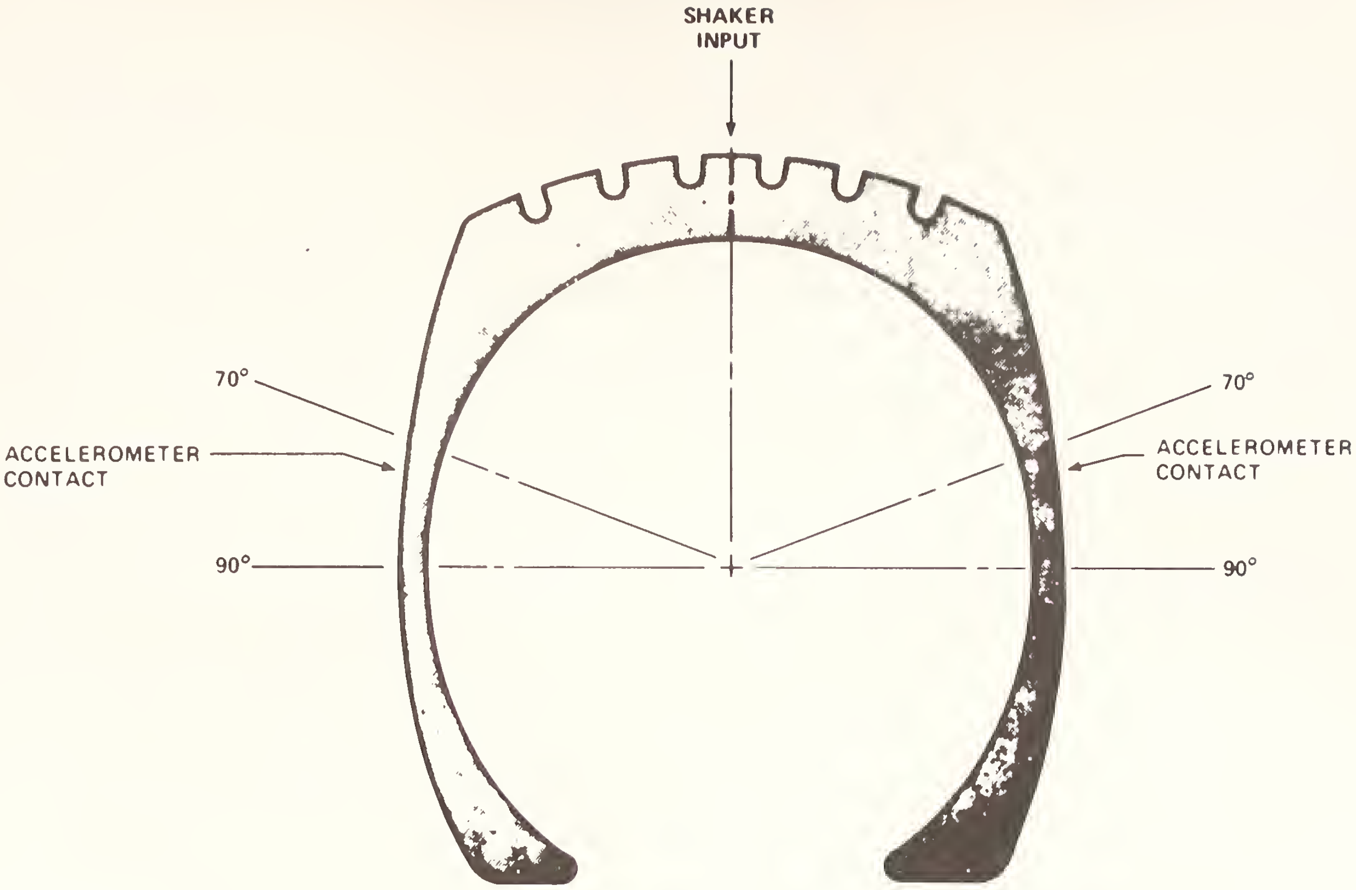


FIGURE 18 - Transducer Position Diagram

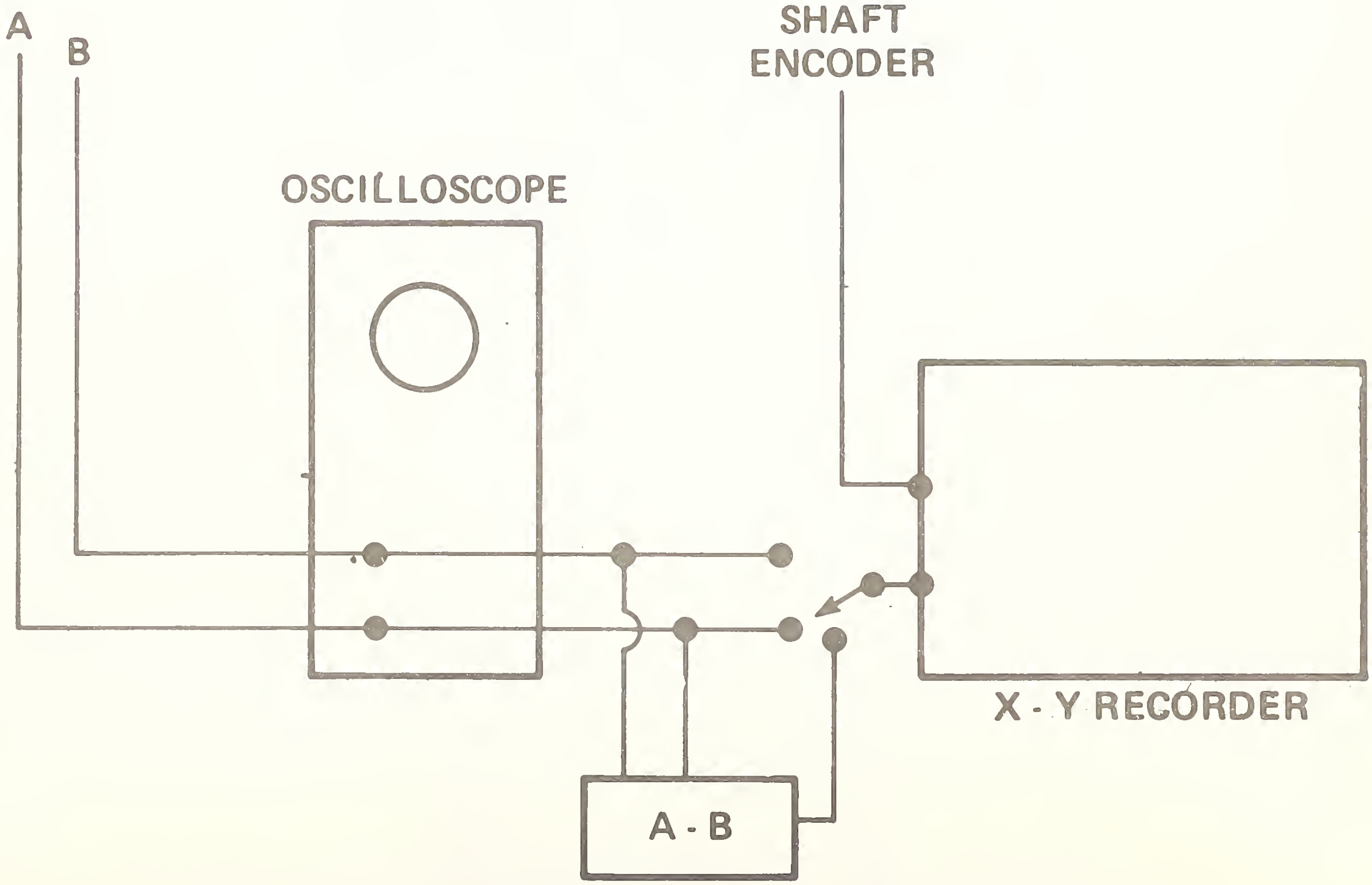


FIGURE 19 - Recording Instrumentation

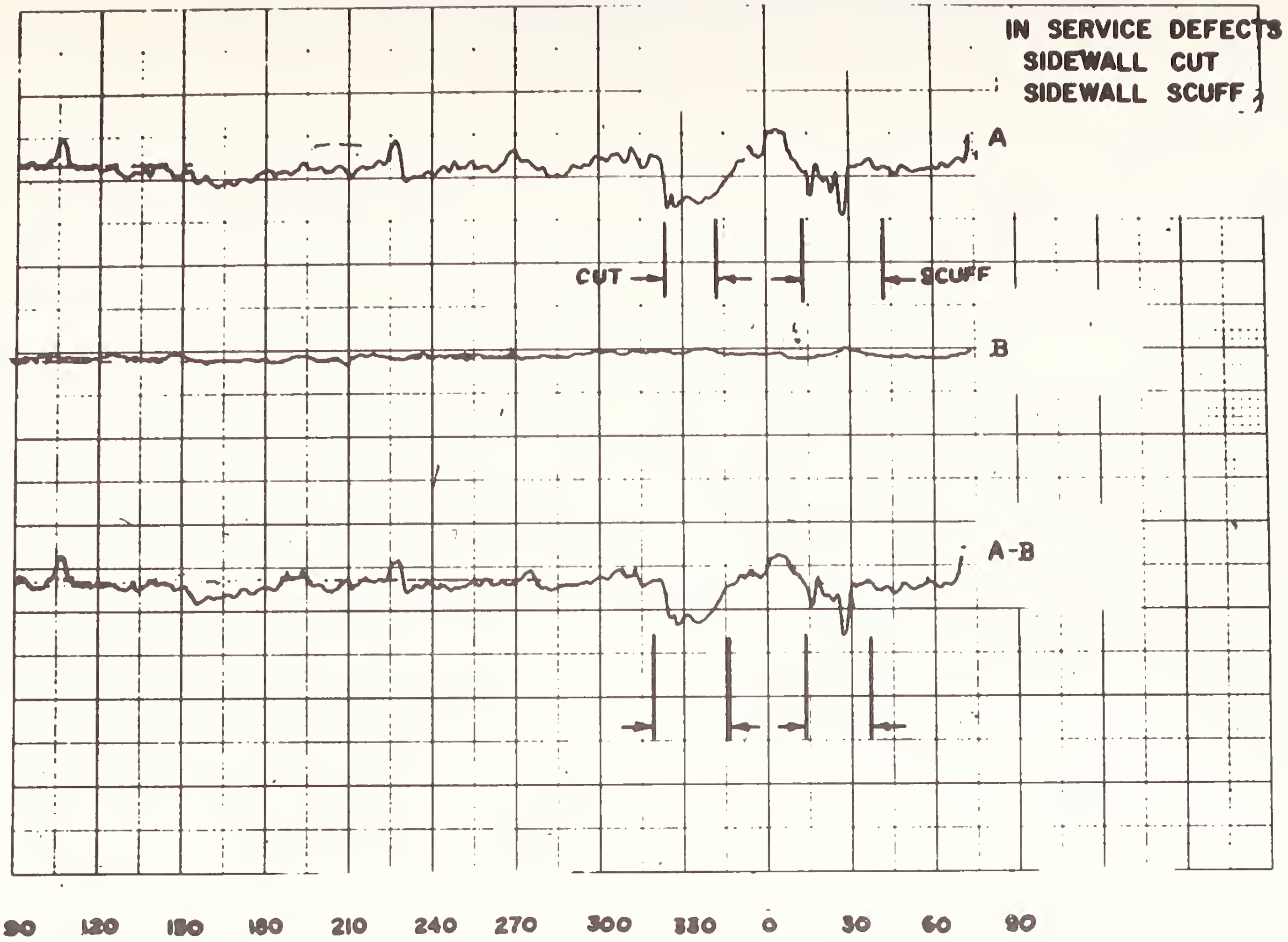


FIGURE 20 - Recorder Trace of a Sidewall Cut and Sidewall Scuff

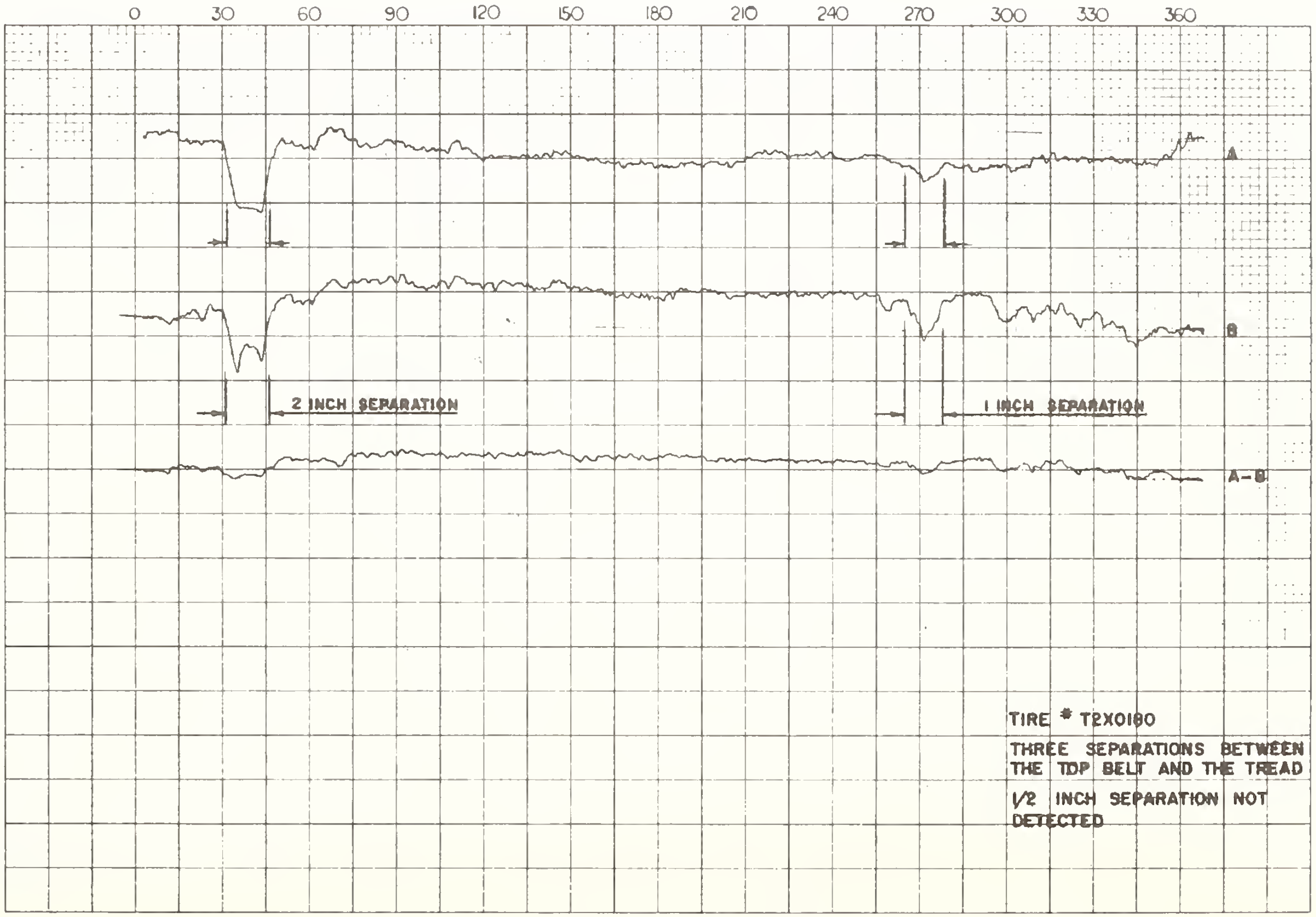


FIGURE 21 - Recorder Trace of a Tire with Separations in the Tread Area

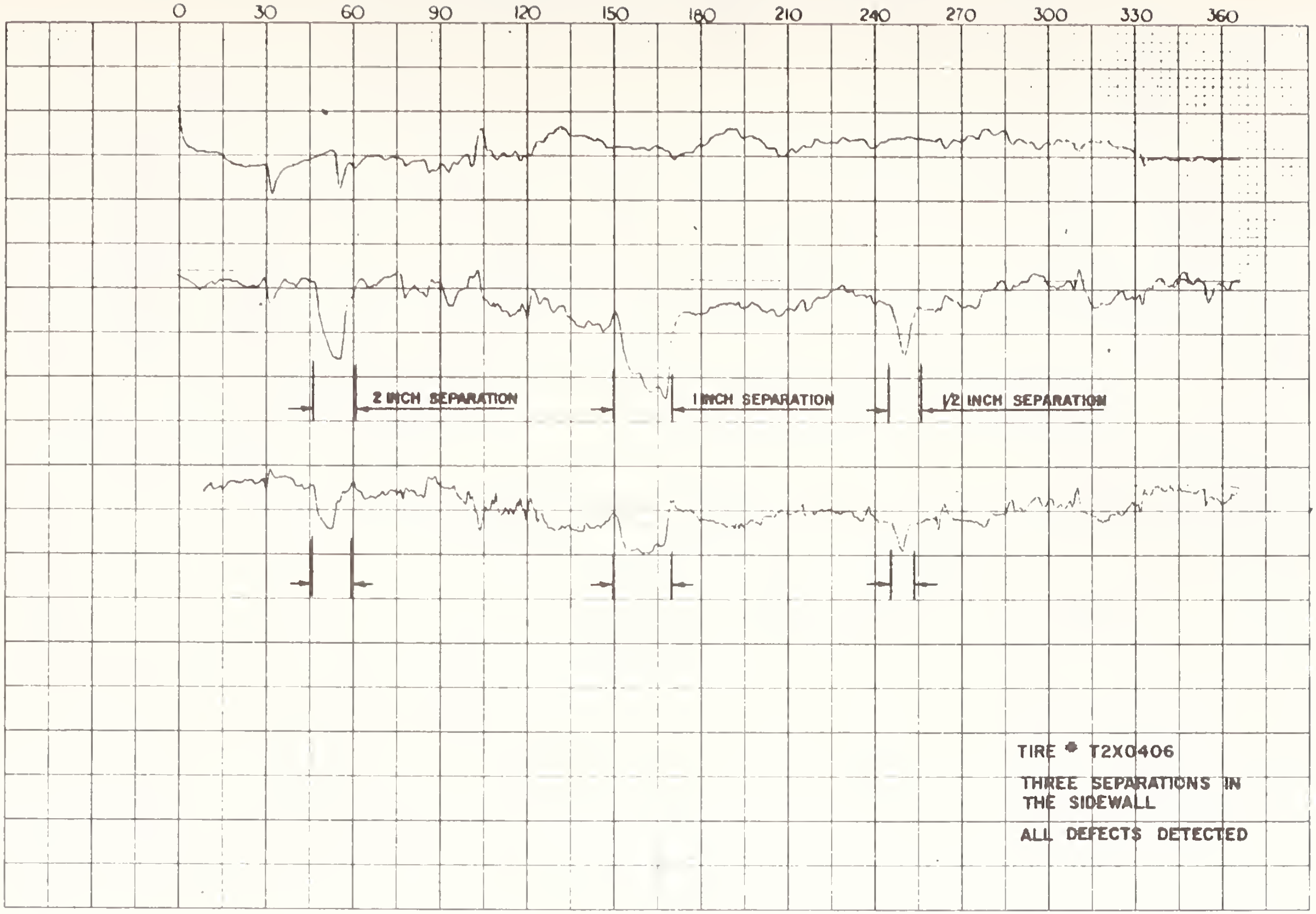


FIGURE 22 - Recorder Trace of a Tire with a Cut and Severe Scuff on the Sidewall

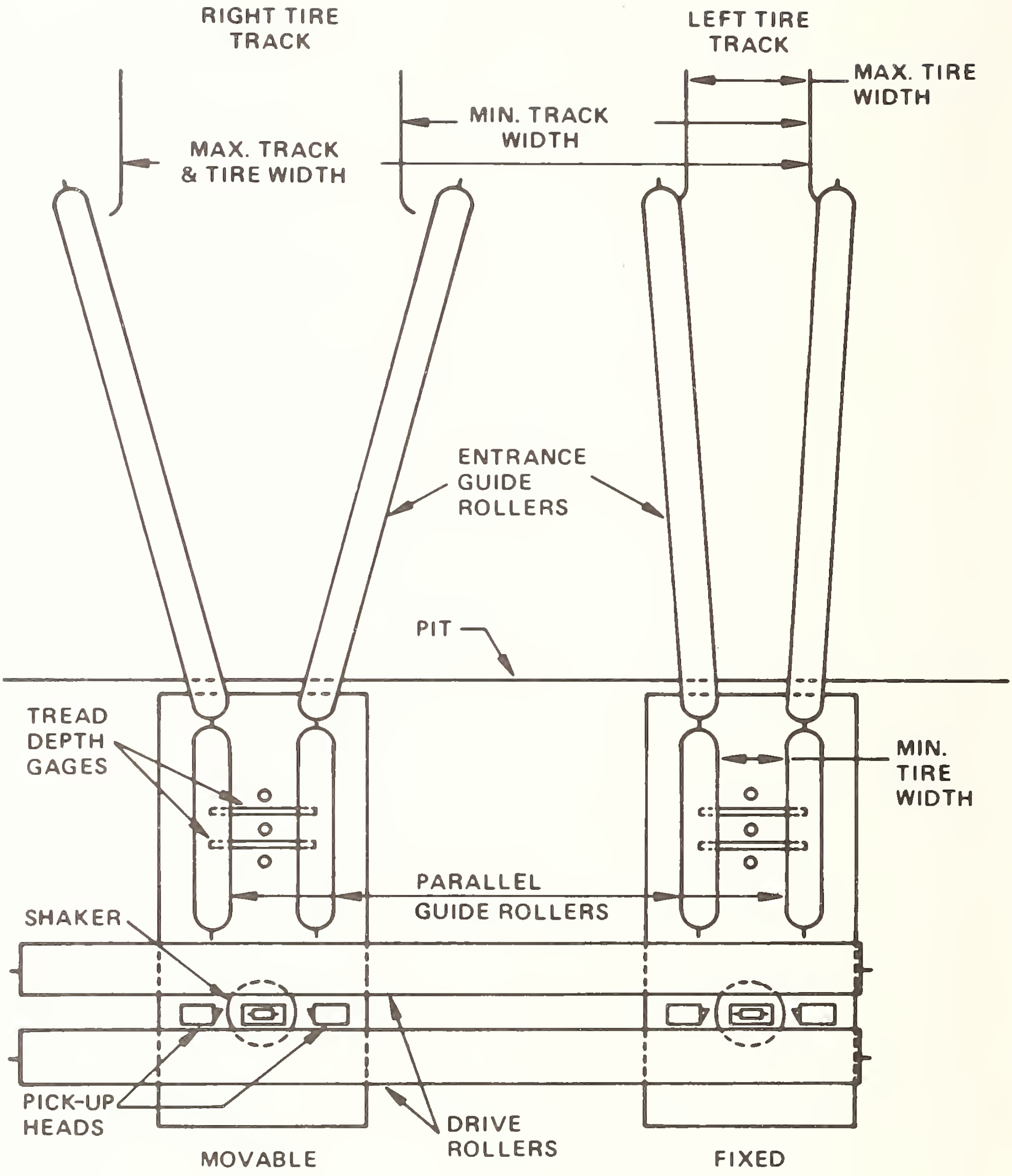


FIGURE 23 - Automatic Centering System

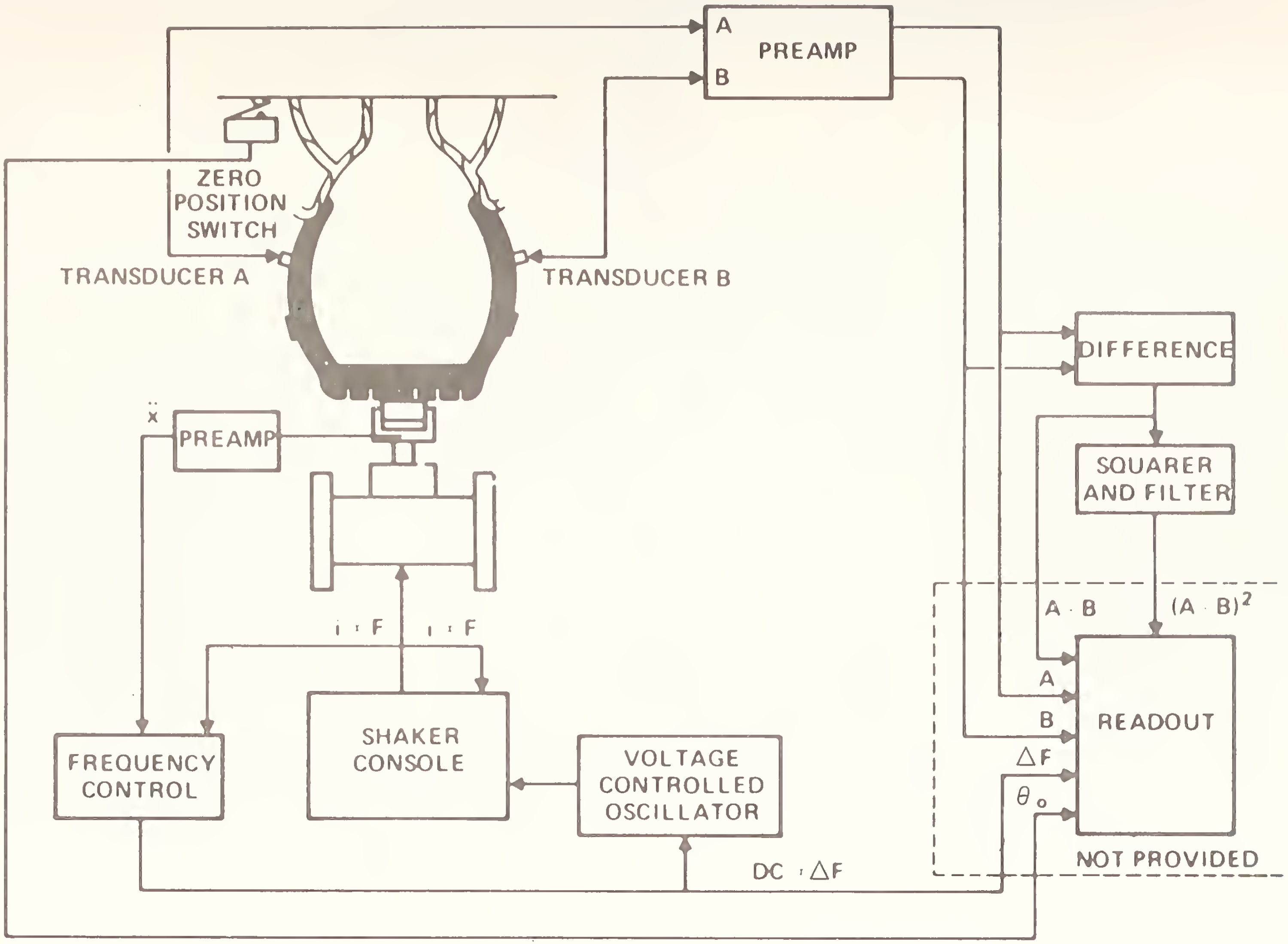


FIGURE 24 - Conceptual Diagram of Vibration Instrumentation

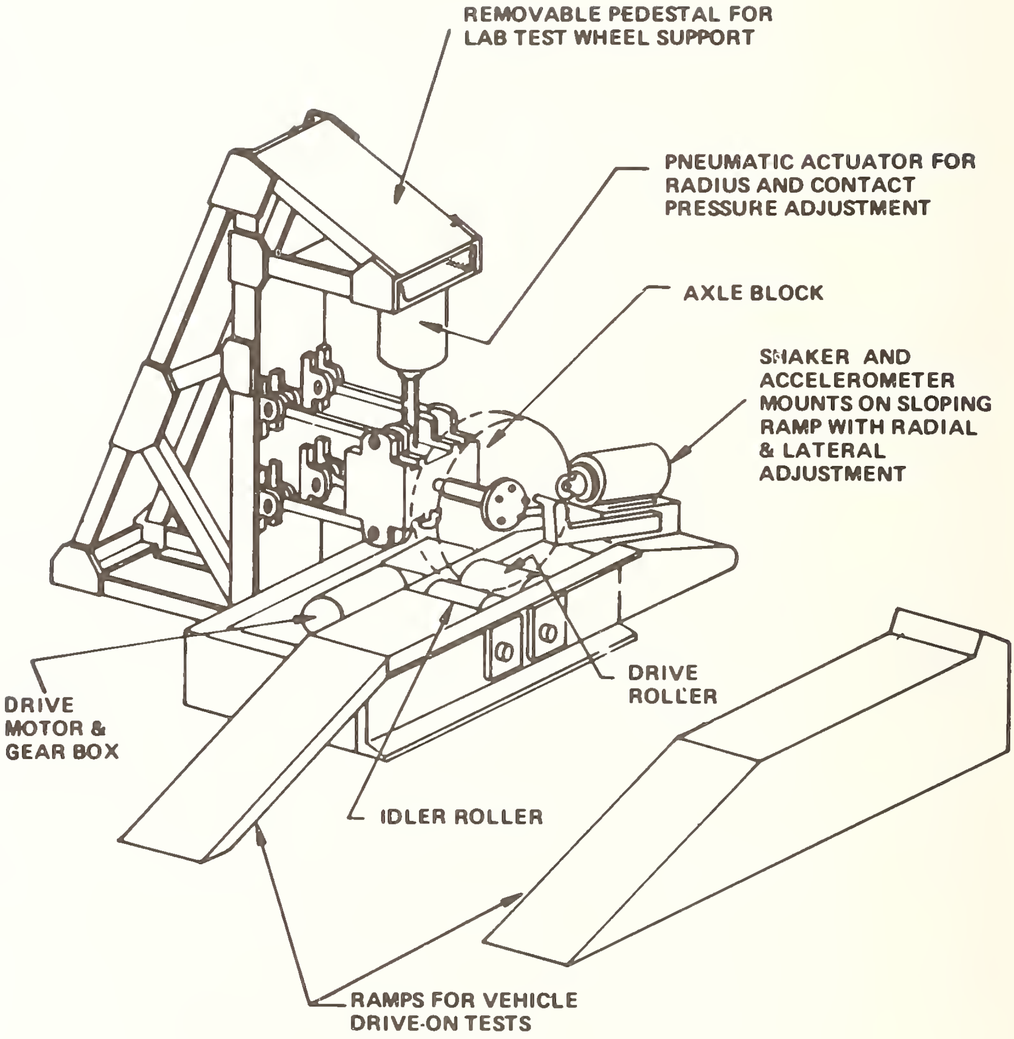


FIGURE 25 - Laboratory Resonance Inspection Apparatus

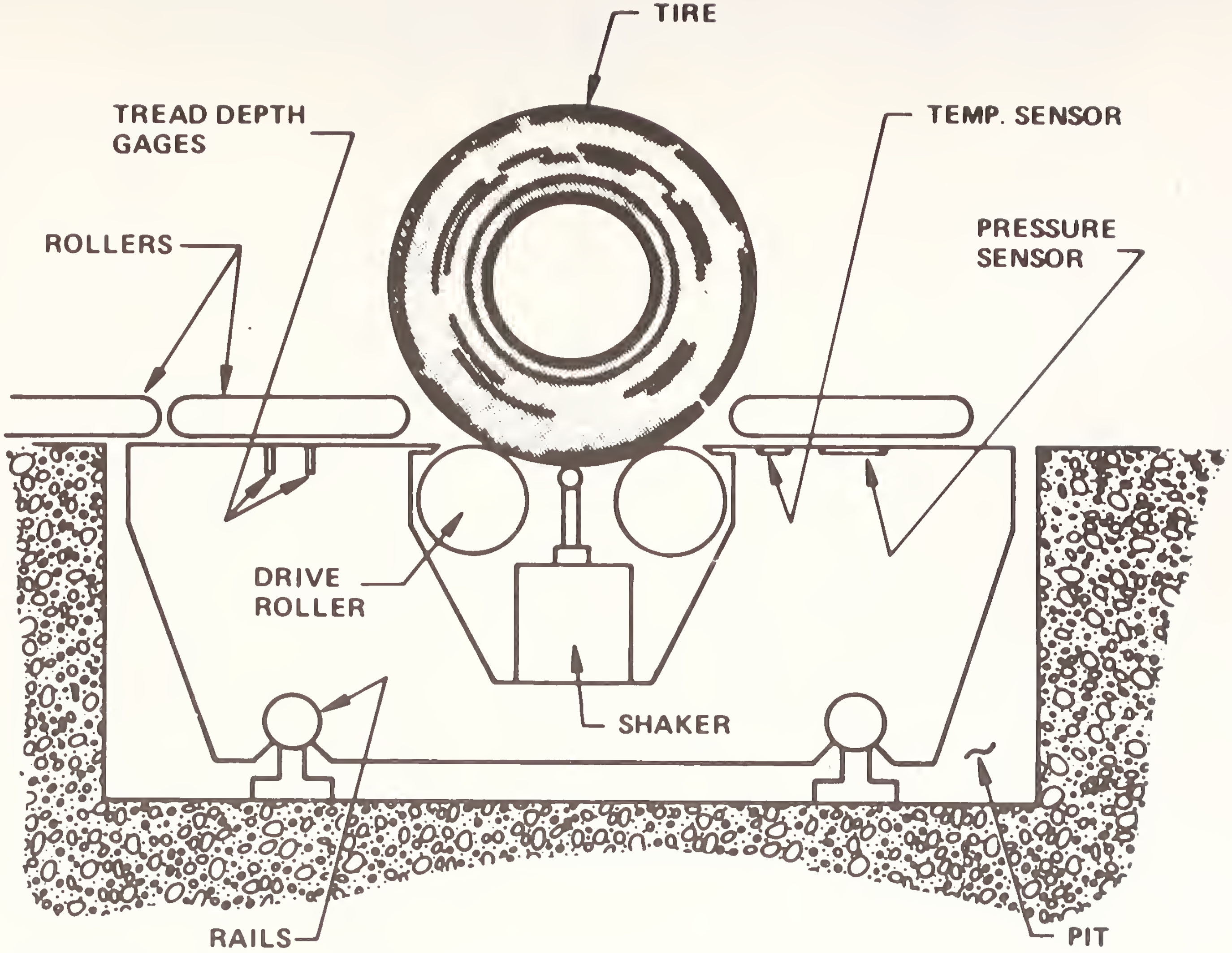


FIGURE 26 - Resonance Inspection Apparatus-Underside Excitation

DISCUSSION

J. M. Chudobiak, University of Saskatchewan: Why do you have to use resonance? That seems quite a drawback. I think that your method is very much the same as Mr. Philips' procedure and you are just measuring changes in symmetry.

L. H. Emery: The TSC results show that the resonance technique would probably be the most practical from an MVI standpoint. At inspection stations out in the states, tires come in dirty and wet - you want to have low cost equipment and maintenance, you want it to be fairly unsophisticated. The decision was made on the basis that resonance had the least drawbacks.

J. M. Chudobiak: Can't you just drive at any frequency? You are tying it down to specific frequencies which increases the sophistication.

L. H. Emery: The second resonance mode seemed to give us the most information in detecting these tire flaws.

J. M. Chudobiak: Did you try to drive it at various frequencies or did you specifically select natural frequencies?

L. H. Emery: We tried to look at just the natural frequencies.

O. E. Compton, Northrop Corporation, Aircraft Division: What would rim effects such as out-of-roundness, dents, etc., have on the side wall when using a resonance type frequency?

L. H. Emery: I don't really know. I think we are going to see that this year.

W. K. Mathison, Puget Sound Naval Shipyard: How do you determine the resonance for a particular tire? Do you use the same resonance frequency for a given type of tire or does it vary with the tire as it is brought into the inspection station?

L. H. Emery: It varies.

W. K. Mathison: How do you determine it, then?

L. H. Emery: The operator goes through the procedure and looks for it.

W. K. Mathison: He doesn't take any holographs?

L. H. Emery: We just use signal analysis.

R. Lenich, Caterpillar Tractor Company: There have been problems with tires because of varying stiffness due to the manner in which the plies were laid. Does this affect the weight pattern or influence your readings?

L. H. Emery: We expect some problems with this. We hope that we will be able to inspect for and find the major causes of tire failure.

E. DuBack, General Dynamics Electric Boat: In your test setup, you mentioned a three-pound load due to the rollers. It seems that in actual conditions you are going to have quite a bit more load when you consider a car.

L. H. Emery: When the car is sitting on the two rollers, the load will be set automatically so that the test head will come up between the two rollers.

J. M. Chudobiak: Are you also trying to get tire pressures from these vibrations?

L. H. Emery: No.

MEASUREMENT OF SPECTRA IN INTERNAL COMBUSTION ENGINE CYLINDERS

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Beaverton, Oregon 97077

The emission of light from chemical reactions is a very general phenomenon. New molecules are being formed with excess electronic energy and when that energy can be given off radiatively, the emissions can be observed. If one knows the exact molecular mechanism of the reaction, the emissions during the reaction can in some cases be interpreted. Observation of such emissions can be of use in two separate and distinct ways: 1) interpreted spectra can lead to models of the reaction mechanism, if not previously known, and identify the emitting species, and 2) empirical relationships can be determined from spectral observations as they relate to known variations in the reacting mixture.

In internal combustion engines, a fuel is mixed with oxygen (from air), compressed, and ignited. The very complex chemical reactions that then take place are quite energetic, take place under high temperatures and pressures, all of which ensure the vigorous emission of light. Spectral measurements of light emitted during combustion processes in the past have been of two types: measurement of temperature through optical pyrometry, and observation of emission of light at single wavelengths. Pyrometric measurements measure an equivalent temperature based upon a black body radiation law (Planckian radiator). Measurements at single wavelengths can be quite useful, but obtaining spectra using this technique would be quite difficult. It would be necessary to sample the spectrum at a known time in the firing sequence of the engine at as many wavelengths (in successive experiments) as is necessary to adequately describe the spectrum. Unfortunately, the intensities vary considerably from firing to firing making a statistical sampling necessary. Needless to say, transient phenomena which could lead to or be the result of a failure would not be seen under such conditions.

It should then be considered: what sort of transient phenomena could be observed and how could they be related to potential engine failures? To illustrate a point, consider some hypothetical failure modes or abnormal operations of internal-combustion engines and what spectral events might occur. Consider four possible abnormal conditions: 1) oil burning, 2) rust or metal shavings in combustion chamber, 3) hostile ambient conditions such as salt mist, 4) abnormal fuel components. The effective temperatures in a combustion plasma can be in the neighborhood of 4000°F[1]; or so. Under such conditions, any small metal fragments, dissolved elements, will be vaporized and atomized in exactly the same manner as in the graphite furnace in an atomic absorption instrument. The atoms thus produced will become electronically excited and emit light at their characteristic wavelengths modified some by the environment. It is then possible to identify them. If condition 1 occurs, then all of the dissolved elements in oil are vaporized and excited. Suppose the oil contained an additive with calcium in it. Then one might expect to see the characteristic calcium emission line at 423nm. In condition 2 which might be an engine that has not been used for a while or one in which there is a catastrophic failure of some sort, the iron emission lines would appear transiently upon starting the engine or at the onset of the failure. Condition 3 might obtain if an engine is operating in a salty mist created by salt-treated roads. One might then expect to see the characteristic emission lines of sodium or calcium if any of the mist penetrates the air filter and into the intake manifold. Similar observations are possible with fuel components in condition 4. The emission spectra in the near infrared measured on a CFR (Cooperative Fuel Research) engine appear to be molecular in origin. It is possible that the addition of fuel components such as methanol, ethanol, or water could change the appearance of that spectrum in a repeatable fashion. Thus, an empirical relationship between the particular fuel component and that spectral observation could be made. Should the origin of the spectrum ever be determined in terms of molecular processes during combustion, the observed effect could be interpreted in terms of the molecular interaction with the fuel component studied. Considerable work is under way to interpret these molecular-type spectra[2,3,4] and we feel that real-time spectral observation will give new impetus to their study.

The instrument that was used to make spectral observations from internal-combustion engines is made by Tektronix, Inc. and is called a rapid-scan spectrometer. Figure 1 shows a skeleton diagram of how the instrument works.

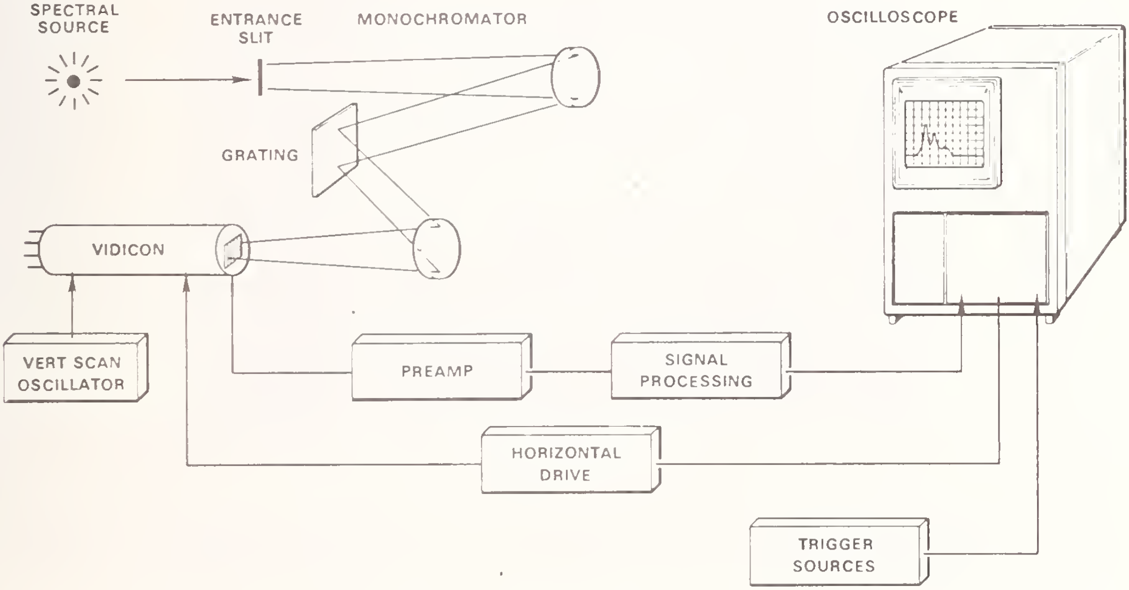

Figure 1. Basic block diagram of the rapid-scanning spectrometer system.

The light to be measured enters the instrument slit and passes through a Czerny-Turner type polychromator in which the light is broken spatially into its component colors or wavelengths. This spectrum is then imaged on the target of a silicon-vidicon image tube. The target is an array of microscopic photodiodes each of which detect light and store the signal in the form of an electrical charge. An electron beam then scans the thousands of photodiodes to read their charge, thereby measuring the intensity of the total light that fell on them. When the beam scans in the wavelength direction, the intensity versus wavelength is read. The signals thus obtained are sent to a cathode ray tube for display as intensity versus wavelength. Since all of the diodes can receive light information all of the time, it is possible to record spectral events at different wavelengths simultaneously. This detector capability is called the multiplex advantage. If a transient event takes place very quickly with respect to the scan time, its spectral distribution will still be recorded. The polychromator and the vidicon detector are all housed in a single small box allowing measurement in some difficult locations. Further, fiber optics can be used to pipe light from the source to the instrument slit.

Spectral observations have been made using a CFR engine through the courtesy of Professor John Mingle at Oregon State University, Department of Mechanical Engineering. An insert was used in one of the many test ports which contained a borosilicate window which allowed observation of the visible light emitted during the combustion stroke. A fiber-optic probe was affixed to this window cooled by forced air. The spectra obtained consisted of two very distinct types: sharp spectra and broad structured spectra. By wavelength position, two of the transient sharp lines were tentatively assigned as due to sodium (589nm) and potassium (768nm). This is reasonable since sodium and potassium occur due to dust particles and dirt. The transient lines could be generated by striking the intake manifold largely confirming this interpretation. Many of the remaining spectral features appear to be characteristic of the combustion process and appear to be molecular in nature. Some work has been done in interpreting these spectra[2,3,4], but with the capability of observing the entire spectrum in real time, perturbation experiments may be possible to confirm assignments or make new ones. Figures 2 and 3 are representative of some of the spectra recorded. The sharp lines are most probably atomic and the broader spectra are more likely to be molecular.

In looking toward future work, the observations could be made with more efficient optical coupling to enhance the weak spectral features and to use window materials that will allow wider spectral observations. It appears that spectral observations can add effectively to the measurement arsenal for the diagnostics of failures in both internal and external combustion engines.

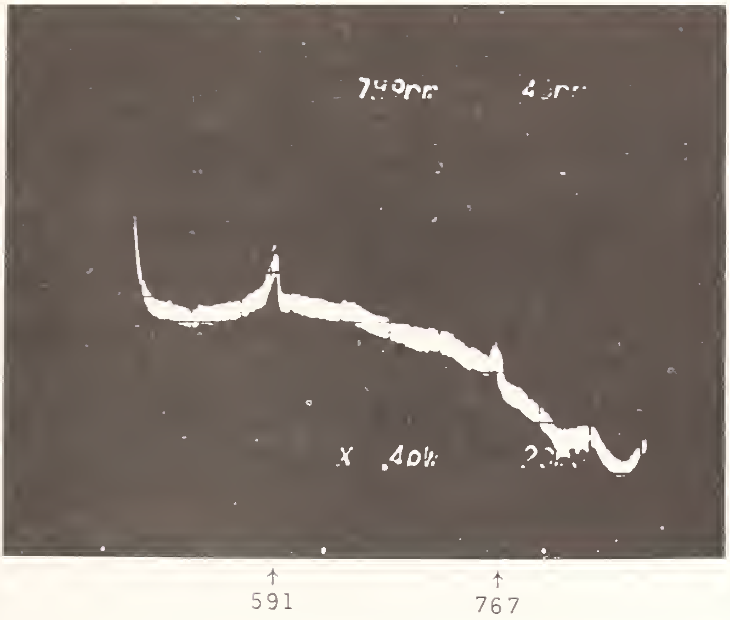

Figure 2. Combustion spectrum showing sharp lines due probably to sodium and potassium. (wavelengths in nanometers)

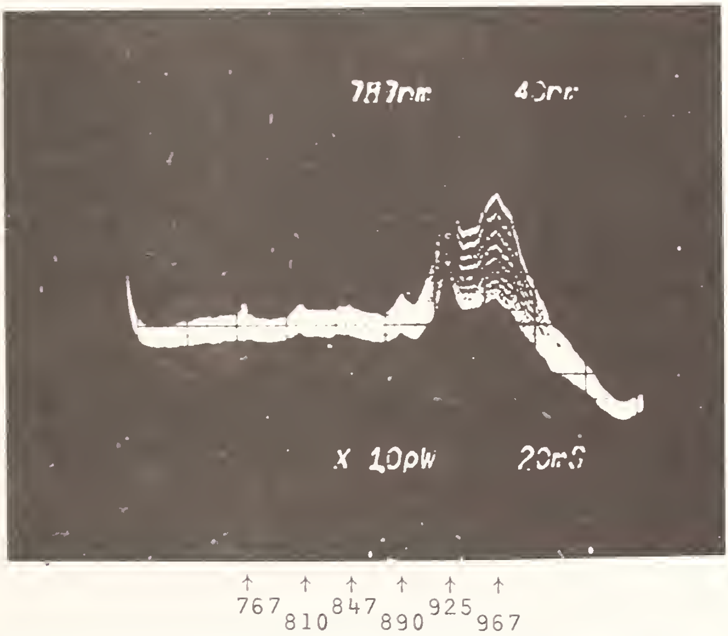

Figure 3. Combustion spectrum in the near infrared produced by the combustion reaction. (wavelengths in nanometers)

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2. Ehigo, R., Nishiwaki, N., and Hirata, M., "A Study on the Radiation of Luminous Flames", Proc. Eleventh Symp. (International) on Combustion, Berkeley, Cal. (Pittsburgh, Pa.: Combustion Institute, 1967) p.381.

3. Liebert, C.H. and Hibbard, R.R. "Spectral Emittance of Soot", NASA TDN-5637 (February 1970).

4. Smith, D.S. and Starkman, E.S., "A Spectroscopic Study of the Hydroxyl Radical in an Internal Combustion Engine", Proc. Thirteenth Symp. (International) on Combustion, Salt Lake City, Utah (Pittsburgh Pa.: Combustion Institute, 1971) p.403.

DISCUSSION

R. Lenich, Caterpillar Tractor Company: Do you foresee picking up dirt or silicon in an engine because of an air intake or air cleaner system?

J. M. Marrs: I'm not sure about silicon, but certainly sodium and potassium are picked up. If there is dirt in an engine, there is going to be sodium in copious amounts and that is probably the most sensitive probe for dirt.

H. O. Northern, Detroit Diesel, Allison Division: Do compounds like carbon monoxide and nitrogen compounds produce a recognizable signature?

J. M. Marrs: Carbon monoxide provides a recognizable signature in absorption in the 2 to 14 micron infrared region. We are not operating in that region. Our detector isn't sensitive in the infrared. However, most carbon monoxide analyzers work by looking at the approximately 1900 wave number absorption spectrum of that species. There is a possibility of measuring emission spectra of nitrogen ions and nitrogen oxides in the combustion process, and this is one of the things we want to look at in further research.

R. Hohenberg, Mechanical Technology, Inc.: Does the quartz fiber give you limitations in the spectra that you observe?

J. M. Marrs: It doesn't limit us in the spectral region so much as it does in the absolute level that we can see. There are losses in the fiber optics at all wavelengths uniformly over the range of the instrument. It would be best, of course, if you could use direct optics rather than fiber optics. It would be very desirable to try to determine the emissions from combustion reactions. The emissions are quite weak and would probably require a very efficient coupling into the chamber. Fiber optics would probably lessen the possibility of seeing the emissions.

C. R. Garbett, Shell Development Company: The width of the spectrum is very limited with your instrument. Can you spread this out so that you might be able to observe various molecular species, the free radicals, and things that would be of great interest to the people working on combustion? Could you in effect take a small range of the spectrum and spread it out across the whole of your scale and look at it in detail?

J. M. Marrs: You can optically disperse the spectrum to a greater degree. The videcon will have about 100 resolution elements across it regardless of how much spectrum is displayed across it.

C. R. Garbett: Not 100,000?

J. M. Marrs: No, not 100,000, but 100. If there are 4 nanometers across the videcon, there will be 0.04 nanometer resolution. My feeling is that under the conditions of combustion in which there are many atmospheres of pressure, you have pressure broadened spectra. It is virtually impossible to resolve such things as vibrational and rotational lines because the molecules are under such pressure. They are virtually continuous from the start with the exception of the single atomic elements which are also pressure broadened. The molecular spectrum would be broadened to the point where it couldn't be resolved even if the instrument had the resolution.

O. E. Compton, Northrop Corporation, Aircraft Division: Does the spectrum change quite radically as a function of the air/fuel flow ratio; that is, the burning mixture itself?

J. M. Marrs: Where we have observed this near infrared spectrum, there is no radical change in the spectrum as the mixture is changed. On the CFR engine you can change these things while you are observing. There was no radical change that I could observe other than a change of overall intensity. When we went to a very rich mixture, the near infrared portion virtually disappeared, although the visible light could still be seen. When we went to a very lean mixture, the same thing occurred. But in the middle region and in the area that is considered optimally tuned, the intensity seems to be at its maximum.

O. E. Compton: How about the oxides of nitrogen? Do they vary as a function of the combustion ratio itself?

J. M. Marrs: Yes, they do. The higher the temperature of the combustion the greater will be the fraction of the oxides of nitrogen. You can get that information without looking at the spectra but ironically it turns out that when the engine is optimally tuned for performance, the output of the oxides of nitrogen is maximized.

J. W. Forest, Ontario Hydro: What is the physical size of the 2500 square array?

J. M. Marrs: It's about an inch and a half round. The diodes are about 25 micrometers apart, so the electron beam actually addresses about 3 diodes at a time. As far as practicality is concerned, it is continuous but if you look in the microscope you can see the individual diodes.

D. B. Board, Boeing Vertol Company: Do you plan to evaluate this technique on a gas turbine engine?

J. M. Marrs: Well, that draws an interesting comparison between internal and external combustion engines. The reactions that go on in internal combustion engines are free radical reactions and many of the spectra that are expected will probably be there. In external combustion engines the reaction is largely an ionic one which might give rise to very different kinds of spectra. We haven't looked at a turbine engine, but we plan to.

D. B. Board: Would this be a suitable device for measuring temperature?

J. M. Marrs: That is a possibility. I have done some very brief reading about temperature measurement using sodium as an internal standard, and it sounds possible.

D. B. Board: If burning is taking place in combustor liners or turbine blades, can spectral lines be obtained from the burning elements as they are ionized?

J. M. Marrs: If the metal gets into the plasma and is excited, I would expect a characteristic emission. Spectral lines will be obtained if the emission is intense enough and is within the spectral range of the instrument.

D. B. Board: Have you to date encountered any problems in the attenuation because the window gets blackened after a period of use?

J. M. Marrs: Yes, it does attenuate it as it runs. In the internal combustion engine, we found that for some of the super fuels the window doesn't get very dirty, but when you switch over to a pure iso-octane mixture, the window blackens very quickly. So in an internal combustion engine, it is a problem. We still see spectra; they are just attenuated.

R. Hohenberg: I just wanted to say a gas turbine is an internal combustion engine with continuous combustion rather than intermittant combustion.

J. M. Marrs: But if it indeed does have an ionic mechanism, there is a very distinct difference.

R. Hohenberg: That's right, but the question really is, is the ionic mechanism associated with continuous versus intermittant combustion rather than internal versus external combustion.

M. Dow, Eastern Airlines: Did you get some feel for how long this high excited state would exist, for instance, in a jet engine?

J. M. Marrs: Molecules which fluoresce typically fluoresce within a few nanoseconds after they are excited. In an engine, however, the plasma lifetime is quite long compared to that. A sort of steady state of emitters is generated even though each one will have an average lifetime of a few nanoseconds. The results are the average of a large number of excited molecules and not of a single decay.

M. Dow: I was thinking about the physical position along the length of the engine. You want to look right at the hottest point, not ten feet back, right?

J. M. Marrs: Yes, it would occur only in the combustion chamber and would disappear long before it would ever exit.

PANEL DISCUSSION: Planning and Executing Experimental Verification

Panel Moderator: R. Hohenberg, Mechanical Technology, Inc.

Panel Members: D. R. Houser, The Ohio State University
G. J. Philips, Naval Ship Research & Development Center
R. L. Smith, Shaker Research Corporation
L. H. Emery, National Highway Traffic Safety Admin.
J. M. Marrs, Tektronix, Inc.

R. Hohenberg: This panel discussion will revolve around a problem that we all face. We are looking for detection, diagnosis, and prognosis technology, and a consistent stumbling block is the demonstration of payoff. Well, that is kind of blunt and crass but really that's the purpose of the technology, to pay benefits back for the doing of the work. This payoff has to be demonstrated and it has to be demonstrated by an experiment which is hopefully planned. I say hopefully because we have seen so often that the statistical problem, the probabilistic comparisons which are necessary, and the human element which is introduced into these experiments tend to upset them. Most of the time many of the experiments that have taken place to demonstrate the payoff of DD&P have resulted in reports that invariably say: 1) the experiment is a success - we have got to call it a success, otherwise why bother to write it up; 2) unfortunately some very necessary data are not available at the time of the conclusion of the experiment; and 3) let's do it over again. Well, I think it's worthwhile to discuss what we can do to plan experiments so that when they are concluded and the reports are written, we don't have to do them over again.

R. L. Smith: DD&P experiments sometimes do lead to meaningful results. The problem then is to convince management to implement your system and sometimes they are not willing to put out the money. The dollar level shown to them is not convincing enough, so you have to sell the diagnostic system more than just telling them of the numbers.

R. Hohenberg: How do you design an experiment that overcomes an inherent problem such as avoiding failures in a population which is usually very large? There is no sense going into diagnostics of machinery unless there is some substantial population. You want to show that if you didn't have the diagnostic equipment, more money would have been put out to maintain the machinery. And you somehow also have to figure in the problems that are incurred due to the false alarms that may be created. How does one set up the experiment? The laboratory experiment is probably the easiest part in demonstrating that a particular mechanism has some benefit. It is more difficult to go to the next step of boxing it up neatly and putting it into service. How do you plan for that?

L. H. Emery: In any project that I have ever been associated with, you always, without exception, would have done it slightly differently if you could do it over again. It's probably impossible to anticipate all of the problems that are going to occur and it's also very difficult to get all the answers when you need them as you progress. It happens quite frequently that you make some decisions along the way based on insufficient or unavailable information.

G. J. Philips: Rudy, if I understand what you are saying, an engineer has to be a reactionary all during the course of his experiment. No amount of super planning is ever going to make every experiment a total success. There are always going to be failures and unknown factors cropping up during the test. These factors must be evaluated and they may change the course of the experiment. You have to maintain a certain flexibility.

D. R. Houser: In the diagnostic avenues, a lot depends on the cost of the test equipment. If you want to determine all the failures in a whole helicopter, the experiments are much more expensive than for examining one bearing. And the statistics become quite different. A statistic of one is not very valid. There are means of analyzing or building experiments statistically which can reduce the total number of tests you have to conduct.

J. M. Marrs: Many times a diagnosis seems like the horse-out-of-the-barn type detection. The failure has taken place. In many cases during failure analysis, you get information about the cause of failure and will be able to change some procedure which will then eliminate these failures. Therefore failures may be prevented rather than just increasing the efficiency with which they may be detected.

R. Hohenberg: There is a school of thought that says that if you spend all the effort that is now spent on failure avoidance and failure detection in improving the basic design, you just won't have any failures at all. And then there is the opposing school of thought which says there is no way of avoiding all failures and that it becomes desirable to make an effort to detect a defect at a time when the burden of the failure is not yet fully realized. You can detect a failure in, say a gear, while the gear is still functioning. A crack is there, but the gear is performing its useful function before the catastrophic failure has occurred and the damage causes loss of life or termination of function of the whole machine.

A. J. Hess, Naval Air Test Center: We are using a diagnostic system that the Navy has developed for its A7-E aircraft that is statistically and cost effective. We have reached a point in the development of our system where we are about ready to implement it in a fleet production-type program. We have gone through a very extensive, sometimes careful, sometimes not too careful, data base expansion and preproduction evaluation program. As we are developing the system we try to collect the statistical data necessary to prove that the system is cost effective in an actual fleet operational environment. We have ten A7-E aircraft with this in-flight engine condition monitoring system on board the Enterprise right now. It has been deployed since last November and it had been operating in naval squadrons for about eight months previous to last November. We have over 5,000 actual operational hours in a fleet environment and we have big lists of finds that the diagnostic system has discovered - engine discrepancies which normal maintenance did not find. We have tracked these finds through maintenance actions and verified a list that was valid and a list that was invalid. Right now we are in the process of putting dollar figures on where we saved in two different areas. One is a possible savings of aircraft since this is a single engine airplane. The second is the area of maintenance and logistics. You can put dollar figures on maintenance man-hours saved at the line level and at the depot level. You can also put dollar figures on secondary damage saved and on the logistics problem. Hopefully, within two or three months we will have data published to be used to verify that this system is cost effective. We ran into problems in setting up the program, and some of the things we learned are unique in the development of a condition monitoring system which don't have to be relearned for the next one when it goes into its preproduction evaluation.

D. B. Board, Boeing Vertol Company: In the past year, one of the mistakes that has been made in our programs was not determining before we started a test whether we were trying to demonstrate diagnosis or prognosis. Far too many reports come out with conclusions that make implications about prognostic capability when the only real testing that has been done that is valid statistically is diagnostic. We seem to say the real measure of a diagnostic system is whether it detects defects. When we find an indication of a defect, we never ask ourselves what its meaning is. It is only meaningful if we know the probability of obtaining a false indication from a part without a defect. Of even greater importance is determining the probability that the defect could not be found. We always go around measuring the probability of finding a defect of a known size. Very infrequently do we really plan the experiment so that we get information that tells us how likely it is that we would have indicated that something was wrong if it was not. That is a statistical problem and it requires a lot of testing. You can't afford to do a lot of testing on expensive machines, so you have to find cheaper ways to do it. First of all you have to realize whether you are doing diagnosis or prognosis. Then you have to design your experiment so that it has enough of a statistical basis so that you are getting both of those reliability or accuracy probabilities - not only the probability of finding the defect when it's there, but the probability of saying it's there when it is not.

P. L. Howard, SKF Industries: One major problem is going after a symptom that was thought to have caused a failure. In a diagnostic approach, it is necessary to define what is being looked for. A very nice diagnostic technique can be developed to look for a defect that doesn't mean anything in the overall running of the system.

D. B. Board: I concur completely. That is one of the toughest nuts we are eventually going to have to crack. Tied to the problem of what's important to detect is the problem of what are the failure progression rates. We can pretty much say what the consequences are going to be if a gear breaks in half or a bearing starts to seize, but we really know next to nothing about failure progression rates in all of the thousands of different applications that machines run under.

R. Lenich, Caterpillar Tractor Company: I agree with Mr. Board. The manufacturer talks about diagnosis and the customer really isn't interested in diagnosis unless he has to be. What he is interested in is prognosis. You can only have prognosis if you have some kind of a deterioration rate. Things that break you can't prognose. The customer knows it, he has detected it, the machine has stopped, and he really isn't interested in spending money on diagnosis. He is interested in having a machine that will run until some overhaul period. At that point he doesn't mind seeing cracks or pits in gears and cracks in weldments provided they haven't broken or damaged the machine. He considers this a good prognosis because he can correct the problem at that point. There must be a certain percentage of problems before people will use diagnostic equipment. The customer really wants product reliability and he expects the manufacturer to do the testing before it is put on the market. What the customer is interested in is prognosis, and he would rather have it on vehicle. It rings a bell and tells the operator to stop the machine, and at no cost increase except maybe $3.00 for a transducer that will last 10,000 hours.

R. Hohenberg: I think you've pointed up something which is very significant; that is, we are talking about two different things. One is verifying that the condition of a new part is acceptable, which is an inspection procedure. The second is a prognostic procedure which determines if a part has a reasonable amount of useful life left.

O. E. Compton, Northrop Corporation, Aircraft Division: One of the weaknesses of our industry is that we too frequently do not issue the proper software, or make an adequate study of the software, that goes along with the testing device. The problem is - how well does the software support the individual doing preventative maintenance?

U. Sela, Exxon Company, USA: I would like to talk as somebody that has been involved with three phases: (1) sitting in a lab and looking at phenomena which could be used to find out something, (2) having been associated with one who tried to develop a system such as signature analysis, and (3) trying to use some of those systems or some of those phenomena. The real question is: (a) what is going to fail, and (b) so what? I tell them that I found all these wonderful things with my wonderful technique. Those gears are seeing 10, 15, 20, 25 g's, the side band ratio is such and such. The question is, can it run, for how many months will it run? Who knows. Then they ask me what happens when it breaks? What position will we be in? What will the damage be? How long will it take to repair? What is still needed is to be able to translate the signal into an actual stress so that we can make a calculation of what the safety factor of the part is and maybe later determine when failure may occur. I feel frankly that with all that we are learning I am no better off today than I was ten years ago.

J. A. George, Parks College of St. Louis University: I disagree with the chairman's comment that we are interested in finding such things as spalls, pitting, corrosion, etc. The component may last many operating hours with these defects. We are right back to what Mr. Sela said - when is it going to fail? In spite of a lot of the work that has been done in many systems, we still don't know how to design a proper experiment for prognosis. One method could be to run to failure. That's kind of difficult if you put a bad gear or a bad bearing in a helicopter and tell the pilot to run this to failure. So you do it in a laboratory. Unfortunately, the mechanisms that we are interested in are more complicated than simple gears meshing together. There is a difference between laboratory experiments and those involved in an actual operating condition. You have got to collect the data in a real life environment.

R. Hohenberg: John, I just want to defend myself a little. I did say that it is desirable to detect spalls, but that is at the inspection level when you are trying to make a part as good as it should be when new. There is a different level of detection in the field when the machine is already running, when you are trying to decide when to stop it. There is a time when you want to detect minute defects and there is a time when you want to detect precursors of catastrophic defects.

J. A. George: My point is, maybe the quality control is too rigorous. Maybe we can stand some of these minor pittings and spalls and yet fulfill some reasonable operational lifetime. Maybe we are trying to make it too perfect.

H. U. Burri, RCA Corporation: What we have been talking about is providing some sort of a magic black box which, when attached to some expensive piece of equipment, will act as a nurse and take the temperature of the patient constantly. Who checks the nurse? I do know that electronic equipment has a tendency to fail. There is a real problem there to make sure that we do not get false alarms or missed detections or fails just because the test equipment has failed.

R. Hohenberg: I think it's a very good thing that you brought that up because it leads us directly to the human interface which does warrant a lot of attention. Any diagnostic equipment must operate to the satisfaction of people, and these people are not scientists, they're not engineers, they're not the owners of enterprises, they are mechanics. To make them satisfied that the equipment is doing the job that it is supposed to do, ideally you want three lights - a green light that says, "Yes, this equipment is fine, leave it alone," a red light that says, "No, stop the equipment, there is a malfunction impending," and a yellow light that says, "The monitor is sick, the nurse is sick."

J. S. Bendat, Independent Consultant: I think there are many aspects to this problem that are being raised simultaneously which is causing some confusion. If you are trying merely to monitor some simple component - bearing, gear, etc. - you're collecting data at one point and looking at either its spectrum, or some other time history, by visual or some other simple method determining whether a change has occurred. On the other hand, if you are trying to analyze more complicated subsystems such as diesel engines, or motors in general, or if you want to analyze larger systems such as automobiles and airplanes, etc., you need to look at the problem from a much broader viewpoint as a multiple input-output type analysis where there are many excitations occurring at many points producing many responses at other points. In all of this work, there is a requirement for practical experience in addition to any mathematical modeling or statistical techniques. However, I would like to note that there are many techniques available for analyzing periodic and random data which are not being utilized as fully as they should. Any results that are obtained should always be qualified to indicate that they are from a particular experiment and were collected under certain conditions which are not likely to be duplicated. If anybody is to usefully interpret these results, there should be some confidence bands inserted stating that the results could be significantly different at some future point in time. If either single point or multiple input-output type analysis is conducted, you can get results which not only will be better for diagnostic purposes, but which also will be a lot more useful for prognosis. I would like to find out if anyone here has worked on some of these larger problems where they are collecting a lot of data simultaneously and trying to unravel all the various interactions and effects that are taking place.

D. N. Fry, Oak Ridge National Laboratory: This is exactly the problem that we are tackling right now in connection with detecting failures in nuclear power plants. Our primary work is not necessarily with rotating machinery, but with failures of structures connected with core components in the nuclear reactor itself. We are presently trying to apply pattern recognition and signature analysis techniques to multiple signal inputs. Part of the problem is to include in the total analysis the error associated with each measurement, so that the algorithm that makes the decision on whether the particular data you have just taken is either normal or abnormal. This takes into account how much data you already have and what the confidence is on the base line signature that you presently have. We are probably not the first ones to do this. I think it's in common use, but we really haven't heard much about it here today.

J. W. Forest, Ontario Hydro: It seems that there is a conflict in the goals which we are trying to establish. There is emphasis placed on diagnosing a defect and there is also emphasis placed on saying how long a component will function (prognosis). The conflict comes from not being able to tell how long something will run until it fails. I have some experience with a vibration monitoring system in a nuclear power plant and on rotating equipment. One of our problems is of a statistical nature because no two failures are going to be the same even if they are the same component. It's quite a task. I think the people that are asking for the quick answer of prognosis are going to have to wait a long time before it's resolved.

A. J. Hess: I'd like to comment on two of the points that were brought up. First is the system/human operator interface. When we first introduced the IECMS system to a fleet type environment, the pilots and the maintenance operators didn't like it much. From a maintenance standpoint, it was an additional engine subsystem which they had to maintain and caused them to perform extra maintenance on the engine. What they found out later was that by using the IECMS system they were better able to maintain their engines. The statistical data that we generated showed that more maintenance was performed on IECMS equipped engines than on engines not so equipped in about the same number of manhours. From that you can deduce that the engines were perhaps better maintained in the same amount of time. Initially the pilots did not like this diagnostic system flying along and recording data and acting as a tattletale on how they operate the engines. But as they used the system, they experienced situations where the IECMS system verified engine gripes and it enabled the pilot, the operator of the aircraft, to interface better with the maintenance department to prove that he was right in situations where the maintenance department said he was wrong. And conversely, we have had situations where the system verified a pilot gripe as being wrong, but saved lots of unnecessary maintenance on that engine. The initial interface between the human and the system becomes a question of confidence level. The only way that you can build up this confidence level is to let them have the system and use it in an operational environment. That's what we did and that's what we experienced. The chairman made an interesting point when he mentioned the three lights. We have three lights in the cockpit; one is to indicate that the system is not operating and to ignore it, the other two indicate that something is wrong with the engine. The other point that was brought up that I would like to comment on is how to handle a multitude of inputs from different types of diagnostics. The IECMS system does several different types of diagnostics such as vibration analysis, gas path analysis, exceedance limits, and oil quality. The only way you can realistically handle all those inputs is by some type of computer software diagnostic logic routine. That's the way we tried to do it. We expended our greatest effort in developing software routines, not in developing the hardware.

P. L. Howard: In summary, the diagnostic manufacturers, as they have in the past will now and probably forever, say that the success of their system is based upon the detection of some fault. Not even the diagnosis but the detection of some fault. The user will say the success of the system is in saving some catastrophic failure, and I think they will stay apart until the significance of the fault and its relation to a catastrophic failure can be demonstrated.

SESSION II

CASE
HISTORIES

Chairman: P. L. Howard
SKF Industries

SONIC ANALYZER - CASE HISTORY

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Introduction

The sonic analyzer was a diagnostic system aimed at detecting malfunctions in gas turbine engines and helicopter transmissions prior to catastrophic failure. The program was active under several sponsors during the 1960's and early 1970's. For a part of the time the overall program was active, two parallel, competitive programs were conducted by Curtiss-Wright and the General Electric Company. At the first MFPG Meeting in April, 1967, both companies described their approach to sonic analysis of gas turbine engines.

The purpose of this paper is to examine what can be learned from the program experience, particularly in those areas that are common to today's diagnostic programs. In order to do this, the Curtiss-Wright approach will be briefly described, its success analyzed and three specific program areas that emerge as significant when the program is reviewed with perfect 20-20 hindsight.

Sonic Analyzer Concept

Sonic analysis as employed is the same as today's vibration signature analysis except that microphones were used rather than accelerometers. The discrete character of the frequency domain spectrum is analyzed and characterized. Most discrete frequencies can be associated with rotating components in the machine. Three types of signal character changes were considered significant. They were changes in:

Amplitude
Harmonic Content
Modulation Character

The kind of changes that were looked for are illustrated in Figure 1 which compares the spectra of two hypothetical engines, one healthy and the other side with the above three symptoms. The oil pump signal at approximately 1500 Hz illustrates the increase in amplitude symptom. The appearance of the thrust harmonic of the fuel pump at approximately 3000 Hz illustrates the harmonic control symptom and the appearance of side bands on the compressor blade passing signal at approximately 1200 Hz illustrates the modulation symptom. This type of analysis is still valid today and was considered quite advanced in the early 1960's.

Figure 2 is a block diagram of the hardware built to implement the concept. It is a standard heterodyne analyzer with two exceptions, the phase lock loop and the frequency ratio synthesizer. These two circuits allowed the analysis of the signals as a ratio of engine speed and thus independent of RPM. Again these two circuit developments as related to vibration analysis were significant advances at the time. Figure 3 is a photo of the sonic analyzer as used in the field. The unit shown included a paper tape reader that allowed full automatic operation of the analyzer, another advance. The unit was portable, however, it obviously could benefit from today's integrated circuit technology. Also, today, a laboratory receiver of the analyzer with superior characteristics can be constructed from off the shelf instruments.

Over the period of its use, the analyzer was applied to the following engines and helicopter transmissions.

Engines	Helicopter Transmissions
J-65	UH1
J-57	CH46
J-79	CH47
J-52	
JT-30	
Jt-80	

Results

Probably no two people associated with the program would agree on a rating of the success of the sonic analyzer. The safest thing that could be said is that it would detect some of the defects claimed for it on many of the engines and transmissions listed above. The purpose of this paper is not to rate the success of the program but rather to review what can be learned from it and applied to other diagnostic programs. The following three characteristics of the sonic analyzer program are common to every diagnostic program.

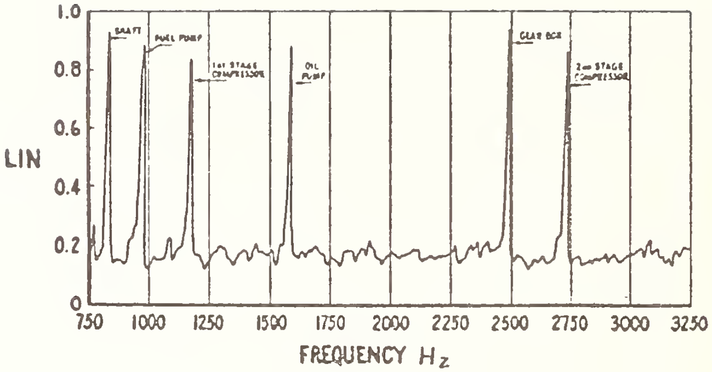
1. Laboratory Vs. Field Testing
2. Human Operation Skill and Bias
3. Assessing the Batting Average

These three characteristics are briefly discussed below and will be expanded upon in the presentation.

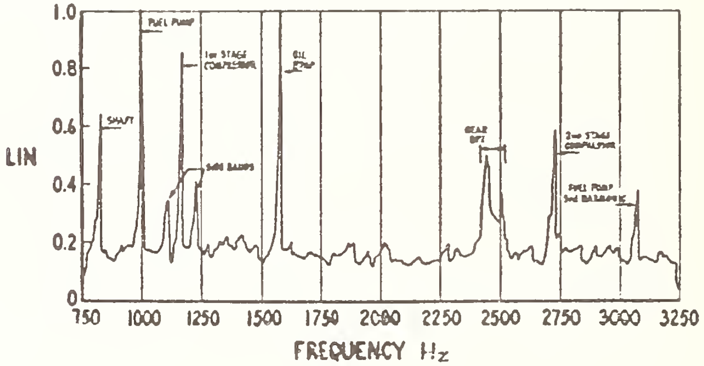
1. There probably is some optimum mix for a given program between lab and field tests. The sonic analyzer program would have benefited by more laboratory testing. For example, mechanical impedence tests to determine signal transmission characteristics and coupling coefficients to the air may have clearly identified the detection of some defects as impossible. Almost all diagnostic programs that have advanced too quickly toward field condition have failed or had to return to more controlled conditions.

2. If an analyzer operator who has a very good understanding of the engine under test and the analyzer, consistently gets better results than one who simply follows directions; then this is an indication that the programmed limits alone are not sufficient.

3. Specific ground rules on how to grade the diagnostic system must be implemented. Comparison with the parts replaced at overhaul is a very unsatisfactory way of grading a diagnostic system. A significant proportion of the cost of any diagnostic system evaluation lies in this area.



SPECTROGRAM OF HYPOTHETICAL ENGINE OPERATING NORMALLY



SPECTROGRAM OF HYPOTHETICAL ENGINE
OPERATING WITH FOUR MALFUNCTIONS

FIGURE 1

(CWEA-3)

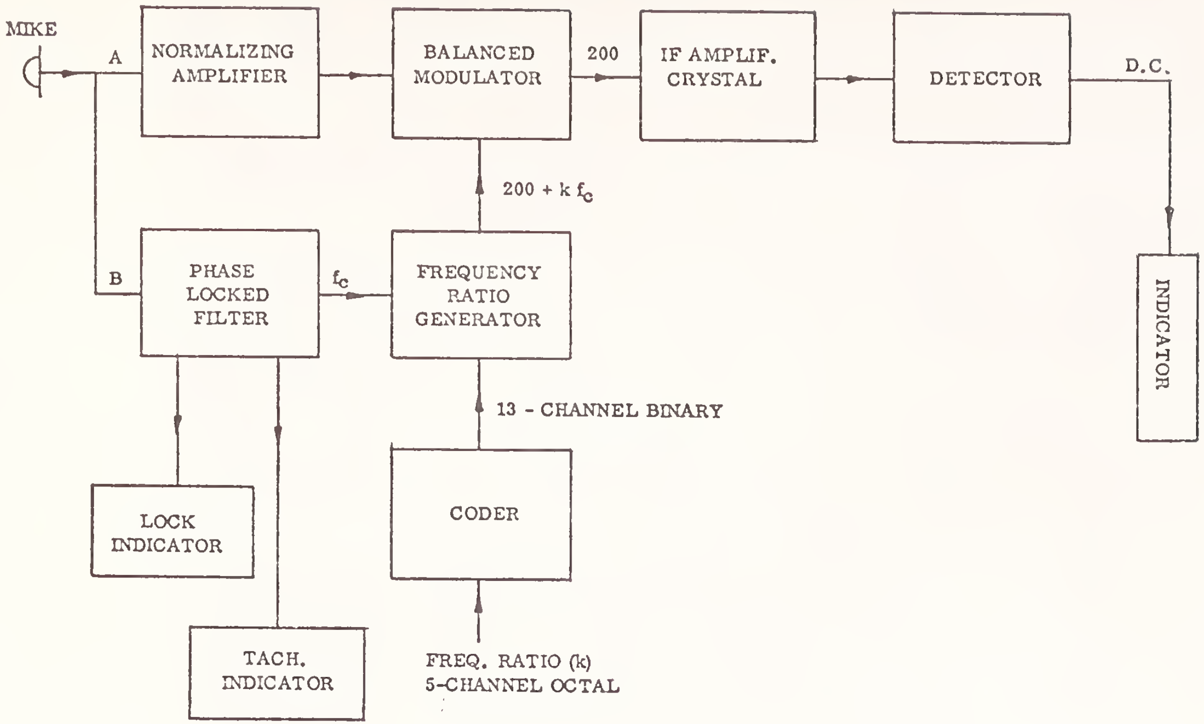


FIGURE 2

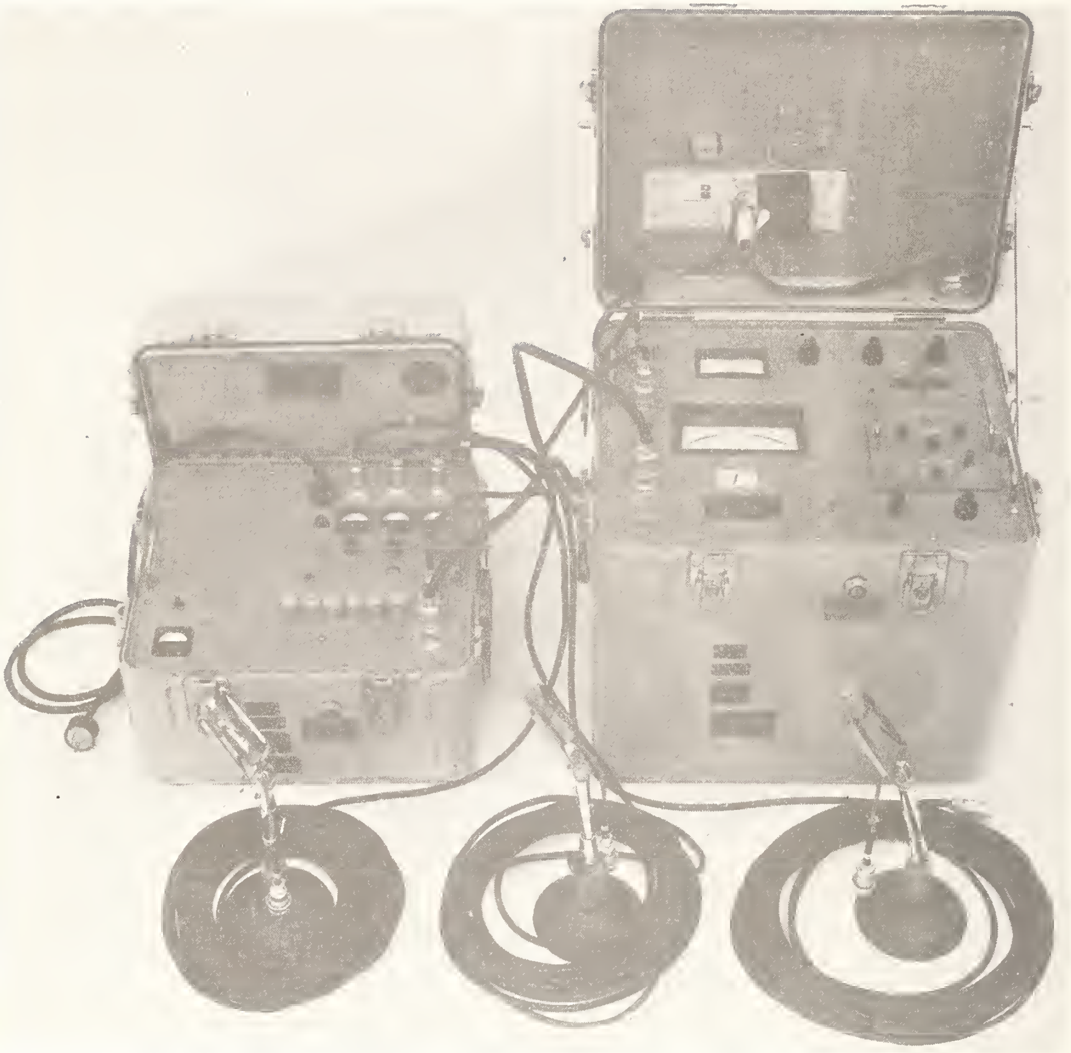


FIGURE 3

DISCUSSION

W. K. Mathison, Puget Sound Naval Shipyard: If you had the chance to start again today with gas turbine engines, would you use the sonic analysis again, or a vibration analysis, or something else?

J. L. Frarey: I would use anything I could lay my hands on that might give me a hint as to what was going on inside the engine. The problem with the sonic analyzer has been that very early in the game, we trapped ourselves into exclusive use of the microphone because it was very easy to use. It was very easy to put a microphone next to an engine compared to screwing on an accelerometer or trying to bury something, or open a port, or this type of thing. Sonic analysis would work in some places. I think that it should have been implemented all along with additional accelerometers.

OIL ANALYSIS IN PERSPECTIVE

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Detection of component malfunction in lubrication and hydraulic systems, prognosis of the course and remaining system life and possible diagnosis of the type(s) of failing component(s) have been the primary objectives of most oil analysis activities. Several previous MFPG papers and one entire meeting were aimed at describing the transfer of spectrometric oil analysis methodology in the 50's from industrial internal combustion engines to rotating machinery, the success of this methodology, and a description of non-spectrometric oil analysis techniques (1, 2, 3, 4). My objective is not to overview these papers but to review the methodology of current oil analysis activities to indicate its weaknesses with respect to future lubrication system design and reliability and to indicate changes that appear to be desirable to provide meaningful "oil analysis" services to future high performance equipments.

Oil Analysis Methodology

Present "oil analysis" methodology may be subdivided into three parts. The first phase is sampling which assumes, sometimes mistakenly, that the oil and the particulates in it are representative of those in the system. The second part, composition determination, is accomplished in a calibrated commercially available instrument; this wear metal concentration data, along with available information such as operating hours since the last sample, and oil change or addition data, is then used by the "oil analyst" to infer that the rate of production of metal in the system is increasing, decreasing, or remaining the same. The oil analyst effectively makes periodically updated estimates of the wear metal production rate based on this data. Ideally, concentration, concentration change with time, and possibly oil consumption/addition data, are inputted by the oil analyst into the equation in Figure 1 to obtain the metal production rate. If the filter in the system is removing but a small fraction of the particulates that are formed, (i.e. the filtration rate is small), the rate at which particulates are settling to sumps and the rate at which dissolved metal is depositing on the system's surfaces are low, then the "oil analyst" can make a fine prediction of the wear metal production rate, its change with time, and a reliable assessment of any change in machinery condition.

The original success of the analyst in predicting problems in diesel and other systems engines which are generally equipped with coarse filters (40 + micron) therefore is understandable. However, others such as the hydraulic systems, which are installed in Naval aircraft and which are equipped with relatively fine (5) micrometer filters, are not as responsive to conventional oil analysis methodology. As a consequence, the spectrometers are not sensitive to the small concentrations of particles present in the system and the comparatively slow rate of change of metal concentration with time, even when the system is wearing at abnormal rates. Unfortunately for the "oil analyst", this trend is continuing because machine designers are beginning to recognize the benefits to be obtained by specifying filters that remove a high fraction of particulates which can be deleterious to the life and reliability of the equipment. For example, the T-700 engine developed for the UTTAS helicopter is to be equipped with 3 micron filters originally tested on the T-53 engine (5, 6).

Particle Size/Concentration and Machine Reliability/Life Relationships

Examination of the relationship between particle size, concentration and machinery reliability and life is best begun by comparing particle size and lubricant film thickness as a function of application for naval equipments. I have chosen aircraft derivative bearings and gears, hydraulic system components and journal bearings typical of those supporting steam turbines as extremes. As may be seen in Figure 2, the film thicknesses in these equipments range from 0 - 0.1 micrometers to 25 micrometers and installed filtration capability begins to compare favorably with film thickness only in the hydraulic and steam turbine journal bearing application. Only in the case of the steam turbine journal application can sufficient particulate matter be expected to be in suspension to be truly susceptible to spectrometric analysis and at the same time not be deleterious to the mechanical system. These conservatively designed systems are inherently very reliable and are not a priority item for oil analysis. The aircraft hydraulic system, because its sliding components are very susceptible to deterioration by particulates and therefore is much less reliable, is equipped with efficient filters and renders spectrometric analysis almost ineffectual. Only in the case of the aircraft bearings and gear systems is the lubrication system susceptible to spectrometric oil analysis because they are not now equipped with efficient filters. The extent of the application of spectrometric oil analysis will decrease as finer filters are installed in these systems to increase life. Preliminary evidence indicates bearing lives and presumably the lives of these film gears can be increased many times by using effective filtration techniques (7).

To illustrate the relationship between wear particle size, concentration detection limits, wear particle-surface interaction rate and surface damage, consider the following (Figure 3). A part per million of iron as iron oxide particles with a one cubic micrometer volume in oil results in a particle number density of approximately 400,000 particles per cubic centimeter. A part per million represents 1 gram in approximately 275 gallons of lubricant or, in other more familiar volumetric terms, 1 drop of vermouth in 16 gallons of gin (Figure 4). A part per million of iron in oil is below the sensitivity of Navy emission spectrometers which actually are not sensitive to concentrations below 2 parts per million (2000 parts per billion). In an elastohydrodynamic contact of a ball bearing with a micrometer film operating a surface velocity of 1000 in/sec, the particle interaction rate with ball is approximately 1 per second. At a film thickness of 0.1 micrometer, the passage of a boulder 1 micrometer in size would occur on the average of every 10 seconds. Experimental evidence indicates these presently unfiltered particulates slowly but surely interact with the surface and initiate surface fatigue cracks, a fraction of which propagate into the interior of the bearing surface and thereby limit life. In addition, skidding damage to future high DN aircraft turbine bearings during thrust reversals will probably be aggravated by particulates.

Oil analysis using today's methodology and tomorrow's spectrometric techniques, such as atomic fluorescence in well filtered systems, will not improve the situation appreciably because most of the wear debris will be in the filter. However, the detection limits for iron of atomic fluorescence spectrometers equipped with flame atomizers and pulsed hollow cathode lamps is 6 x 10^{-4} parts per million, which is a significant improvement over emission spectrometers in use today (8).

Oil Wetted Surface Condition Monitoring/Options for Future Lubrication Systems

The application of filters efficient in the 0.1 to 1 micron range in hydraulic and lubrication systems will require that current oil analysis methodology and instrumentation be abandoned or changed. An oil analysis system using today's methodology and spectrometric instrumentation sensitive in the low parts per billion range will only rely on the presence of newly created wear metal particles, the small number of statistically available particles that have previously passed through the filter, and changes in soluble metal compound content to detect abnormalities in the lubrication system. Abandonment of these oil sampling and analysis procedures and introduction of inline detectors, although presently unavailable, to detect the concentration of the available wear debris or wear debris and dissolved metal and to provide time averaged concentrations and approximate wear metal production rate data, is a second alternative. However, attempts to use light scattering, high energy fluorescence, capacitive, and neutron activation detectors which have been developed or proposed, or even inline Ferrographic devices for these purposes, would be probably frustrated by the low wear metal concentrations. As a third alternative, design into and installation of centrifugal particle separation devices in hydraulic and lubrication systems would provide wear debris for microscopic and spectrometric analysis, and would be desirable in some equipments. In other equipments, where redesign is not practically or economically feasible, new types of filters may provide the particle separation capability needed to improve equipment performance and life, and provide wear particulates for diagnostic and prognostic analyses of machinery condition. High gradient magnetic separators, which separate ferro or paramagnetic materials by magnetic forces, may provide a measure of the desirable characteristics listed in Figure 6 and are being evaluated for these applications.

To conclude, it is appropriate to mention the report of Alan Beerbower's study of mechanical failure prognosis through oil debris monitoring (5). Although the study was restricted to assessment of current oil analysis methodology and suggestion for the improvement of oil analysis techniques for helicopter transmissions, his recommendations are generally applicable. Beerbower finds that nearly 100% of transmission failures could be detected if spectrometric analysis is augmented by particle analysis of the larger particles which are collected by chip detectors or the presently installed filters. Mr. Senholzi will indicate in a later paper how complementary techniques are being evaluated for these purposes. Beerbower's report, in addition to providing the data upon which to base his recommendations, provides a description of wear mechanisms, wear particle size distributions, and description of non-spectrometric oil analysis tools available today.

FIGURE 1

DEFINITION OF WEAR METAL PRODUCTION RATE

$$r_{PRODUCTION} = r_{ACCUMULATION} + r_{REMOVAL}$$

$$= m_l \frac{dc}{dt} + \frac{c\,dm_l}{dt} + r_{filter} +$$

$$r_{settling} + r_{deposition}$$

$r_{PRODUCTION}$, $r_{ACCUMULATION}$, $r_{REMOVAL}$ - RATES OF METAL PRODUCTION IN, ACCUMULATION IN, AND REMOVAL FROM THE SYSTEM (GRAMS/SEC)

m_l - MASS OF LUBRICANT IN SYSTEM, (GRAMS)

c - CONCENTRATION OF WEAR METAL IN LUBRICANT (GRAMS METAL/GRAM OF LUBRICANT)

r_{filter}, $r_{settling}$, $r_{deposition}$ - RATES OF WEAR METAL REMOVAL BY FILTRATION, SETTLING AND DEPOSITION MECHANISMS (GRAMS/SEC)

FIGURE 2

MOVING SURFACE SEPARATIONS

	FILM THICKNESS MICROMETERS	FILTER CAPABILITY MICROMETERS
GAS TURBINE BEARINGS, GEARS	0.1-1	10-40
HYDRAULIC COMPONENTS, AIRCRAFT	0.5-3	5
SHIP JOURNALS	25	25*

* ANTICIPATED

FIGURE 3

WEAR PARTICLE CONCENTRATIONS - 1 PPM IRON

1 GRAM IN 1,000,000 GRAMS FLUID

1 GRAM IN 275 GALLONS FLUID

500 BILLION PARTICLES IN 275 GALLONS

1.8 BILLION PARTICLES IN 1 GALLON

400,000 PARTICLES IN 1 CUBIC CENTIMETER

PARTICLES - 1 CUBIC MICROMETER OXIDE PARTICLES

FIGURE 4

EMISSION SPECTROMETER SENSITIVITY

CONCENTRATION OF IRON (PPM)	READING (PPM)	RANGE (PPM)
0	0 or 1	0-1
0.5	0 or 1	0-1
1	±1	0-2
10	10 ±2.2	8-12
100	100 ±10.2	90-110

1 PPM = 1 DROP IN 16 GALLONS; 80 "FIFTHS"
1 CENT IN $10,000
1 INCH IN 16 MILES
1 MINUTE IN 2 YEARS

FIGURE 5

PARTICLE - SURFACE INTERACTION RATE

BASIS:

GAS TURBINE BALL BEARING CONTACT
25 METERS/SEC SURFACE VELOCITY
1 MICROMETER FILM THICKNESS
1 PPM IRON - 1 CUBIC MICROMETER OXIDE PARTICLES

RATE: 1 PARTICLE PER SECOND

FIGURE 6

IDEAL FILTER CHARACTERISTICS

0.1 - 1.0 MICROMETER

HIGH DEBRIS CAPACITY

LOW PRESSURE DROP

PERMANENT FILTER ELEMENTS

WEAR PARTICLE RETRIEVAL FOR ANALYSES

NO EXTERNAL POWER

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7. Dalal, H.; et.al., "Final Report on Progression of Surface Damage in Rolling Contact Fatigue", ONR Contract N00014-73-C-0464, Feb. 74, AD 780453.

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DISCUSSION

L. Enochson, Time/Data Corporation: You indicated that the methods would have to be abandoned with improved filters. Why can't you just examine what's in the filter after you tear it down for inspection?

M. Hoobchaak: It should be examined periodically and not just at filter teardown because then you have to go into the system and possibly disturb the system itself.

R. Hohenberg, Mechanical Technology, Inc.: You referred to a report by Beerbower. Could you give us more information on that?

M. Hoobchaak: The title of the report is "Mechanical Failure Prognosis Through Oil Debris Monitoring." Beerbower has torn apart filters and looked at the chips. He has also examined the debris in magnetic debris collectors. He was able to detect almost all the failures which occurred because large particles were found which were indicative of very imminent failure in the transmissions.

P. L. Howard, SKF Industries: That paper points out one of the problems that diagnostics people continually face. When a diagnostic system indicates a problem, corrective action is usually taken. The corrective action quite often reduces the effectiveness of the diagnostic system.

INSTRUMENTATION FOR PREDICTIVE MAINTENANCE MONITORING

Ralph James, Exxon Chemical Co., Baytown, Texas 77520

BACKGROUND

Plant tests conducted by Exxon Chemical Company U.S.A. and The Boeing Company in 1972 and 1973 at Baytown, Texas demonstrated the applicability of onstream acoustic measurements to diagnose the condition of process equipment. The basic high-frequency acoustic techniques for predictive maintenance was reported at the 28th Annual ASME Petroleum Mechanical Engineering Conference, September 17-20, 1973 at Los Angeles, California.[1] In general, the mechanical "electrocardiagrams" studied during these tests were shown to be effective for early detection of small defects in bearings and gears, growing cracks in shafts and weld joints, loose parts, and operating deficiencies such as pump cavitation. However, the monitoring and interpretation of the data was manpower intensive and could not be economically justified on a plant wide basis. Therefore, to utilize this technology it would be necessary to automate most of the data comparison; indicating service caused flaws and detrimental changes in rotating machinery.

SYSTEM DESIGN PHILOSOPHY

(1) Ultimate Goal - Provide meaningful early indication of impending failure of critical process equipment so that: (a) corrective actions can be taken, or (b) provide enough lead time so that the majority of required maintenance can be performed during planned, scheduled shutdown, or (c) for the case where there are no scheduled shutdowns, production can be continued until the "final hour" with minimum probability of a catastrophic failure.

(2) Payout - Provide a minimum calculated benefit to cost ratio of 1.5 to 1. Estimated benefits were based on a statistical analysis of plant failure data-assuming a cost differential credit for predictive maintenance planning, increased mechanical availability, material and labor savings from a reduction in "wrecks" and manpower released from routine vibration readings and associated checkouts.

(3) Reliability - (a) Design mean time between failures of monitoring instrumentation to be significantly greater than that of the machine being monitored -- say a minimum of 10 to 1. (b) All sensing elements must be self-checking; i.e., loss of signal would alarm, etc. (c) All primary sensing elements maintainable with equipment in operation. (d) False alarms due to transients should be minimized.

[1] See article in Oil and Gas Journal for December 17, 1973.

(4) Safety - Monitoring system must meet all required safety codes -- intrinsic safety preferred.

(5) Flexibility - Initial system to be primarily set up to read acoustic signals via accelerometer, but must be: (a) readily and economically expandable; (b) capable of monitoring existing machinery alarms such as non-contact probes, temperature and delta temperature alarms, and system or cycle efficiency calculations. However, in the initial phases the emphasis was placed on the more nearly universal or fundamental monitoring sensors such as high frequency acoustic signature analysis. Another promising on-line analytic technique to be pursued is the use of the principle of X-ray fluorescence to detect impending failure by detecting wear and/or degradation particles in liquid or gas streams. These two monitoring techniques are the only ones we know of that show promise of onstream detection of fatigue cracking of turbomachinery rotors and shafting.

(6) Alarm vs. Shutdown - Since the emphasis is on early detection of impending failure the shutdown decision is retained by operating personnel. However, conventional minimum automatic shutdowns are locally controlled on critical items such as low oil pressure, thrust bearing temperature and high level in suction drums, etc. Also, a few machines such as high-speed-air compressors have vibration shutdown switches.

PREDICTIVE MAINTENANCE MONITORING SYSTEM

Using the above stated criteria a plant system consisting of three minicomputer controlled surveillance systems was developed. The number of sensing channels totaled about 800. Total plant area monitored was about 230 acres.

In order to obtain the specified benefit to cost ratio it was necessary to make a number of trade-offs between cost and technical wants. For example, we had to limit the computer controlled system to process equipment considered essential to production. A portable acoustic emissions analyzer was made a part of the plan to permit periodic monitoring of about an equal number of less critical machines. This analyzer can be used for shop tests. Also, the number of sub-multiplexers had to be optimized at the expense of additional sample time intervals. A final example is that the co-ax cables within the unit limits were placed in existing cable trays or strapped to existing piping instead of being encased in conduit.

Exxon Chemical Company approved the installation of the proposed system in August, 1973. By December, 1974 one of the three minicomputers was in operation under engineering control (not yet released to operations). The other two systems are scheduled for completion in mid 1975.

The first minicomputer covered four operating units and associated cooling tower and pump slabs. The sensor channels are divided as follows:

Crack detectors	63
Sleeve bearings	35
Gear interface	12
Gear interface plus 1 or 2 anti-friction bearings	52
Anti-friction bearings	207
Total	369 Channels

Process equipment monitored includes pumps, motors, compressors, turbines, extruders, gear boxes, turbochargers, and compressor header and lateral piping.

INSTRUMENT DESCRIPTION

A. General

A single link through this system would consist of a high frequency acoustic transducer, a preamplifier, and associated cabling and electronic processing circuitry for detecting those characteristics of the acoustic signal which are representative of the incipient failure in the device under consideration. The transducers, which use a PZT-5A crystal, are mounted as close as possible to the machine part for which incipient failure data is desired using an appropriate cement. The particular type of cement is dependent on the application. For example, we have had sensors cemented in place for over 1½ years in a severe vibration and weather environment in the Baytown facility. Dental cement was utilized and proved highly satisfactory in this application.

Short coaxial cables carry the signals from the transducers to preamplifiers located close to the transducers. Preamplifiers are required because of the long cable runs from the instrumented machinery back to a field sub-multiplexer or to the Control Room where the processing equipment is located and because of the high electrical noise activity common in many petrochemical plants. Low voltage D.C. power to the preamplifiers comes from the same unit that it is feeding its high frequency data to over the same coaxial cable. Thus a small coaxial cable, such as RG 174/U (0.1 inch diameter), can be used.

The transducers, preamplifiers, and associated cabling are capable of operating in Class I, Division II hazard areas, as defined by the National Fire Protection Association (NFPA) Bulletin No. 493, without any special provisions. For equipment operating in Class I, Division I hazard areas, barriers must be used in the cabling feeding the DC power to the preamplifiers which makes the cabling and preamplifiers intrinsically safe. Thus, protective conduit does not have to be used in these areas.

B. Antifriction Bearings and Gears

Antifriction bearings and gears are monitored sequentially. A maximum of two bearings and one gear, all in close proximity to each other, may be monitored by the same transducer at the same time. The monitoring sample time ranges from 10-seconds to 2-minutes, 40-seconds. The variable sample duration is computer controlled and depends on the statistical randomness of the acoustic signal. The sequential sampling is sufficient for antifriction bearings and gears since even if the maximum time of 2-minutes, 40-seconds were required for each bearing and gear group, a minimum of 540 groups could be covered in one day. Since high frequency acoustic data usually provide at least a week's warning before catastrophic failure of an antifriction bearing or gear, this is generally a sufficient sampling frequency.

The bearing and gear frequencies for all constant speed machine (± 1% variation in RPM) bearings and gears being monitored are stored in the computer, and used by the antifriction bearing and gear processor in generating the spectral line data. For variable speed machines, tachometer inputs to the computer adjust these frequencies to their correct values.

Figure 1 is a block diagram of a typical antifriction bearing and gear system.

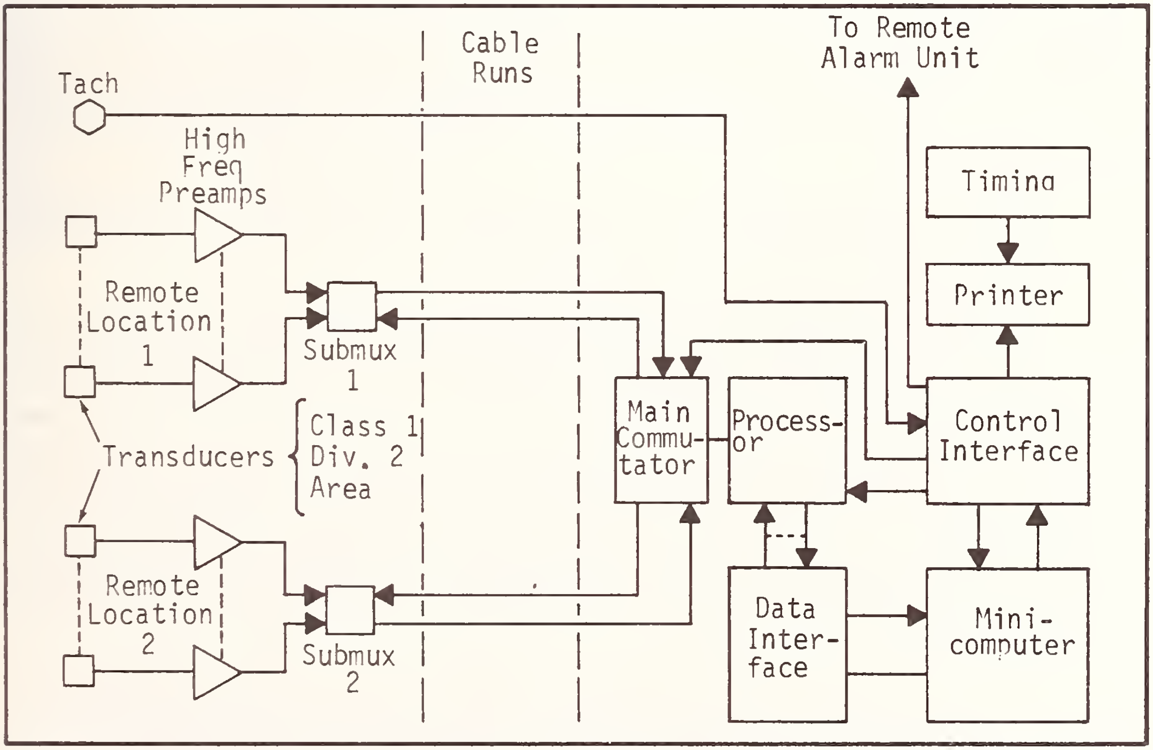


Figure 1 Anti-friction Bearing and Gear IFD System

Since the antifriction bearings and gears are sequentially sampled, they can be sampled in the field by a set of sub-multiplexers since this will reduce the cost of cable plus installation. Thus, instead of hundreds of cables, (as in Remote Location 1 in Figure 1), going from the pre-amplifiers to the Control Room, they terminate at a sub-multiplexer, and only two cables are required from the sub-multiplexer back to the Control Room.

The sub-multiplexers are all under the control of a main commutator which is in turn under the control of the mini-computer through the control interface. The sequence of events which allows the main commutator to command a sub-multiplexer to switch from one transducer to the next is as follows. Assume that we have just switched to a transducer monitoring two antifriction bearings and a gear. After 10 seconds of monitoring, the antifriction bearing and gear processor has generated nine outputs which are representative of the following amplitude characteristics of the high frequency signal from the transducer.

(a) RMS Signal Level

(b) Spike Energy

(c) 7 envelope detected spectral lines for the three frequencies associated with each bearing and the gear frequency.

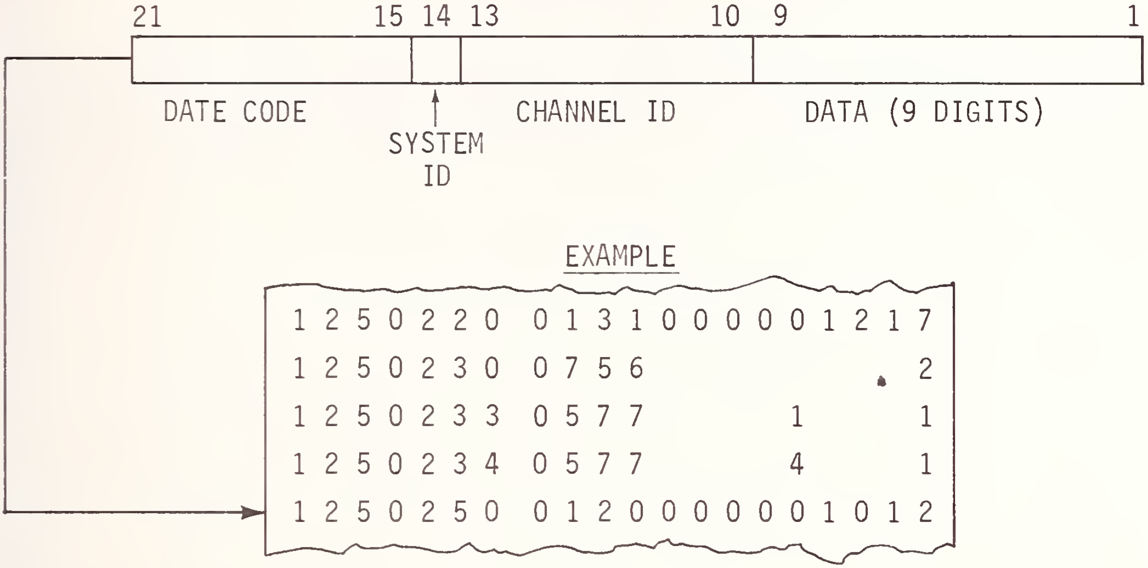
These nine outputs are compared by the computer with the nine values it obtained the last time it looked at this bearing. If the values are the same within some pre-set limits, (there are ten pre-set limits for each variable), the computer commands the system to switch to the next transducer. If the values are different, they may be different for one of three reasons.

1. A failing mechanism is occurring in the antifriction bearing or gear.
2. The machines operating condition is changing, such as a changing load will cause the RMS Signal Level to change.
3. The ten second sampling time was not long enough to obtain a good statistical average for the random data being processed.

In order to eliminate item 3, the computer doubles the sample time, and continues processing the data. Comparisons are again made at the end of 20 seconds. The process continues up to a maximum of 160 seconds or until all nine values are in agreement with the previously measured values, after which the computer commands the system to switch to the next transducer.

Any time a measurement from any of the processors does not agree with its previous measurement within some pre-set limits, the change is recorded on a digital printer along with a channel identification and the date and time of occurrence. Thus, only changes are recorded and the requirement for maintenance personnel to look at reams of strip chart recorded data to determine if any data changes are occurring is obviated.

The Printer prints 21 columns of information. This information is broken into fields as shown below, along with an example of ANTIFRICTION AND GEAR DATA.



```
1 2 5 0 2 2 0  0 1 3 1 0 0 0 0 0 1 2 1 7
1 2 5 0 2 3 0  0 7 5 6                 2
1 2 5 0 2 3 3  0 5 7 7         1       1
1 2 5 0 2 3 4  0 5 7 7         4       1
1 2 5 0 2 5 0  0 1 2 0 0 0 0 0 0 1 0 1 2
```

Column Assignments Are as Follows:

Column 1	SPIKE ENERGY			
Column 2	RMS LEVEL			
Column 3,4,5	#1 BEARING	-	OUTER RACE	SPECTRAL LINE
			INNER RACE	SPECTRAL LINE
			ROLLING ELEMENT	SPECTRAL LINE
Column 6,7,8	#2 BEARING	-	OUTER RACE	SPECTRAL LINE
			INNER RACE	SPECTRAL LINE
			ROLLING ELEMENT	SPECTRAL LINE
Column 9	GEAR MESH	-	MESHING FREQUENCY	SPECTRAL LINE

If only one bearing is being monitored, only zeros will appear in the unused columns.

This technique for antifriction bearing monitoring is patented by The Boeing Company.

C. Sleeve Bearings

Since sleeve bearings can fail very rapidly, and since it would be possible to miss cracking in a sleeve bearing lining material if the bearing was sequentially sampled, all sleeve bearings are continuously monitored.

SLEEVE BEARING DATA (COLUMNS 1 & 5)

Only two columns are employed for sleeve bearing data (1 & 5).

Column 1 is a measure of SPIKE ENERGY
Column 5 is a measure of RMS LEVEL

Figure 2 is a block diagram of the sleeve bearing circuit. Computer comparison with the previously measured data is done every ten seconds.

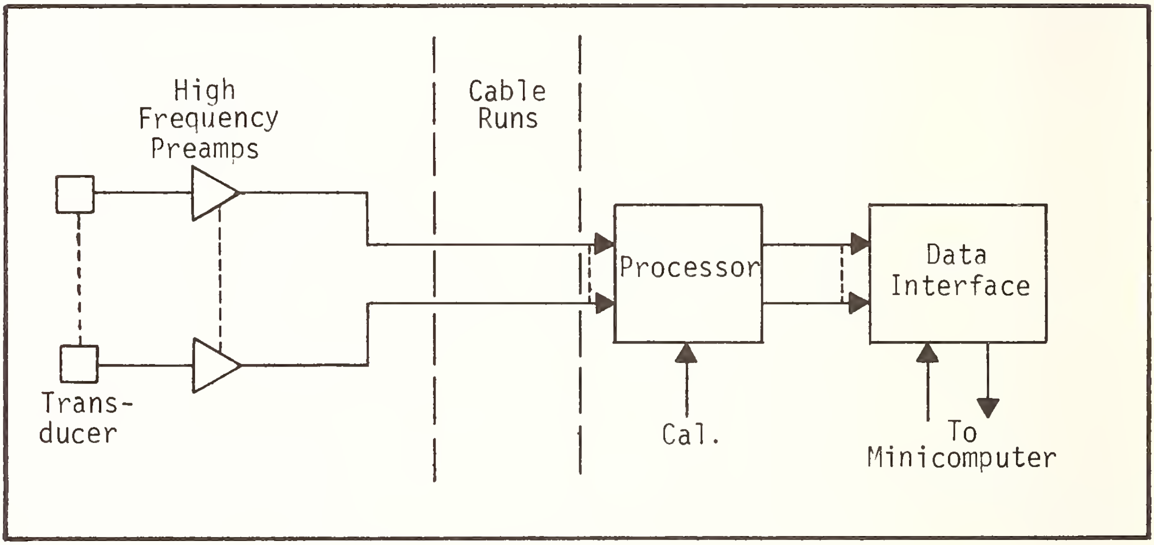
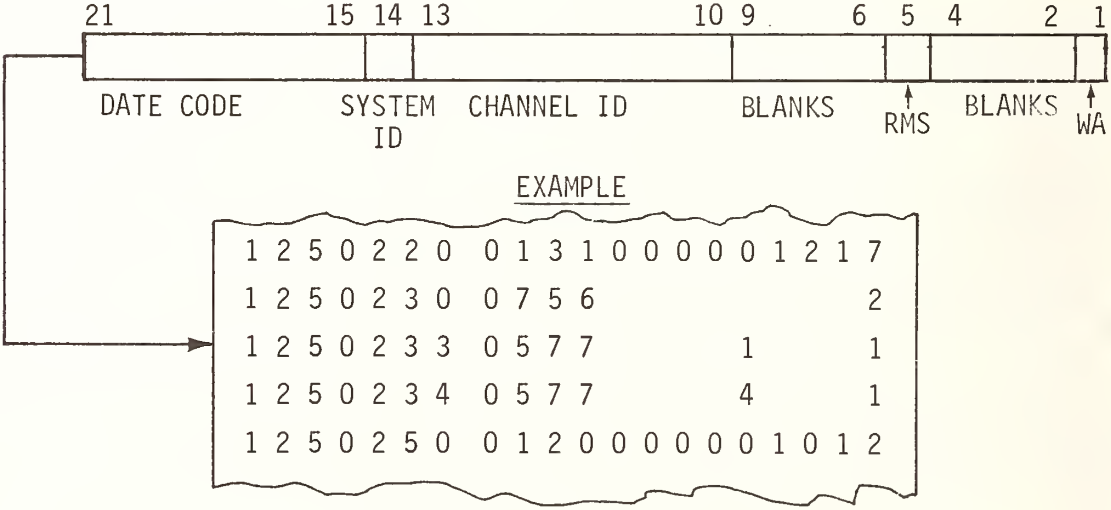


Figure 2 Sleeve Bearing Acoustic Monitor

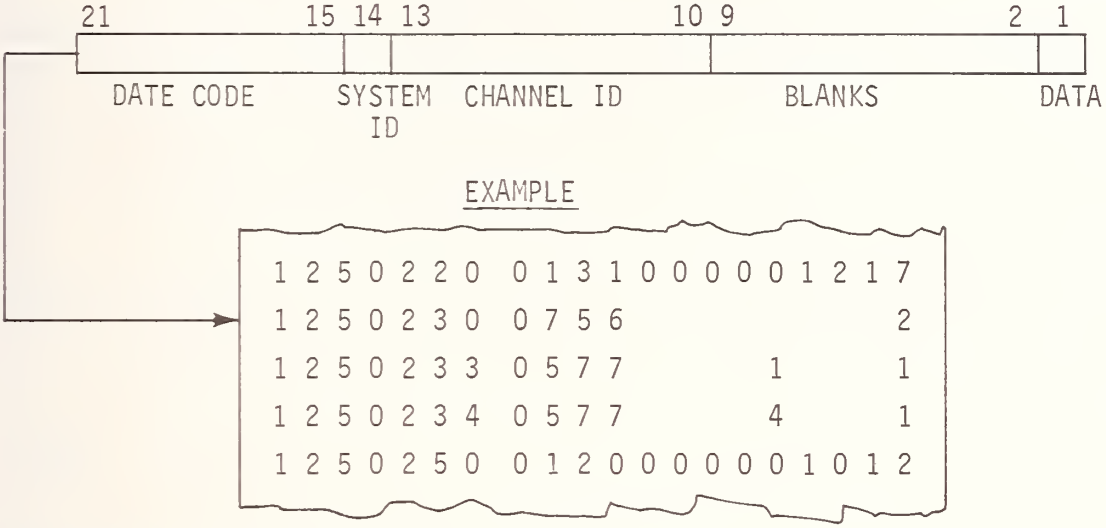


```
1 2 5 0 2 2 0   0 1 3 1 0 0 0 0 0 1 2 1 7
1 2 5 0 2 3 0   0 7 5 6                 2
1 2 5 0 2 3 3   0 5 7 7         1       1
1 2 5 0 2 3 4   0 5 7 7         4       1
1 2 5 0 2 5 0   0 1 2 0 0 0 0 0 0 1 0 1 2
```

D. Crack Propagation

Again, since it would be possible to miss any crack propagation if the suspected structures were sequentially sampled, all crack detectors are continuously monitored. Comparison with previous data is made every 10 seconds - any acoustic emission pulses from a propagating crack are counted.

CRACK DETECTOR DATA



```
1 2 5 0 2 2 0  0 1 3 1 0 0 0 0 0 1 2 1 7
1 2 5 0 2 3 0  0 7 5 6                 2
1 2 5 0 2 3 3  0 5 7 7         1       1
1 2 5 0 2 3 4  0 5 7 7         4       1
1 2 5 0 2 5 0  0 1 2 0 0 0 0 0 0 1 0 1 2
```

CRACK DETECTOR DATA (COLUMN 1)

A single column is used for crack detector data (Column 1). It is a measure of crack growth in pressure piping.

DATA CODING

The data in each column is independent of any other column and can have a value from 0 to 9. This is trend data and only indicates the magnitude of change from a previous data sample. Large changes will be printed in RED and are indicative of serious problems with the unit being monitored. It should be checked immediately and Mechanical Technical Service notified to further analyze the problem. Small changes are printed in BLACK and indicate less serious problems with a unit.

Figure 3 is a block diagram of an acoustic emission crack detector system.

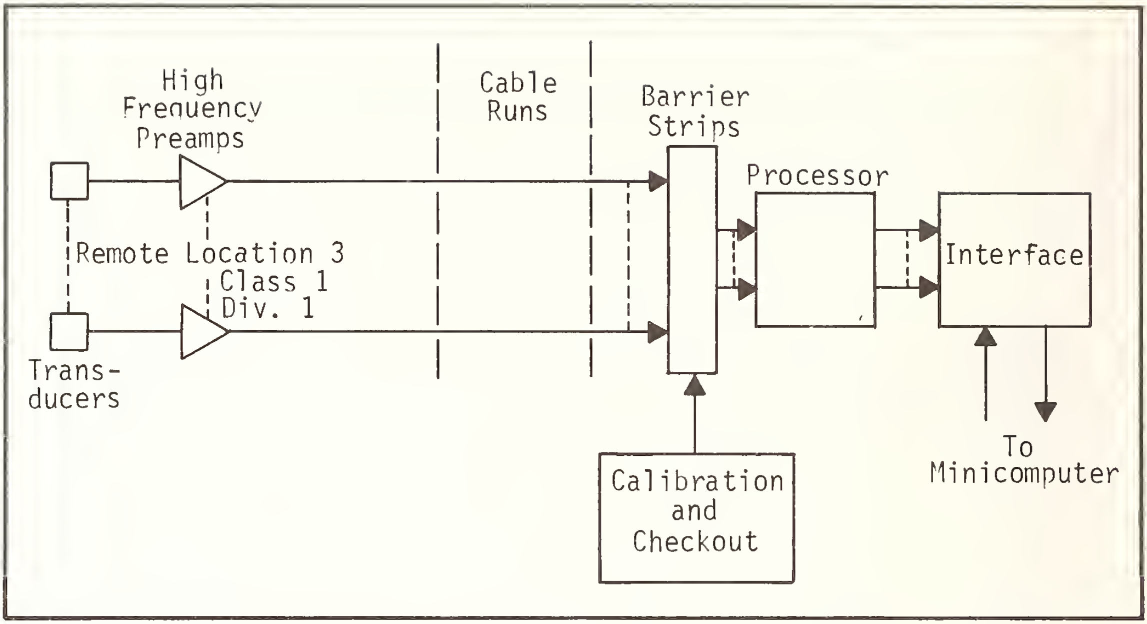


Figure 3 Acoustic Emission Crack Detector System

DISCUSSION

J. L. Frarey, Shaker Research Corporation: Do you plan to incorporate the low frequency vibration, the proximity probe outputs, and the startup-shutdown critical speed analysis into the same minicomputer?

R. James: We do plan to incorporate all the failure detecting devices in the same mini-computer.

B. C. Baird, Sr.: The system has a TI 960 computer in it. It's using about 8K of memory right now. It's expandable to about 32K and the racks are large enough to include a lot of equipment so that a lot of processing can be done on the same mini-computer.

W. R. McWhirter, Jr., Naval Ship Research and Development Center: Can you explain some of the problems you had with the mini-computer?

B. C. Baird, Sr.: IC's were the major problem. A lot of this was caused during our checkout phase by switching the computer off at night and switching it on the next morning. I think we were thermally cycling the computer and it was causing failure every fourteen days, or so.

W. R. McWhirter, Jr.: Do you feel that this failure was peculiar to the computer you used?

B. C. Baird, Sr.: It might have been because the computer components are not thermally cycled before being shipped. Now we just leave the computer on. Since it's been left on, it's been running for four or five months and the first failure has just occurred.

U. Sela, Exxon Company, USA: Are you looking at the acoustic emission or are you using proximity probes as sensors for spectrum analysis?

B. C. Baird, Sr.: Several parameters from each bearing were measured, but the proximity probes apparently just measure displacement. We haven't done any spectrum analysis on the sleeve bearings. We just measure an overall RMS signal and a spike distribution signal.

R. James: The proximity probes do measure displacement on each one of the four rotors and these are the only vibration probes in the whole plant that trigger automatic shutdowns. Due to the unreliability of the proximity hardware, most of our proximity probes are only on alarm.

B. C. Baird, Sr.: We use high frequency (about 120 KHz) acoustic emission for taking most of the data in the plant. We found this to be a good frequency for defect detectability and for minimizing the background noises and noise from other sources.

R. Lenich, Caterpillar Tractor Company: Have you had to do work because of false alarms in the system?

B. C. Baird, Sr.: We haven't had any false alarms, as far as I know.

R. Lenich: What kind of experience have you had with the wiring of connectors in the system?

B. C. Baird, Sr.: Wiring transducers and printouts is a problem. We develop and build our own transducers very inexpensively. The wire we use is RG174/U coaxial cable. There are about 600,000 feet of this cable in the plant. The RG174 was selected because it costs 2 1/2 cents a foot. In certain vulnerable places, the cable is sometimes inadvertently cut and has to be spliced. We are trying to protect the cable in these places by putting casing and conduit around it.

O. E. Compton, Northrop Corporation, Aircraft Division: Have you trended any of the data from the results you obtained to define planned periodic maintenance intervals? Is the computer cost effective?

R. James: We don't feel like we have enough data yet to tell whether it is cost effective. We are looking at at least a year's run in order to get some information that would enable us to make a prediction.

C. R. Garbett, Shell Development Company: Do you have any experience detecting flaws or incipient failures in pressure vessel equipment?

R. James: We have used this in the field to check for cracks in compressor piping. We glued transducers to a pipe that we knew contained cracks and discovered that we could find a running crack. Because of this favorable experience, we have put 63 crack detectors on this particular system. We do not have them on reactors at the present time, but the next step is to put them on some low temperature reactors which are subject to brittle fracture.

J. W. Forest, Ontario Hydro: Could you give us some examples of computer readouts? Do you take into account flow variations, process changes, etc.?

B. C. Baird, Sr.: We do not consider those variables. We measure the overall RMS signal level with a high frequency (120 KHz) acoustic signal. We measure the signal level that exists above the 5 sigma threshhold, which is a spike type signal. We do an envelope detection of this signal and we look for the spectral lines that are associated with the bearings in the machine. We have a little 21 line printer. Included in the information on the printout is the date, time of the day to the minute, and the transducer number. We have 10 quantized levels for each variable. Initially we trend data for a good bearing day run and quantize it in 6db increments. We are looking for gross changes in this high frequency signal. Typically, from the inception to the end, the signal will grow 100 to 1. We have an alarm level set so that if some threshhold level is reached, we look at it. Built into the system is the trend that is built up to this alarm level. The reason for this is to get trend data to more fully understand the failure mechanism that is taking place. How long can a man go before he must shut down? Can he wait until a planned shutdown or should he shut down right now? The only way we are going to determine this is through a lot of operating experiences, a lot of failures, a lot of collected data.

D. M. O'Dea, Exxon Research and Engineering Company: You have one process variable that you are measuring, that is machine speed. I am a little unclear as to why you are measuring it for variable speed machines. Is it only because you measure the bearing frequencies as well as the acoustic energy?

B. C. Baird, Sr.: Most machines vary only one percent. The band width of the analyzer can be set wide enough to still give good sensitivity and good defect detectibility and still stay within that band width. If the machine varies one percent or so you can still pick out that spectral line. For a machine that varies over fifty percent because of an operated change (one day it's operating at 100 RPMs, the next day at 200 RPMs), we set up a tachometer to measure that machine speed. This information is fed into the computer which then calculates the actual bearing frequencies of the spectral lines that it wants to look at. It sets up the spectrum analyzer inside the system to look at just those spectral lines associated with the ball pass frequencies. We feel this is the earliest indication of a bearing defect. In all of our tests, the earliest indication of any defect in that bearing, like a small spall, starts with a spectral line starting to grow. The high frequency envelope detects a spectral line perhaps months before the bearing actually fails. The second indication is an increase in spikes. The third and final indication is that the RMS starts to grow. Bearings of different manufacturers may have different frequencies due to design. You may not be aware of whose bearings are being monitored. Therefore, you have to rely on spike information or RMS information. There isn't as early a warning as we would like.

D. M. O'Dea: Are you saying that you may simplify the system in the future if you find you really don't need to know the spectral line?

B. C. Baird, Sr.: You get the earliest warning from spectral lines. On some curves that were shown there was an 8-day warning from pure RMS. You introduce spikes and you get an earlier warning than that. You introduce the spectral line and you get a still earlier warning.

P. L. Howard, SKF Industries: What is the logic for determining when to change a bearing or gear?

R. James: Right now, we use either high frequency analysis or regular RMS or, in some cases, a metric vibration meter. We will change a bearing if the meter reads 0.5 to 0.6 inch per second. That is the limit on most of our process equipment. If it's up to 0.9 inch per second, we shut down immediately.

P. L. Howard: How do you correlate between damage level and those limits?

R. James: Those fires tell us.

C. Dean, Solar, International Harvester: You mentioned that you monitor the anti-friction bearings periodically. At what intervals do you monitor them?

B. C. Baird, Sr.: The computer is set up to look at a bearing for 10 seconds. It continuously moves from bearing to bearing every ten seconds, so if there are 260 bearings, it will take 2600 seconds to look at all of them. There is a statistical probability that you will obtain the correct data if you look at a bearing for 10 seconds. From the first 10 second look, we set up our base line data and quantize the base line measurements. If the second 10 second look agrees with the first look, we go on to the next bearing. If it doesn't agree, we keep on looking and quantizing and normalizing the data until we have looked for up to 2 minutes and 40 seconds, which we found is about as far as you have to go to get good statistical data. If there still is no agreement, we feel that the bearing condition has changed and this is printed up. Typically for one unit with 370 points, you may get around to the bearings every two or three hours. Sleeve bearings and cracks are monitored continuously.

D. L. Dennis, Naval Weapons Center: How does management view funding your effort at the present time and in the future?

R. James: Our management is extremely interested in predictive maintenance. We consider the program that we are engaged in to be a 5-year research and development program. We are in the second year now. The Baytown plant is the experimental guinea pig for the rest of the circuit. We expect to know how good this approach is by the end of the 5-year program. We actually had two years of field tests before we got into the computerized version. So we were able to convince our management, through problems they saw in the operation of the plant, that predictive maintenance needed to be worked on.

D. R. Houser, The Ohio State University: Can you say anything about your gear detection work?

R. James: This is one of the big values of acoustic emission testing. Consider a one-to-one gear box on a rubber plant extruder. If we get a high signal, we don't know whether it is a gear, a shaft, or a bearing unless we make a detailed analysis. We have been able to detect cracks in shafting on this large one-to-one gear box as well as pick up incipient bearing failures. We can actually tell by looking at the acoustic signal whether the extruder is being operated correctly. It is an operating guide.

PANEL DISCUSSION: Case Histories Applications

Panel Moderator: P. L. Howard, SKF Industries

Panel Members: D. B. Board, Boeing Vertol Company*
R. Eisenman, Endevco*
R. Hohenberg, Mechanical Technology, Inc.*
J. L. Frarey, Shaker Research Corporation
M. Hoobchaak, Naval Sea Systems Command
R. James, Exxon Chemical Company

*Panel members so identified delivered short presentations prior to the panel discussion. These presentations are not included in the Proceedings.

R. Eisenman: I think that any diagnostic program lends itself to answering some very basic questions and I think there are three areas that should be considered. First, the user should determine what type of problem he has - is he worried about gear contact problems, bearing stability problems, plain old misalignment, flow problems. The second point is to select a transducer that will provide the necessary information for evaluation of the problems. The third logical point would be to determine whether the user wants to develop his own inhouse capabilities, or whether he just wants to monitor the signal for trend diagnosis and call in somebody more specialized in diagnostics when he sees increasing trends.

P. L. Howard: Jack, would you like to lay out a nice hypothetical program?

J. L. Frarey: I have to say the same thing I said earlier; that is, if you want to rate a diagnostic system, the system has to tell you what is wrong, what failure mode is involved, and the severity of the problem. You have to tear the machine down as rapidly as possible and immediately look at the component and determine whether the system told the truth. We can't take a part out of an engine and let it sit around for a month getting rusty and then try to make a decision as to what the diagnostic system said. It's got to be done quickly, it's got to identify the failure mode, and it's got to tell you the severity of the problem, and I suspect anything other than that should be graded as a failure of the diagnostic system.

P. L. Howard: This points out one of the problems in trying to do diagnostic work. There is an indication of a potential problem, but you find that you are not the most important part of an evaluation program. There are 17 other tests that have to be run and it won't be possible to tear down the machine for three weeks. At that time, they will tell you whether you were right. One other thing is that quite often a diagnostic technique is preceded by a large marching band of marketeers. Two points that marketeers always make, are (a) it's simple, and (b) it can be evaluated by almost anyone who has a high school education and no previous criminal record. The first job of the diagnostician is to come through and say, "Well, yes that is almost right, but we still have to take your machine apart." One of the most intelligent approaches to finding out whether a diagnostic technique is going to pay off is the approach that Ralph James is taking. He has already set aside a block of time. He is not bowing to what I am sure were initial marketing pressures to fully evaluate the system in two weeks and write a final report in 48 hours thereafter. He is going to take a long term look at it. What is the feeling of the panel on the problem faced in diagnostic evaluation - that is, the diagnostician would like to gather data forever so that his conclusion is firm and final, the user quite often can't wait forever?

R. Hohenberg: The problems of the moment always seem to be the most important ones and the most significant ones because they exact the greatest limitations on our actions. However, they can be minimized and we were all taught when we went to school that there was a way to conduct an experiment. When an experiment is to be run, you must define what it is you want to do, what the objective is, what methodology is to be employed, how the physical laws that are understood and known will be invoked and played off against each other to achieve the result, and also the kind of result that is to be expected. Now that's simpleminded in the very complex situations that we have, but in many cases none of this is done. People rush into the test area, they rush to slap the equipment on and they wait to see the results. Then they wonder how it can be explained. The explanation in the classical experiment is a selection of which of the anticipated results were achieved rather than a searching of what really did happen and I think that is one of the fundamental problems that we face today. The experiment must be limited and focused on the population to which you want it to apply.

P. L. Howard: Would any of the users like to comment on how you overcome the impatience in your own management in order to give a diagnostic technique a fair evaluation.

R. James: Our present program is quite similar to what we had to go through on gas engine diagnosis techniques. We had to convince management that the maintenance costs on all of our gas engines were too high. We had to ask for a period of time to prove that we could bring the maintenance costs down. We did demonstrate that and got the maintenance costs down in about a year and a half. It takes that long to train the people and the people that use the equipment are the key factors. We did prove it, and when we cut back on the monitoring work, the maintenance costs went up. But it is a statistical type thing. That's the only way you can prove it.

M. Hoobchaak: Our problem has been failures in hydraulic systems of gun mounts. Down time has been 30 percent or higher in some cases. We are going to analyze the oil over a two year period. We are 8 months into the program. We have been given the luxury of some time right now.

P. L. Howard: I'm glad to hear that you really recognize that, with the diagnostic manufacturers, time is a luxury. I would like Joe Kukel to give us the benefit of his experience on AIDAPS and how he has tried to overcome some of the diagnostic evaluation pitfalls that these people have faced.

J. Kukel, Garrett Corporation: We are trying to follow the procedure that Rudy Hohenberg mentioned. We are running experiments and developing our technology level. I haven't come to the point of application yet, that's the next step. You want to make sure the technology level is firm.

P. L. Howard: Mr. Hess, would you like to tell us what pitfalls you have encountered in the A7 program and how you have tried to avoid pitfalls in determining whether the A7 diagnostics are successful and how successful they are?

A. J. Hess, Naval Air Test Center: We had lots of pitfalls, of course, and I think there is a lot to be learned by some of the things that we went through. As our evaluation program progressed, it seemed like our basic definitions of what a valid and invalid diagnostic was, changed. We had a Navy evaluation team on site gathering statistical data on maintenance lines, safety flight lines. It seems like they had one set of definitions, program management people who were trying to market it within the Navy had another set of definitions, all the contractors had their own definitions. To really prove a system cost effective, you have to develop the statistical data, and if you are using a bunch of different definitions, the statistical data may not mean much. In any diagnostic program, one of the first things that should be done is to agree on a basic set of definitions.

We are trying to prove our system effective from the safety applied standpoint. Since we are operating in a fleet environment, we had a big problem with recordkeeping. The fleet had its own missions to fly everyday - the pilots weren't very concerned about keeping accurate records on our system, yet we needed their inputs. You have the problem of a sophisticated condition monitoring system. During the development phase the software is continually changing. It is a big problem to document these changes so that you know at any point in time exactly what software is being evaluated. We had to convince our program people that, while there were some major problems with the system, software development was such that we were close to solving the problems. To do that type of convincing, you really have to have a handle on the documentation of software.

Another major problem was deciding when the development effort actually stops and the evaluation begins. Eventually you run out of time and you have to stop the development - the evaluation starts then and you ignore the statistical data that was generated during the development effort and just pay attention to the evaluation.

P. L. Howard: Do you find that that is best done arbitrarily? Just say, OK it's done?

A. J. Hess: You have to make an intelligent judgment.

D. M. O'Dea, Exxon Research and Engineering Company: I think all of us have fallen into pitfalls in setting up programs - starting out too early in many cases or starting out with the wrong equipment. We all have been called on to evaluate our equipment to see what we can do to improve reliability and availability. We have to make these evaluations and usually we have to decide just what is the basis for determining whether a system is good or bad. Different techniques are applied. One famous technique is to pick something simple like counting the number of pumps going into a shop before a program is started. Then start the program and keep track of the number of pumps going into the shop, and see how much of an improvement there is. That has been very successful. One other approach has been to look at the number of times there has been a failure and count how much down-time has been spent on equipment in terms of days or lost product, then start a program, see how many times you have either avoided down-time or avoided the failure, or see how much faster you can come back on line with the new program. These are basically the evaluation tools we use. What we find is that we have to stay simple. Ralph, you didn't mention it, but I'm sure you are counting the fires.

R. James: Sure do.

P. L. Howard: One of the things diagnostic suppliers are continually faced with is proving that there is a benefit from using the diagnostic technique. It is usually in the form of a cost benefit. How do you go about showing the cost effectiveness of a technique? I don't think there is a diagnostic manufacturer here who wouldn't agree that serendipity is one of the better ways of proving the cost effectiveness of a system. Are there any other people who have planned cost effectiveness tests for diagnostic equipment?

C. Dean, Solar, International Harvester: I can cite an example of how it shouldn't be done. I entered into strictly a verbal agreement with a manufacturer of diagnostic equipment to conduct some tests on some of our equipment. The first phase was going to cost our company say X number of dollars. The second phase, which was outlined at the time we began the program, was going to cost about 10X dollars which we were prepared to spend at the time. However, at the end of the first phase, we really didn't get a report or any assurance that we had accomplished what we had set out to do. I had no confidence that we could gain anything from the second phase, so I terminated the program. I have had many second thoughts since that time, because maybe I prematurely shut off a program that was worthwhile to the company. However, I had to make a judgment, and from the information that I had at that time, I just could not take the second step. My recommendation would be that before a program is undertaken, the goals and pitfalls should be clearly defined. The progress of the program should be thoroughly reviewed from time to time to see if these goals are being met.

D. M. O'Dea: We have spent many hours and many thousands of dollars trying to identify failures, and we have found two basic causes for this loss of dollars. One of these is what could be considered infant mortality, which is the failure of new machinery that's just been installed. The other is the problems associated with a machine over its lifetime - wear-out problems, or problems that come up as time goes on. We have found that we can't separate the two causes completely. We have been able to significantly reduce the infant mortality rate. Lifetime problems on the whole are not that serious except where they cause safety hazards or really influence production. Everything we have started to do is based on a failure analysis. What we would like to accomplish is to run our machines for the longest periods of time without any internal inspections, without any overhauls. Before we start a program, we have to identify what type of failure we are trying to avoid. If there are existing engines that have been running, you can look at the history of failure in those engines and then start a program of evaluation on the basis of that history. If there is a new product or a totally new design, what you have to do is a failure analysis on the basis of the histories of components you are putting into that new design before you really begin to set up a diagnostic program.

R. James: I should have mentioned the importance of failure analysis. Until we began to do a detailed failure analysis of every failure, we weren't making much headway. At that time everything was a maintenance problem. But since we have been doing failure analysis, we have found that maintenance is only one leg of a tripod. There are operator problems and we have been able to correct many failures by training the operators to operate the equipment properly. The third leg of the tripod is design. Some of the failures are due to faulty design. We try to indicate the basic cause of failure in our failure analyses.

A. Jaudét, Électricité de France: What Dennis O'Dea said is exactly the kind of procedure we have followed in Électricité de France. We tried to determine what kind of mechanical failures could occur in turbines. From 10 years experience in running 250 megawatt machines, we have established that most failures come from blade fractures or from high pressure inlet valves. So we have established a way to diagnose such failures. Now personnel that work on such power plants ask me not only for diagnosis but for prognosis. They want to know because they have only a certain period of time each year to do maintenance of their turbines.

P. L. Howard: Would each panelist give us a short summary?

D. B. Board: First, before you start a program, you should clearly establish what your objectives are - are you trying to diagnose or are you trying to prognose? Secondly, you should establish ahead of time whether you are going to test the hypothesis, or if you are going to demonstrate the feasibility of application for whatever you are going to do. Thirdly, whatever you do, the person who plans the experiment or the program and is responsible for carrying it out should not be the same person who evaluates the results and draws the conclusions. And finally, I think it is most important that any program should involve not just one perspective. For instance, in the aircraft diagnostics field, you have got to have equal involvement of the airframe or engine manufacturer, the diagnostic hardware manufacturer, and the using organization. You absolutely must have those different perspectives or your program really isn't a program.

R. Eisenman: It is extremely important in any diagnostic program that there be adequate feedback from the user. This is a very difficult channel of communication, because often the problem that you have diagnosed is discovered by a millwright on a graveyard shift and he never tells anybody about it. So again I can't overstate the importance of feedback.

P. L. Howard: It is a two way street. If they want a good evaluation in the user house, they have to do some work.

J. L. Frarey: I liked what Bob Eisenman said during his talk - that you have got to combine diagnostic systems to get the total result. I happen to be an advocate of high frequency vibration. Frankly in our day-to-day troubleshooting in the petro-chemical and utility industries, we probably make about 80 percent of our decisions based on low frequency data from proximity probes-low frequency vibrations.

R. Hohenberg: My goals are to find desirable applications for people who have a significant problem where the failure mechanisms are understood. An approach can then be found with a simple methodology which looks at the failure mechanism rather than at the traditional operating parameters to, in a simple manner, define and prognosticate the situation. And the approach I firmly believe in is at the sensing end. It should be kept firmly in mind that the voltage coming out of a transducer is an observable which consists of useful signal and noise.

If you can find or develop a transducer that has a higher signal-to-noise ratio, the extent of analysis that is made subsequently is much reduced.

M. Hoobchaak: I agree with Rudy on keeping it simple. The simpler you can make your system, the more likely it is that something will be done if there is a failure.

R. James: That reminds me of our "KISS" program. It means "keep it simple stupid," and we have had good results from trying to do that. Our problem is that we don't start necessarily with the best equipment. We start with initial cost considerations. I think we should look at the long range cost of this equipment and look at the minor details such as the bearings. If we did that, we wouldn't waste our time on things that should have been prevented in the design stage. Now in order to do that you have got to take the system approach and have an early input from the maintenance engineer, from the design engineer, the process engineer, who sometimes goes his merry way without any consideration for the equipment.

SESSION III

ON GOING PROGRAMS

Chairman: H. R. Hegner
General American
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GAS TURBINE ENGINE DIAGNOSTIC TEST RESULTS UTILIZING A THERMODYNAMIC ANALYSIS TECHNIQUE

BY

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1.0 Introduction:

The US Army has a requirement to evaluate automatic inspection diagnostic and prognostic systems (AIDAPS) for use on future aircraft. An effective engine health monitoring technique will be an important part of the total aircraft diagnostic system. The T53 engine approach currently being taken on the UH-1H prototype AIDAPS program is to collect data on pertinent measurable parameters while the engine is operating nominally and while known degraded parts have been implanted. The above two groups of data are then compared and differences noted for the proper fault isolation message. By implanting known degraded parts, much more pertinent data can be generated and fault isolation software accomplished during a given period of time. The purpose of this paper is to review and analyze the results of the thermodynamic analysis on selected AVCO-Lycoming test cell data.

2.0 Thermodynamic Analysis Concept:

A flow chart showing the various steps in the thermodynamic process is given in figure 1. Gas path logic is based on the principle that parameter measurements are uniquely related to component physical condition (i.e. deterioration) since parameter and performance measurements are uniquely related and performance measurements and physical deterioration are uniquely related.

Engine performance monitoring for the purpose of tracking engine health normally consists of three basic steps: (1) establishment of baseline performance, (2) comparison of current performance with baseline performance, and (3) interpretation of performance deviations. However, particular techniques can differ from one another in terms of measured parameters, method of computation of performance indices and method of interpretation of performance deviations.

In the AIDAPS approach variations in the performance indices are obtained by the influence coefficient method[1]. In implementation form, engine-installed sensors measure certain gas path parameters (temperatures, pressures, etc). A test of the data is then made to determine that it satisfies thermodynamic stability criteria.

Extensive background in the development of turbine engine controls has demonstrated that the transient operation of an engine can significantly affect the diagnostic results. For instance, the occurrence high steady-state temperature would be indicative of a potential engine degradation but that same vibration which occurs during a transient would only be indicative of the energy available to accelerate the engine. A method of minimizing the effect of transient performance was needed. The conditions that have been set up for steady-state involve basically two requirements; sufficient high power and sufficiently steady engine operation. Power is tested in terms of N_1, and a minimum N_1 of 85% is required. It turns out that in terms of the relative magnitudes of the changes, sequence of occurrence, duration, and settling rates, SHP and EGT are the best transient indications. The rate limits on these parameters are 0.2HP/sec and 0.2°F/sec, respectively[2]. The rate-of-change calculation and limits provide a settling typically between 10 seconds and 30 seconds, depending on the magnitude of the transient.

During steady-state, uncorrected parameter data are summed in 10-second segments. If steady-state criteria are met throughout a steady-state segment, the segment sums are added to interval sums. At the end of a steady-state interval, the interval sums are averaged, producing averaged values of the uncorrected parameters. If the steady-state intervals persist for more than 18 segments, the summing is terminated, averages calculated, and steady-state criteria reset to ignore the rest of that steady-state interval. Thus, a steady-state interval sample consists of uncorrected parameters averaged over 10 to 180 observations.

Following calculation of the averages, corrected parameter deviations from baseline are computed and these are compared to sensor credibility limits and engine degradation limits. Exceedance of a limit triggers an appropriate indication to signal the need (to maintenance) for diagnostic processing. These operations are performed for each steady-state interval data set.

Each steady-state interval data set (parameter averages) is stored. The process of looking for steady-state, forming steady-state interval data sets, testing the data set parameters, and storing the data sets is continuous. The philosophy is to accept as much good data as possible, since it has been estimated that this will amount to only 5 to 20 steady-state interval data sets per flight. Present storage allocation is such that at least 5 flights worth of data can be collected before routine processing for refined health checks and prognosis will be required.

Additionally, if no steady-state segments are encountered within a 10-minute period during engine operations, an unaveraged set of data together with steady-state counter data are recorded to determine the cause of the lack of steady-state. Ground logic will isolate the cause to either a particular instrumentation fault or to an engine instability.

Having satisfied the above mentioned steady-state conditions the deviation of the measured parameters from that of the normal engine condition are calculated. (In corrected form).

The primary measurable parameters are:

T_1	Compressor Inlet Temperature
P_1	Compressor Inlet Pressure
T_3	Compressor Discharge Temperature
P_3	Compressor Discharge Pressure
N_1	Gas Producer Spool Speed
N_2	Power Turbine Spool Speed
W_f	Fuel Flow
Q	Torque Pressure
T_9	Exhaust Gas Temperature

A second calculation, using the engine thermodynamic relationships is then used to determine performance changes of the engine from normal by means of influence coefficients. The AIDAPS coefficients are based on a differential equation model of the engine as shown in figure 2. Model sets are stored for P_3 = 70, 80, 90 and 100 psi.

In applying the model, a coefficient set is formed for the particular measured value of P_3 by interpolation between model sets. The following independent parameters are then calculated:

T_5	Turbine Inlet Temperature
W_2	Airflow
ηc	Compressor Efficiency
A_5	Gas Producer Turbine Nozzle Area
ηg	Gas Producer Turbine Efficiency
ηpt	Power Turbine Efficiency

The above parameters have direct diagnostic meaning. T_5 is a general health parameter, but also reflects on hot section condition and degradation prone operation. W_2 and ηc reflect compressor condition.

A_5, ηg and ηpt reflect the conditions of the 1st stage turbine nozzle area, gas producer turbine efficiency and power turbine efficiency, respectively. The tests on T_5 and W_2 will also consider VIGV operation. A_5 will be used as an indicator only with removal threshold significance placed on the effect of A_5 variations on T_5 and ηg.

Limits on the performance changes as established from implant tests using physically deteriorated parts (implants) or maladjustments are used in a comparison manner to determine if the engine has exceeded acceptable limits. Prognosis is to be established by time-trending and projection to the removal limit. Current diagnostic limits are shown in figure 3.

3.0 Results:

Major test results that will be discussed are compressor fouling and erosion, fuel nozzle clogging and gas turbine temperature erosion[2,3]. These problems are considered as major problems of the T53 engine.

COMPRESSOR FOULING TEST

The results of a compressor fouling test are shown in figure 4; the compressor was progressively fouled by spraying oil-wood ash and oil water into the compressor inlet. The top graph tracks the drop in compressor efficiency and airflow (a three-point moving average was used). The bottom bar graph shows the average of the computed performance parameter changes (model results). At that low point, AVCO-Lycoming test engineers believe that it was representative of the degree of fouling that can be encountered in an operational environment. Following the calibration runs, the engine was given a double cleaning that appeared to restore its former performance level.

COMPRESSOR EROSION TEST

The results of an eroded compressor test are shown in figure 5. This test was a combination compressor rotor (implant #AID 132) and compressor housing (implant #AID 133).

All of the components were obtained from an engine which had been returned to depot because of a surge condition. In the case of the compressor rotor, erosion wears away the blade airfoil resulting in reduced pumping efficiency. AID 132 has minimum erosion damage that is within overhaullimits. AID 133 also has minimum erosion damage that is within overhaul limits. In the case of the axial compressor housing, erosion wears away the vane airfoil (axial compressor stator vanes) and increases tip clearance resulting in reduced pumping efficiency. In the case of the impeller housing, erosion wears away material resulting in increased clearance between the housing and the impeller with a resulting loss in pumping efficiency.

The housing impeller clearance is considered critical because the majority of compressor work is performed in the centrifugal stage. For AID 133 the impeller housing shows severe wear at the entrance and exit.

In this test the drop in compressor efficiency tended toward larger magnitudes with engine power level (the minimum change was about -2 percent; the maximum -3 percent (shown)). The results indicate that the change in efficiency can be attributed almost entirely to the compressor rotor, while the compressor housing erosion is responsible for about 1/2 of the change in pumping capacity.

FUEL NOZZLE TEST

Fuel nozzle clogging and erosion and consequent hot spots have been identified as the only significant combustion section problems for the T53 engine.

Figure 6 shows the results of successively clogging three nozzles; No. 11; Nos.11 and 10; and Nos. 11, 10, 9. All of these results were clearly detectable.

The unshaded bars show the normal temperature distribution while the shaded bars show the deviations for the test case. In each case the temperature distribution rotates before reaching the thermocouples so that the minimum temperatures are detected by thermocouples 1 and 2 rather than 11 and 12. These results show that a clogged nozzle, or cold spot can definitely be identified by EGT spread measurement on the T53 engine. However, it appears doubtful whether hot spots due to eroded, high flow fuel nozzles can be identified. The problem is compounded by helicopter operation (power turbine rpm is held essentially constant). The result is that exhaust gas in the tailpipe, has a varying degree of swirl dependent on power level. Since there is a certain degree of natural temperature distribution in the exhaust gas, the swirl causes a variation in the temperature profile measured by the EGT thermocouples.

BURNED 1ST STAGE GAS PRODUCER ROTOR TEST

Deterioration of the 1st stage gas producer rotor begins with a general deterioration of the 701 coating along the leading and trailing edge of the blades. The rate of progression is slow until the combined effects of the coating and sulfidation of the parent material progresses at a rapid rate, resulting in material loss. The change in geometry of the blades (e.g. increased tip clearances) results in decreased turbine efficiency and an accompanying general increase in turbine inlet temperature. The increased temperature level can be expected to increase the degradation rate and initiate or promote the deterioration of other turbine section components. The temperature increase also raises the operating line of the compressor, thereby reducing surge margin.

Implant AID 153 is in the final stages of sulfidation. The vane contour shows loss of material due to erosion and burning. The vane tips still have some of the original contour remaining. Both the leading and trailing edge tips have been lost.

Analysis results are shown in figure 7. The implant has caused a severe loss in efficiency and a corresponding, essentially one to one, increase in turbine inlet temperature. The decrease in airflow and increase in compressor efficiency are so-called cycle rebalancing effects; that is, the increase in turbine inlet temperature has caused the operating point of the compressor to move towards decreased airflow and increased efficiency. While these latter changes are substantial, they are small in comparison to the change in turbine efficiency.

This implant is considered representative of degradation significantly above the threshold that AIDAPS is intended to detect.

4.0 Conclusions:

The last year of test cell work has conclusively shown that thermodynamic analysis can pinpoint major gas turbine engine degradation modes. Flight testing has also indicated that similar defects can be detected by an on-board prototype system. However, further areas of work have been identified.

The variability of the measured gas-path parameters has to be kept within an acceptable band (± 1/2 percent). This has resulted in some instrumentation changes (new compressor inlet pressure (CIP) and torque sensor transducers, and a relocated compressor discharge pressure (CDP) sensor installation).

Two prognostic tests, temperature erosion (burning) and sand and dust erosion were conducted in the test cell. These tests both demonstrated the relatively slow rate of degradation, especially of the GP section.

Realizing that in practical day-to-day engine monitoring, sensor malfunctions can occur that do not go off the scale, a sensor malfunction and quality assessment of the diagnostic results must be fully developed and tested.

The development of a bleed/leakage model to provide an auxiliary capability for identifying increased bleed usage (associated with a malfunction of a bleed using device or significant external leakage flow occuring prior to the turbine section. Use of the bleed model, however, is complicated by its high sensitivity. If this problem can be solved this model would supplement the basic model in the proper interpretation of turbine section deterioration.

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1. UH-1H Automatic Inspection Diagnostic and Prognostic System (AIDAPS) Test Bed Program, Hamilton Standard Division of United Aircraft Corporation, USAAVSCOM Technical Report 72-18 August 1972

2. Second Interim Technical Report, AiResearch Manufacturing Company of California, United States Army Aviation Systems Command, Contract No. DAAJ01-73-C-0874(P3L) November 8, 1974.

3. Third Interim Technical Report, AiResearch Manufacturing Company of California, United States Army Aviation Systems Command, Contract No. DAAJ01-73-C-0874(P6C) April 1, 1975

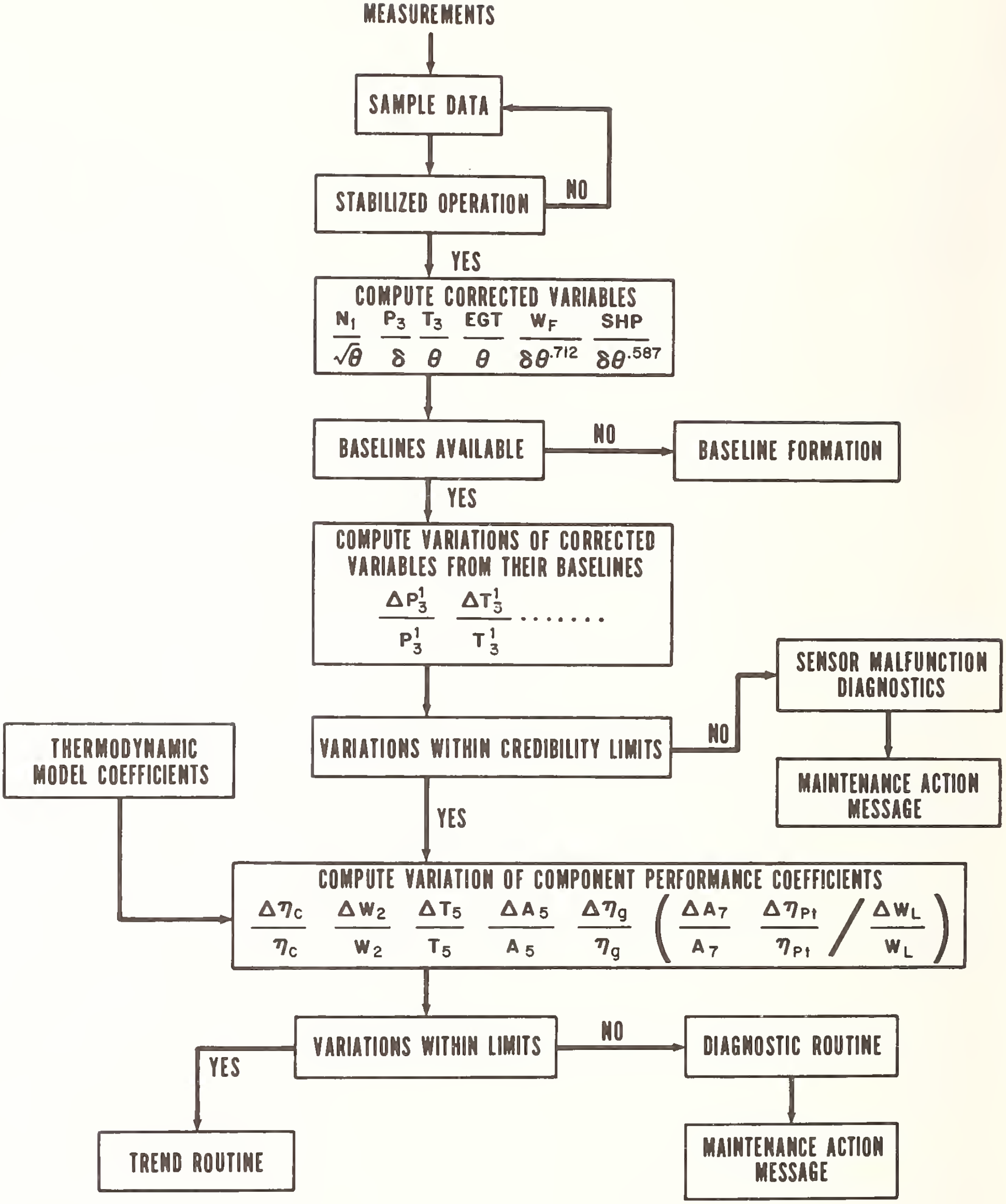MEASUREMENTS
SAMPLE DATA
STABILIZED OPERATION
NO
YES
COMPUTE CORRECTED VARIABLES
$\frac{N_1}{\sqrt{\theta}}$ $\frac{P_3}{\delta}$ $\frac{T_3}{\theta}$ $\frac{EGT}{\theta}$ $\frac{W_F}{\delta\theta^{.712}}$ $\frac{SHP}{\delta\theta^{.587}}$
BASELINES AVAILABLE
NO
BASELINE FORMATION
YES
COMPUTE VARIATIONS OF CORRECTED VARIABLES FROM THEIR BASELINES
$\frac{\Delta P_3^1}{P_3^1}$ $\frac{\Delta T_3^1}{T_3^1}$ ....
VARIATIONS WITHIN CREDIBILITY LIMITS
NO
SENSOR MALFUNCTION DIAGNOSTICS
MAINTENANCE ACTION MESSAGE
THERMODYNAMIC MODEL COEFFICIENTS
YES
COMPUTE VARIATION OF COMPONENT PERFORMANCE COEFFICIENTS
$\frac{\Delta\eta_c}{\eta_c}$ $\frac{\Delta W_2}{W_2}$ $\frac{\Delta T_5}{T_5}$ $\frac{\Delta A_5}{A_5}$ $\frac{\Delta\eta_g}{\eta_g}$ $\left(\frac{\Delta A_7}{A_7}\ \frac{\Delta\eta_{Pt}}{\eta_{Pt}} \Big/ \frac{\Delta W_L}{W_L}\right)$
VARIATIONS WITHIN LIMITS
YES
NO
TREND ROUTINE
DIAGNOSTIC ROUTINE
MAINTENANCE ACTION MESSAGE

Figure 1.

	$\Delta P_3/P_3$	$\Delta T_3/T_3$	$\Delta W_f/W_f$	$\Delta SHP/SHP$	$\Delta EGT/EGT$
$\Delta T_5/T_5$	.000	.408	-.129	.126	.886
$\Delta W_2/W_2$	.000	.140	1.234	-.242	-1.705
$\Delta \eta c/\eta_c$	.743	-2.278	.000	.000	.000
$\Delta A_5/A_5$	-1.090	.376	1.290	-.196	-1.377
$\Delta \eta g/\eta_g$	-.936	1.900	.232	.175	-1.171
$\Delta \eta pt/\eta_{pt}$	.000	-.128	-1.140	.5535	.943

Example: $$\frac{\Delta T_5}{T_5} = .408\,\frac{\Delta T_3}{T_3} - .129\,\frac{\Delta W_f}{W_f} + .126\,\frac{\Delta SHP}{SHP} + .886\,\frac{\Delta EGT}{EGT}$$

Figure 2. Coefficient Matrix Set, N_1 model ($P_3 = 80$)

T5, Turbine inlet temp: + 5%

W2, Airflow (or comp pumping capacity): - 3%

ηc, Compressor efficiency: - 3%

A5, Gas producer turbine nozzle area: + 4%

ηg, Gas producer turbine eff.: - 3%

ηpt, Power turbine eff.: - 3%

VIGV full open pt: 94 ± 1.5% N

Figure 3. Diagnostic Limits

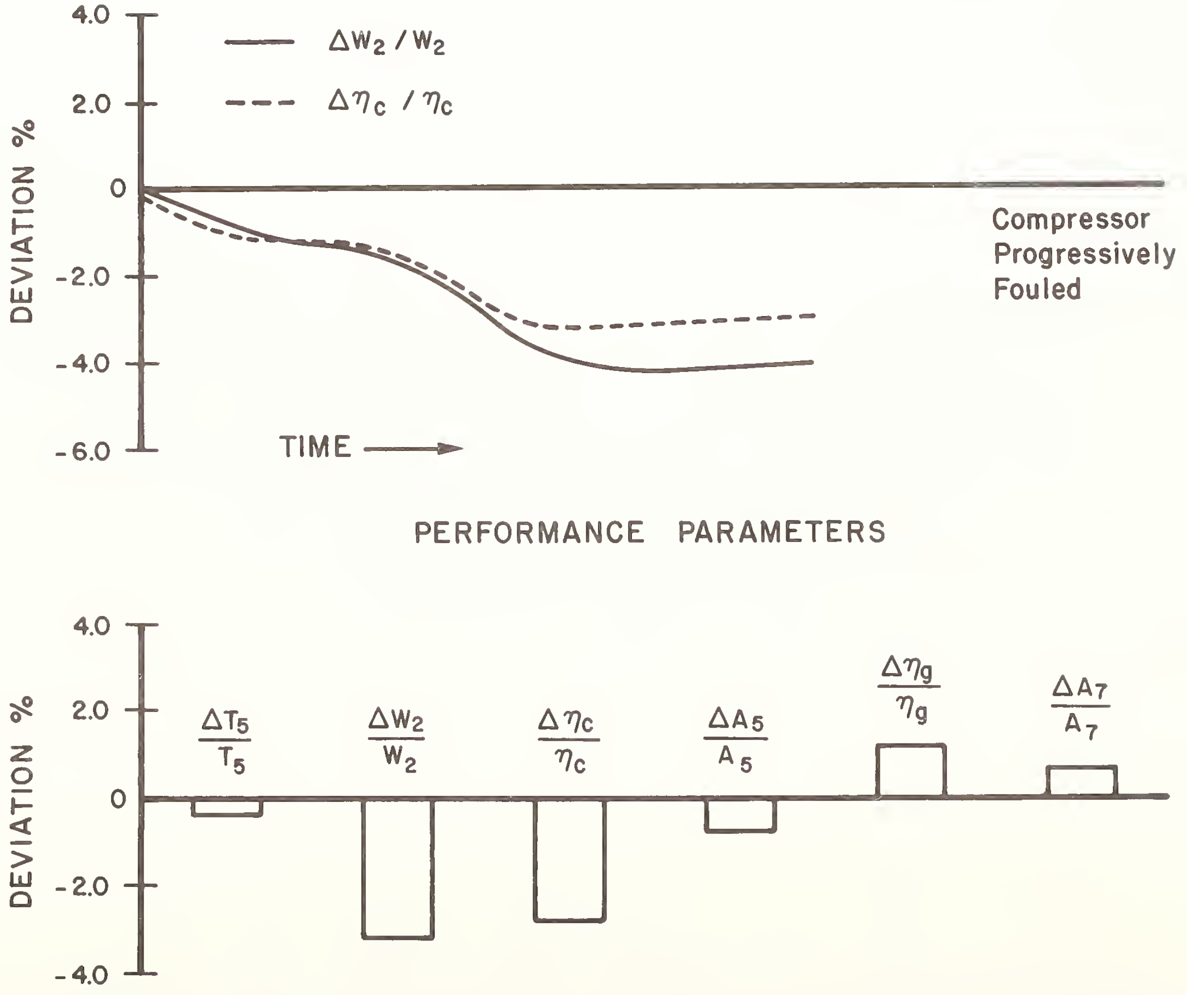

Figure 4. Compressor Fouling (N_1, Constant)

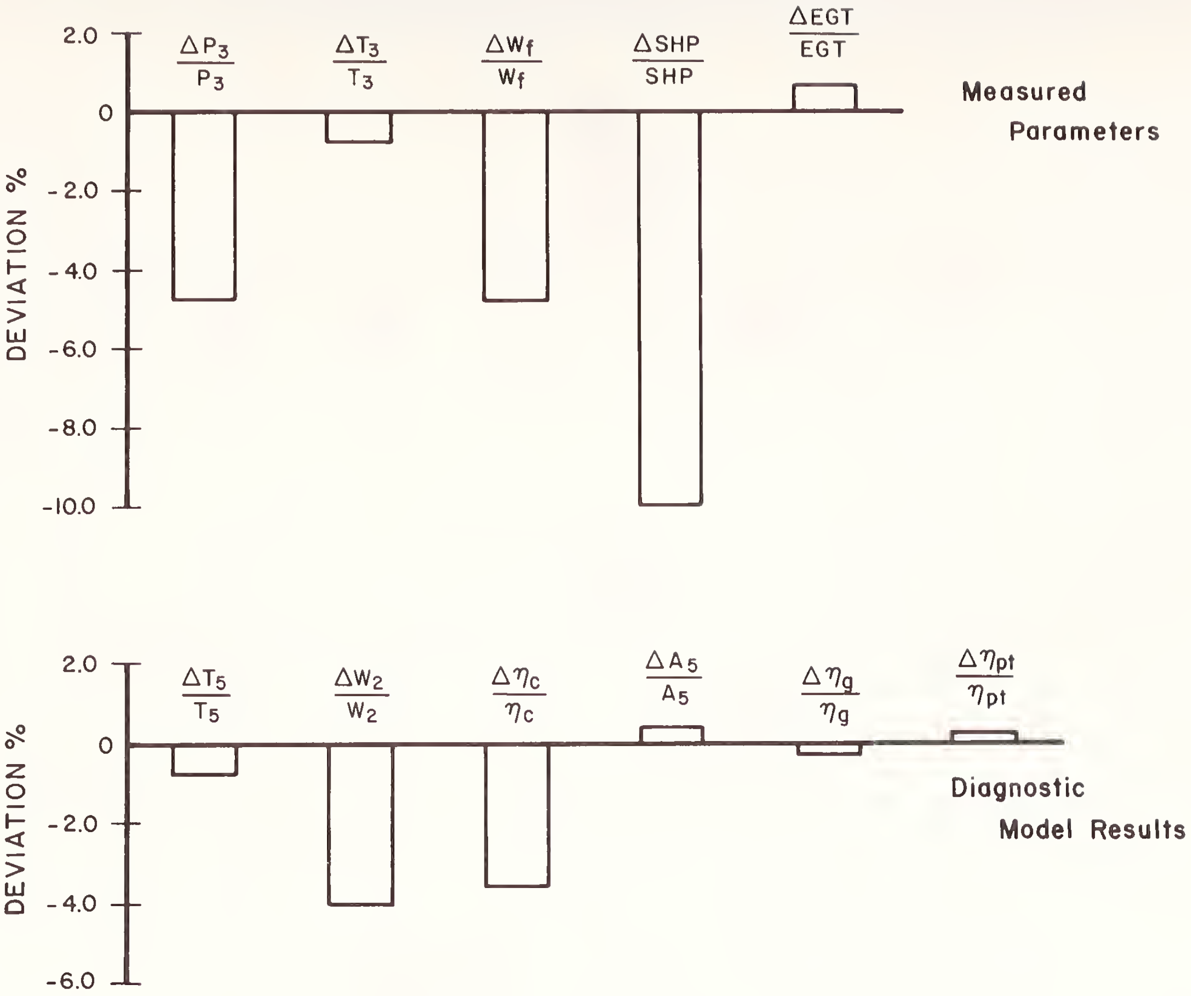

Figure 5. Eroded Compressor (N_1 Constant)

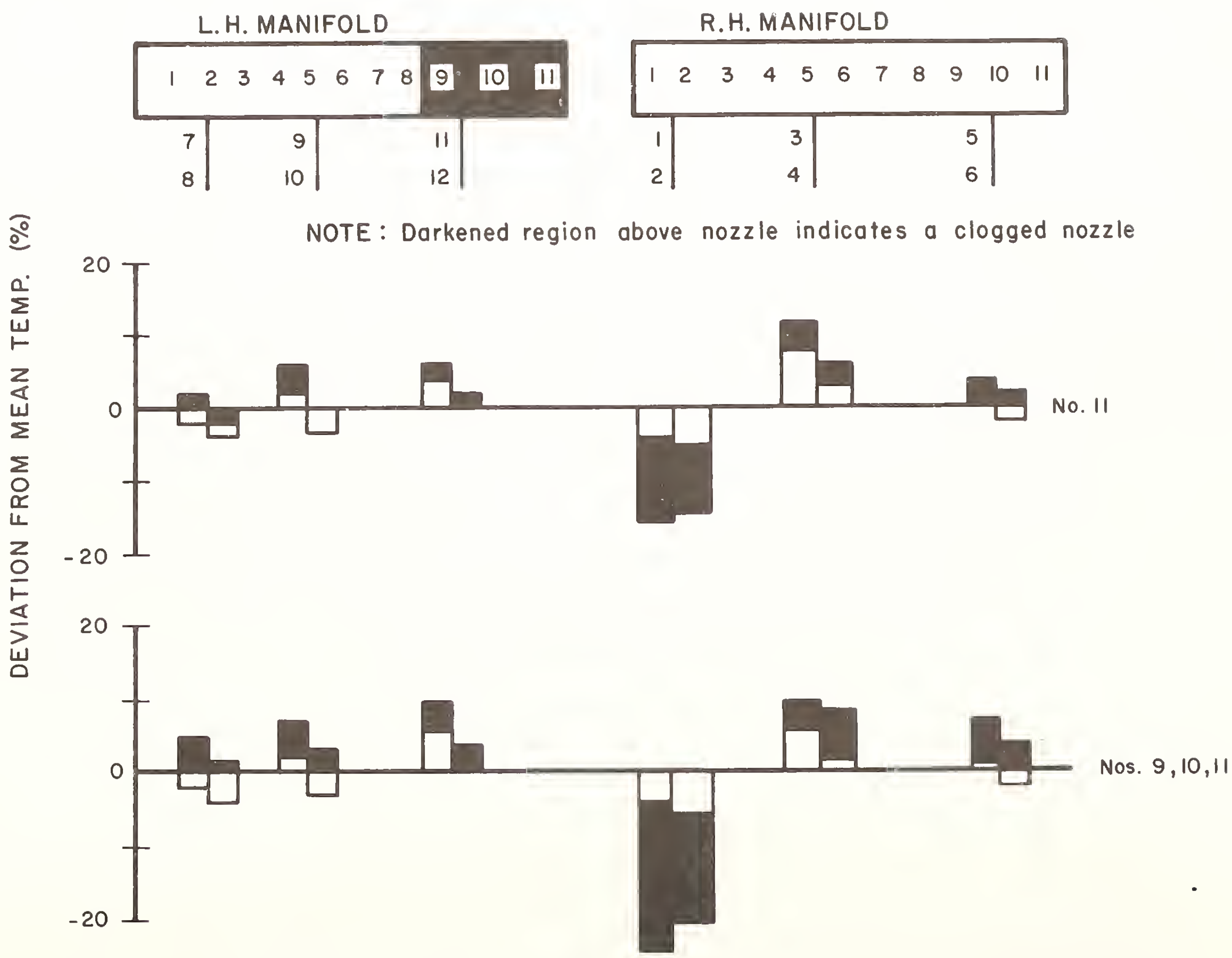

Figure 6. Clogged Fuel Nozzle EGT Patterns

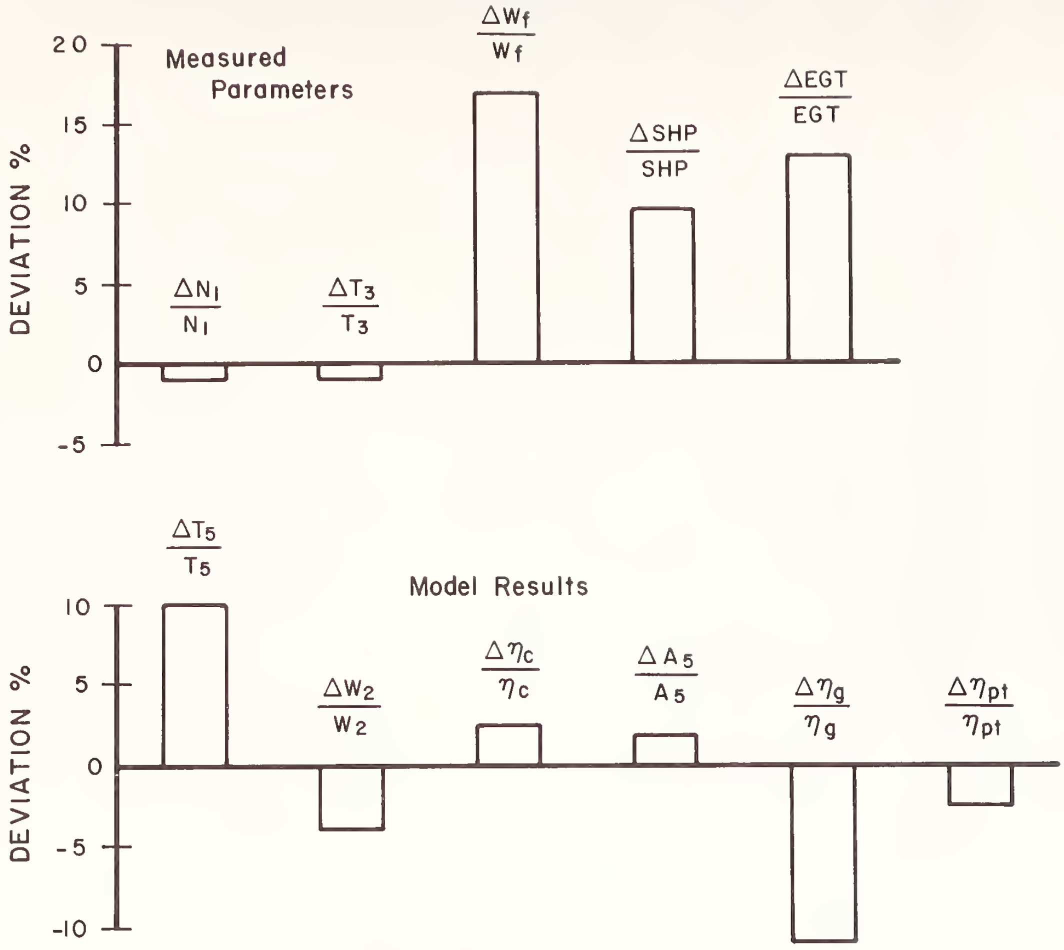

Figure 7. Eroded First-Stage GP Rotor (P_3, Constant)

DISCUSSION

C. R. Garbett, Shell Development Company: What kind of meter did you use to measure torque?

R. L. Stenberg: It was a torque pressure sensor. What we identified was that the current torque pressure sensor that is on the UH-1H aircraft may not have the repeatability we need for this system, so we do have an alternate sensor on the aircraft. We are evaluating both sensors in parallel.

O. E. Compton, Northrop Corporation, Aircraft Division: What type of correlation did you obtain between the air/fuel flow ratio and the measured temperature analysis?

R. L. Stenberg: We had a very close correlation between the air/fuel results and the model results that we obtained.

O. E. Compton: Is that how you define the clogging of your nozzles?

R. L. Stenberg: Yes, that was one of the indications.

PROBLEM AREAS ENCOUNTERED IN ESTABLISHING A DATA BASELINE AND EVALUATING THE A-7E INFLIGHT ENGINE CONDITION MONITORING SYSTEM

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Various Engine Health Monitoring (EHM)systems have been formulated and tested as operating prototypes with varying degrees of success. The true worth of any such EHM system can only be determined after the prototype system has been developed to the point where an expanded data baseline can be employed and a significant number of pre-production systems can be deployed in an operational environment.

The expanded data baseline is required to define the boundaries of the distinctive variations or signatures of individual engines over the general population of all engines to be monitored. That is, the expanded data baseline is required to "fine tune" the software which was developed and demonstrated with the prototype EHM system. A significant number of pre-production EHM systems deployed in an operational environment is required to generate the statistical data necessary to prove the cost-effectiveness of the system. This statistical data is required not only to demonstrate system effectiveness but to generate essential information on the system reliability and maintainability.

SYSTEM DESCRIPTION

A system for engine health monitoring to detect actual and impending engine and component malfunctions and to define necessary corrective maintenance actions has been designated as IECMS (Inflight Engine Condition Monitoring System) by the U. S. Navy. The IECMS has been developed for the TF41-A-2 engine installed in the A-7E aircraft. The engine manufacturer, Detroit Diesel Allison (DDA) Division of General Motors was assigned prime responsibility for system development and software generation while Teledyne was chosen to supply the system avionics.

The basic objectives of the IECMS were defined as:

- To detect actual and impending engine flight safety malfunctions.
- To define engine health status and indicate corrective maintenance actions.

To achieve these basic objectives, the following system design goals were originally defined:

- To reduce engine caused aircraft losses by 50%.
- To achieve a minimum of 90% data recoverability.
- To achieve a minimum level of 90% valid engine diagnostics.
- To handle current and anticipated engine problems.

The IECMS consists of four major elements as follows:

- Engine mounted sensors, transducers and subsidiary hardware for measurement of 51 engine and airframe parameters.
- Aircraft mounted Engine Analyzer Unit (EAU) for data acquisition, signal conditioning, data management (logic) and data output of the engine and airframe parameters.
- Aircraft mounted Tape Magazine Unit (TMU) for mass storage of pertinent airborne data.
- Ground based Ground Station (GS) for complete analysis, presentation and storage of airborne collected data.

The IECMS sensor package consists of a total of twenty-one transducers that have been installed on the engine for the measurement of temperatures, pressures and flows necessary for diagnosing engine operation. Twenty-four additional sensors relating to switch positions, amperage, voltage, etc. are monitored by way of modifications made to existing engine components and/or wiring. Eleven sensors are extracted from airframe associated components. Appendix 1 gives a listing of IECMS parameters.

The EAU continuously receives and monitors signals from engine and airframe parameters. These signals are conditioned, multiplexed and converted to digital format within a signal acquisition section of the EAU. A data management section contains the airborne logic program in an addressable 8K core memory, advanced digital computer which receives digital data inputs at a specified sampling rate. A special signal conditioner is provided to convert certain unusual signals (vibration, fuel flow, etc.) to a type that can be easily accommodated by conversion circuits. Self test capability is incorporated via software programming to continuously monitor memory and input/output functioning. Data is outputted to the TMU as directed by the program logic flow. The EAU measures 7.5" x 6.25" x 20.6" long and weighs 32 pounds. The front face of the unit contains twenty engine limit exceedance status flag indicators, thumbwheels for entering documentary data, "self test" pushbutton and lamp indicator and an electrical test/input connector for external readout/entry functions.

The TMU is designed to store two parallel channels of digital information, with a data capacity of 2.8 x 10 bits on an endless loop magnetic tape. A minimum of four flights can normally be stored on this 2.7 pound unit. If required a minimum of 44 minutes of continuous recording can be accomplished before overlap occurs.

The GS accomplishes the final processing and evaluation of the airborne data recorded on the TMU. The central processing facility of the GS is a Digital Equipment Corporation Model PDP 11/15 computer unit featuring 32K of addressable core memory. All programs required for data analysis, presentation or storage are located on a 1.2 M word mass storage disc drive unit. A reel type magnetic tape drive system is used for flight history, data transfer and program update purposes. The additional elements that make up the GS include a computer command console, line printer unit, high speed reader/punch and tape interface unit.

The IECMS operational functions commence with the airborne EAU. The EAU continuously monitors all sensor parameters, determines the present mode of operation (start, take-off, etc.) and decides on the need for recording data on the TMU. Recorded data is directed if any of the following conditions exist:

- -Start/Take-off.
- -Engine exceedance.
- -Engine transients.
- -Engine power loss or fluctuation.
- -Pre-defined conditional modes (ground idle, stable, flight idle, end-of-flight).

After every flight, visual inspection of the Flag Display section determines if immediate analysis of the data is required. If no exceedance flags were tripped and no pilot "gripes" registered, the engine is considered in a "go" status for the next flight. After a series of no exceedance flag flights, data is generally analyzed at the end of daily operations.

Whenever data analysis is required, the TMU is removed from the aircraft and played back by the GS. Data analysis is performed within the GS by a serial investigation of the airborne collected data. Logic flow is determined by record mode identification and/or "reason for record" indicators appropriately tasked by the EAU. Abnormal operation engine problems or discrepancies found by the GS logic are documented by "hard copy" message on the line printer. This engine health diagnostic message will be accompanied by the associated corrective maintenance action requirements. Presently, 230 diagnostic messages are available in the software program. Preceding data analysis, the GS is programmed to automatically search and output the engineering data relating to the diagnostic message to be used for further documentation and/or to aid the operator in verification of the message.

The following additional programs are available to the GS operator for various types of data presentations:

- -Flight profile.
- -Engineering calculation trace.
- -Detailed vibration program.

- -Plot routine (9 parameters vs. time).
- -Engineering data presentation.

BACKGROUND

Interest in an EHM system for the A-7 aircraft began in 1971 when an inflight oil quality indicator called the Environment One (EV-1) unit was flight tested at the Naval Air Test Center (NATC). The need for a more comprehensive engine health monitoring system was recognized as the EV-1 unit showed potential as a useful indicator of inflight oil quality. The EV-1 engine health monitoring program expanded in scope first becoming NADS (Naval Airborne Data System) and then IECMS. A combination A-7 IECMS feasibility study and prototype "fly off" was accomplished at NATC with two teams of manufacturers. Pratt and Whitney Aircraft and Hamilton Standard developed a prototype IECMS for the A-7B aircraft while DDA and Teledyne developed the A-7E prototype IECMS. Late in 1972, the A-7E IECMS was chosen to continue development during a ten aircraft baseline/pre-production evaluation in two operation squadrons based at NAS Lemoore. This evaluation culminated with the IECMS equipped aircraft deploying on the USS Enterprise in the fall of 1974.

To date the A-7E IECMS has demonstrated operational capability in both a shore and aircraft carrier based environment with approximately 5000 flight hours in over 3000 sorties. Evaluation reports indicate that the IECMS hardware has demonstrated good reliability for a pre-production system. The associated diagnostic software routines have been developed to the point where they have demonstrated considerable potential as a maintenance tool which can automatically define actual and impending engine discrepancies.

A significant number of IECMS diagnostic "finds" have been recorded and validated. The majority of these have been engine maintenance action indications but a few could be construed as safety-of-flight items. IECMS hardware has passed all military specification bench testing. The IECMS software has demonstrated the ability to recognize individual engine vibration and performance baseline signatures. IECMS generated flight history data has been used by the DDA engine Component Improvement Program (CIP) for mission analysis investigations and to develop long range trending capabilities.

THE EXPANDED DATA BASELINE

An expanded data baseline program is a necessary step in developing an EHM system from a single prototype system to a system capable of accurately diagnosing the health of any engine within the general population of all engines. The main reason for conducting the expanded data baseline program is that every engine within the general engine population is an individual and operates slightly different than the next engine. Any single sample prototype development effort would, by necessity, tend to "tailor" the EHM system to that single sample engine. An expanded data baseline program is necessary to overcome this tendency to "tailor" the system development to a singular sample engine and to develop an EHM system which is useful for all engines in a general population.

The A-7E IECMS experienced this single sample "tailoring" tendency during the initial prototype development. The need for an expanded sample data baseline program was recognized and implemented with the 10 aircraft pre-production IECMS evaluation. Several of the unique problems involved with establishing the expanded data base program will be presented in the following discussion.

The major difficulty the A-7E IECMS effort experienced during the baseline program was that the problems involved with going from one to ten aircraft were underestimated. Thus, the expanded data baseline program was planned to be conducted concurrently with the actual pre-production evaluation. This was an impracticable situation, where the pre-production evaluation could not actually begin until the data baseline effort developed the IECMS to a satisfactory level of operation. Ideally, the data baseline effort should be well along into providing a developed system before the pre-production evaluation begins.

Another major problem experienced by the A-7E IECMS was that some new hardware was introduced into the data baseline systems without having been first tried on the prototype system. Of particular trouble to the IECMS was a change from velocity type to acceleration type vibration sensors. This hardware switch caused large amounts of development time lost because of the necessity to troubleshoot ten systems instead of just a single prototype system. Thus, in the development of any EHM system, hardware changes which are not first tested on the prototype system must be very carefully planned.

Operating a large sample of development systems in a fleet type environment for an expanded data baseline causes difficulties. The fleet operators have operational commitments and specified missions to fulfill. These operational missions are not always in keeping with the types of missions necessary for an ideal data baseline program. The operational missions always have priority and often, the data baseline program and system development effort lose control over the aircraft. This makes for a very long development phase as was the case experienced by the A-7E IECMS program.

The process of going from a single prototype system to an expanded sample data baseline program involves many inherent "shake down" problems. These problems would be common to the development of any avionics system but are especially bothersome in the case of an EHM system. This is because of the initial difficulty in determining whether many unexpected system problems were hardware or software generated.

There is again the problem of "tailoring" the EHM system to the prototype situation. Operational pilots in a fleet environment, operated the aircraft and engines very differently than the test pilots who flew the prototype system. The limits of these operational differences had to be defined at the beginning of the data baseline evaluation. This was the first problem the A-7E IECMS experienced when initially introduced into a fleet type environment.

The development or "fine tuning" of the EHM system software is the major purpose of the expanded data baseline program. This in itself, is a major problem area of a continuing duration. Along with this major concern is the sheer logistics of continuously changing and updating the software programs for a large number of aircraft. During software development, decisions have to be made as to which engines and aircraft are most representative of the general population. Additionally, all development efforts must be faithfully recorded for both evaluation and documentation purposes. Similarly, the problem of documenting all software changes during this development phase is a large task.

The Pre-Production Evaluation

The whole process of justifying the effectiveness of an EHM system becomes a statistical data gathering exercise. All diagnostic indications have to be tracked, documented, and verified as either valid or invalid. This becomes a very tedious but necessary bookkeeping task. Any safety-of-flight diagnostic "finds" have to be well substantiated and publicized for these "finds" will give the greatest credence to the general acceptance of an EHM system. Maintenance man-hours saved is one of the hardest items to accurately document but must be carefully recorded. An attempt should also be made to show savings in the overall engine logistics support effort and to define possible impacts on any engine development or component improvement program. A successfully implemented EHM system should influence all of the above-mentioned areas.

A well planned and thoroughly executed pre-production evaluation can generate the statistical data necessary to prove the EHM system effective in all areas of concern. The uncertainity of the conclusions about the particular EHM system decreases as the accumulation of accurate statistical data on its performance increases. The A-7E pre-production IECMS evaluation tried to generate the statistical data necessary to decrease any inherent uncertainties and prove the IECMS effective in the operational environment.

In April 1973, the Naval Aviation Integrated Logistic Support Center (NAILSC) was tasked to monitor and evaluate the application of the IECMS for the maintenance of the A-7E aircraft. The NAILSC effort, in conjunction with the monitoring of the technical development of the IECMS by the NATC, encompassed the pre-production evaluation.

While generating statistical data on the IECMS performance during the course of the evaluation, NAILSC was tasked to monitor and evaluate fleet usage of these systems with particular attention to the following:

- Identification of those IECMS required maintenance actions which would have resulted in safety-of-flight situations if not detected.
- The validity of maintenance actions indicated by IECMS.
- The in-service reliability of IECMS.
- The comparison of maintenance performed on IECMS equipped and non-IECMS equipped engines.
- Operation availability of IECMS equipped engines and aircraft.
- The logistics support requirements for IECMS and IECMS equipped engines.

In order to perform the pre-production evaluation, a detailed test plan was written. The test plan stipulated the precise requirements of all activities and persons involved in the evaluation. This test plan had to be agreed to and approved by all concerned persons involved with the IECMS program before the evaluation could commence.

In spite of the meticulous preparation and planning, certain problem areas emerged during the course of the A-7E pre-production IECMS evaluation. These problem areas seem to be unique to the evaluations of any inflight EHM system. These unique problem areas are presented and commented upon in the subsequent discussion.

Probably the most difficult milestone to determine in any pre-production evaluation is that point in time when the system development effort stops and the actual evaluation begins. Statistical data, gathered during the system development phase, could show poor system performance because of major unsolved development problems. Unpredicted hardware and software problems inherently occur during any system development effort and would necessarily bias the results of a premature evaluation. The A-7E IECMS program experienced exactly this phenomenon.

The pre-production evaluation took several "false starts" which were "called back" because of yet unsolved hardware and software problems. These hardware and software problems were causing too great a negative bias on the statistical results to perform an accurate evaluation. This problem is magnified by the fact that for a sophisticated EHM system, the software development is an ever continuing effort.

A problem which must be faced at the commencement of the evaluation is the definition of a valid diagnostic "find". This definition of a valid "find" must be agreed to from the program onset by all persons concerned with not only the evaluation but the whole program. The inherent tendency to change the basic definition of a valid diagnostic during the course of the evaluation could cause great inaccuracies in the statistical data. This confusion occurred during the A-7E IECMS program. The situation developed where every evaluator plus the system manufacturer and fleet operators seemed to have a different definition of a valid diagnostic "find" by half way through the evaluation. The same rule for a single and continuous definition of the valid diagnostic "find" holds true for the definition of an invalid diagnostic.

As with the valid diagnostic "find", an exact definition of what is a safety-of-flight item should be stated from the beginning of the evaluation. Again, all persons involved should concur with this definition and a working list of safety-of-flight items should be developed. This problem also occurred with the A-7E IECMS evaluation. As engine discrepancies were discovered by the IECMS, there was great disagreement on which "finds" could be considered as safety-of-flight items.

The subject of safety-of-flight brings up the topic of operator confidence level. A pre-production EHM system will not and should not have a total operator confidence level. As the system develops and proves itself, the confidence level will increase. A major problem area develops when the EHM system has a cockpit warning indicator. The question arises, should the pilot heed a system cockpit warning of a safety-of-flight problem and abort an assigned mission or should the pilot consider the warning just a false indication of a yet to be completely developed system? This dilemma of operator confidence level is most prevalent to a lesser degree when involving inflight indications but also is present to a lesser degree when involving ground maintenance diagnostic indications. The A-7E IECMS evaluation addressed this problem of operator confidence level by following the doctrine of always believing the system unless there are obvious contradictions to the system indications present.

Validating diagnostic finds create another major problem area. Every system diagnostic indication must be verified and validated by the performance of a resulting maintenance action. This becomes a significant bookkeeping exercise for both the evaluation personnel and the operational maintenance department. Special records must be kept on every engine discrepancy indicated by the system until the diagnostic is verified either valid or invalid. This problem becomes especially large when the diagnosed engine component must be sent to a distant overhaul facility for verification. A detailed documentation plan that addresses diagnostic verification should be implemented well before the actual evaluation begins.

The documentation problem also extends to the EHM system software development. The software programs will continually change as the EHM system is developed. Updated documentation of the total system software programs should be supplied to the evaluating activity throughout the evaluation. The current software documentation will greatly aid in determining the total system integrity as development problems are addressed and solved.

The EHM system development effort and data baseline expansion program must necessarily be conducted by the manufacturer's engineering personnel. This was the case with the A-7E IECMS program. The system manufacturer personnel also operated and maintained the IECMS during the pre-production evaluation. This situation caused the A-7E IECMS pre-production evaluation to generate incomplete statistical data on system maintainability and reliability as well as on required operator skill level necessary to effectively use the system.

The evaluation should be conducted with user personnel operating and maintaining the total EHM system so that a positive determination can be made of system performance under actual operational conditions. After the evaluation begins, the manufacturer personnel should be on site only for diagnostic assistance or operator consultation. All contractor assistance must be documented so that additional personnel training can be initiated to eliminate deficient areas.

The user personnel involved in the evaluation should receive a thorough training course on system software operation and hardware maintenance well before the evaluation begins. To obtain the most accurate statistical data from the pre-production evaluation, the user personnel must operate and maintain the total system. If this situation occurs a responsive training plan can be developed and system maintainability and reliability deficiencies can be defined early enough to allow corrections to be made before the production EHM system is implemented.

CONCLUSION

It has been previously stated that the whole process of justifying the effectiveness of an EHM system becomes a statistical data gathering exercise. The A-7E IECMS experience has proven this true and shown that the processes of setting up and conducting the required data baseline and pre-production evaluation programs are far from easy. Much careful planning and coordination must go into structuring these programs to give the most informative and accurate results. Nevertheless, unexpected problem areas will arise, causing the data baseline and pre-production programs to be less than 100% effective. Some of these problem areas unique to the development and evaluation of an EHM system can be reduced by the thoughtful observation of the mistakes made during previous programs as the A-7E IECMS experience.

IECMS MASTER PARAMETER LIST

ITEM NO.	PARAMETER
1	HYDROMECHANICAL GOVERNOR PRESS.
2	HP PUMP INLET PRESSURE
3	HP PUMP OUTLET PRESSURE
4	LOW PRESSURE GOV. DELTA P
5	MAIN MANIFOLD FUEL PRESSURE
6	PILOT MANIFOLD FUEL PRESSURE
7	BY-PASS STATIC PRESSURE
8	BY-PASS TOTAL PRESSURE
9	HP COMPRESSOR OUT PRESSURE
10	OIL PRESSURE (DELTA P)
11	TURBINE OUT PRESSURE
12	LP COMPRESSOR INLET TEMPERATURE
13	HP COMPRESSOR OUT TEMPERATURE
14	TURBINE OUT TEMPERATURE
15	PMG L.H. SHORTING LOOP CURRENT
16	IGNITION EXCITER L.H. PRIMARY CUR
17	PMG A.C. VOLTS (L.H. COIL)
18	PMG R.H. SHORTING LOOP CURRENT
19	IGNITION EXCITER R.H. PRIMARY CUR
20	PMG A.C. VOLTS (R.H. COIL)
21	PMG D.C. VOLTS
22	AUTO RELIGHT ACTUATOR
23	COLD START SOL. VOLTS
24	DOUBLE DATUM ARMED
25	OVER DATUM RELAY
26	LPC SOLENOID CURRENT
27	LPC SOLENOID VOLTS
28	LP ROTOR SPEED
29	OIL SCATTER
30	OIL ATTENUATION
31	OIL FLOW
32	OIL MONITOR FAIL
33	FILTER (OIL) DELTA PRESSURE
34	INLET GUIDE VANE POSITION
35	POWER LEVER ANGLE
36	OIL TEMPERATURE
37	LP COOLING AIR
38	OUTSIDE AIR TEMPERATURE
39	TURBINE VIBRATION
40	COMPRESSOR VIBRATION
41	ACCESSORY VIBRATION
42	AIRCRAFT G. LOADING

APPENDIX 1

ITEM NO.	PARAMETER
43	1H SPARK RATE
44	R.H. SPARK RATE
45	HP ROTOR SPEED
46	FUEL FLOW
47	OIL LEVEL NORM
48	OIL LEVEL (1/2 FULL)
49	A/C IGNITION
50	A/C MAIN/MANUAL FUEL CONTROL SW.
51	A/C MANUAL FUEL VALVE POSITION
52	STARTER AIR
53	A/C WEAPON FIRING SWITCH
54	OIL COOLER DELTA P
55	LANDING GEAR SQUAT SWITCH
56	ALTITUDE
57	MACH NUMBER
58	
59	HP PUMP FAILED
60	STALL DETECTOR
61	H.P. COMPRESSOR OUT PRESSURE
62	RUMBLE FILTER 1
63	
64	TIME
65	FUEL TEMPERATURE
66	L.P. FUEL PUMP OUT PRESSURE

NOTE: Recently several of these parameters have been dropped due to cost-effectiveness considerations.

DISCUSSION

O. E. Compton, Northrop Corporation, Aircraft Division: Did you identify the signature of a given engine on the test cell on the ground?

A. J. Hess: The procedure followed when installing IECMS for the first time is, in the process of normally trimming the engine, to establish a base line by stabilizing at 4 or 5 RPM points. The system automatically records the engine data. This establishes the base line signature information for each individual engine. The only time you have to redo it is when you change airborne units or change something within the gas path of the engine.

O. E. Compton: What if you were to place that engine in another airplane?

A. J. Hess: If you place the engine in another airplane, you would have to obtain another base line signature, but placing the engine in another airplane requires another trim procedure anyhow, so you could get that data with 20 minutes additional ground work.

O. E. Compton: So basically, the identification of a signature is an engine that is installed in the vehicle, and not on the test cell?

A. J. Hess: That's right.

O. E. Compton: What type of induction system variances, environmental control variances, and shaft horsepower variances do you find among different vehicles in trying to identify the specific signatures?

A. J. Hess: In a turbo-fan engine, you don't worry about shaft horsepower. But, each engine does operate differently. We establish nominal curves representing the general population of all the engines. Then rejection tolerance bands or limits are established around each curve. The tolerance band has to be large enough to take into account the variances within all engines in the general population, but it can't be too large or engine discrepancies will be missed. A large part of the data base expansion program is trying to find where to put the tolerance bands.

J. S. Bendat, Independent Consultant: In regard to the vibration analysis, did you do any narrow band analysis, any transfer function analysis, or any of the more advanced analyses that would really define what was going on?

A. J. Hess: Allison may have used these techniques, but they didn't recommend them to be used in IECMS. Essentially, the vibration team looks at these things: (1) the overall engine vibration level for each of the three transducers, and (2) each of the 21 discrete one-third octave frequency bands for a change either up or down above a certain established tolerance limit. If either of these two things occur, we get an exceedance flag. That tells you that there has been a change in the vibration signature. This new signature is compared with signatures for specific component failures. Those signatures were generated from actual test cell failures that Allison experienced.

R. Hohenberg, Mechanical Technology, Inc.: What are the requirements of transducers in order to achieve your goals?

A. J. Hess: The vendor, Allison, picked the transducers. We do have a requirement for very good accuracy. And we do have a requirement for the transducers to live in a hostile environment, namely, the engine bay where there are extreme changes in temperature and pressure. With these requirements, the transducers are costly. The pressure transducers are costing us about $1,000 a piece.

R. Lenich, Caterpillar Tractor Company: In what ways do the prototype pilots differ from operational pilots in the way they handle airplanes and which is more severe on the airplane?

A. J. Hess: The fleet pilot is much more severe. At Patuxent River there are very experienced pilots who have been through the test pilot's school. In developing the prototype system, these pilots fly profiles to aid the contractor in developing the software. They usually do what is asked of them. They are very smooth in the way they handle the throttle and stick. In a fleet environment there are both experienced and brand new pilots. Naturally, there are differences in how they fly and in how they handle the engine. Also the missions they fly are entirely different. Also the way the engine is handled differs according to whether the pilot is flying lead or wing. The wing man moves around quite a bit more than the lead man. As fallout from the IECMS program, we're learning very much about how that engine is actually being operated. In the fleet environment, one of the things we are using that information for is to develop some type of low cycle fatigue counter for certain critical engine problems.

T. Tauber, Tedeco: I have two questions: (1) did you attempt to correlate your data with SOAP results and (2) what other oil analyses techniques were considered and were evaluated and ultimately rejected?

A. J. Hess: This whole program started with the environment-one oil quality transducer. We haven't had an airborne oil problem to date (5,000 hours). We had a bearing failure on the IECMS equipped engine that was run on a test cell at Allison. The environment-one unit picked it up before the test cell vibration equipment picked it up. The Navy is looking at new types of magnetic flux chip detectors. Those could easily be integrated into an IECMS program. SOAP is a normal program in the Navy. We had false indications for the environment-one unit early in the program. These were caused by the unit failing. We did correlate them with SOAP.

M. Dow, Eastern Airlines: Can you give me some idea of how many man hours have gone into the program development so far?

A. J. Hess: I don't know how many man hours were involved, but the development phase cost several million dollars. It took us the first couple years to develop the hardware and it took us another year and a half or two years to develop the software. I don't think the feasibility study has to be done again for the next system. Using state-of-the-art-hardware, you could rely on our precedence and just go into the development effort of software.

M. Dow: Are there a large number of people engaged in this work?

A. J. Hess: Fifteen.

TRI SERVICE OIL ANALYSIS
RESEARCH AND DEVELOPMENT PROGRAM

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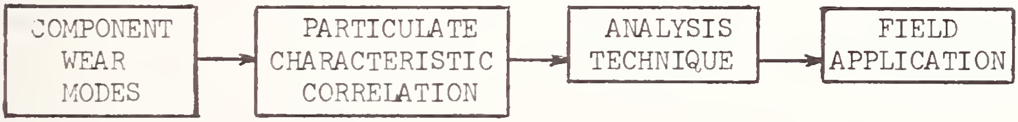
Oil analysis can be described as a preventive maintenance concept utilized to predict impending mechanical failure through the examination of used oil samples. This concept, although varying in technique, has been applied for many decades. Initially, physical properties of oil were considered indicators of equipment wear. However, consistent results were not obtained until examination emphasis shifted to the analysis of oil carried wear particulates. The term oil analysis has thus become synonymous with oil particulate analysis.

Spectrometric oil analysis has developed as the foremost analytical technique utilized at the present time. This technique involves the concentration measurement of various elements contained in a used oil sample. Spectrometric analysis has demonstrated that the analysis of wear metal particulate matter that accumulates in a closed cycle oil wetted system can, with varying degrees of success, be used as a means of gauging wear and thus predicting mechanical component failure. The technical basis for the effectiveness variations exhibited by this technique, as well as related techniques, has not as yet been factually defined.

The optimal development process of an oil analysis technique can be broken down into four distinct phases as shown in Figure I.



OIL PARTICULATE ANALYSIS
Figure I

The first element in any such development program is the definition and categorization of all pertinent mechanical system wear modes. This categorization would list wear modes that contribute to lubricant particulate content. All oil wetted components would be considered in such a study.

The second element of the development program would be to experimentally determine wear particulate characteristics and parameters and relate these factors to the wear state of a component. This correlation effort would be instituted for each wear mode and serve to highlight critical parameters. The monitoring of these critical parameters could be directly related to the wear state of a component.

Based on the determination of critical particulate parameters, an analytical technique or combination of techniques can be developed. This technique definition comprises the third element of the respective program.

The fourth and last element of this program would be the field application of developed techniques. This application would serve to provide effectiveness data as well as serve to dictate modifications if required.

Based on research performed under the Tri Service Oil Analysis effort, the following determinations were formulated with respect to past oil analysis technique development:

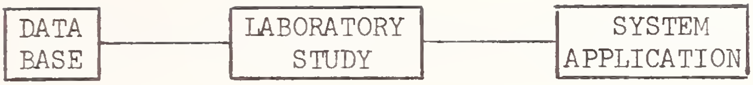
- Numerous wear mode classification efforts have been performed.
- Many analytical techniques have been developed.
- Many techniques have been field tested.
- An insignificant amount of effort has been performed correlating wear modes with wear particulate characteristics and parameters.

These determinations reveal that a major element of the oil analysis technique development program has been neglected. Very little work has been performed which serves to clarify which particle characteristics should be monitored. Analytical techniques developed to date are based on critical particulate characteristic assumptions and have been applied by trial and error.

The Tri Service Oil Analysis Research and Development Program was conceived by the Naval Air Engineering Center (NAEC) to bridge the technological gap that now exists with respect to oil analysis techniques as described above. Its goal is to place oil analysis on a more secure basis. Briefly the program can be summarized as follows:

> Laboratory testing to determine the feasibility of predicting the wear state of oil wetted components through the utilization of critical wear mode parameter monitoring.

In order to achieve this program goal, a three phase effort has been instituted by NAEC. These phases consist of data base formulation, laboratory study, and system application as depicted in Figure II.



OIL ANALYSIS PROGRAM
Figure II

Each program phase shall be discussed separately as follows:

(1) Data Base

The data base phase of the program serves to provide information necessary to initiate meaningful laboratory testing as well as effectively evaluate test results. The initial thrust of this effort was the derivation of wear mode matrices for each prime oil wetted wearing component. Matrices were derived for ball bearings, roller bearings, gears, and sliding contacts. These four components were determined to be prime components of oil wetted systems. Each matrix relates component operational parameters to particular wear modes. Wear conditions encountered under laboratory test are cataloged through utilization of these matrices. Matrices are enclosed as Appendix I.

A secondary effort under the data base phase is the categorization of oil carried wear particle morphology. Under this effort, a number of distinctive particle types have been identified. The particle types are as follows:

Rubbing Wear Particles

Rubbing wear particles are generated whenever two pieces of metal rub together in the presence of a lubricant. It has been found that they originate in a shear mixed layer which, in the case of steel, is in the order of 1 μm thick and exhibits only short range crystalline order. This layer, the significance of which has only recently been appreciated, has unique properties different from those of the underlying metal. Most wear of rubbing metal surfaces is the result of flaking off of pieces of the shear mixed layer as the result of a network of cracks that gradually develop with repeated passes of the opposing surface. This type of wear is relatively benign and is fundamental to boundary layer lubrication.

Oxide Particles

Some wearing systems show large quantities of the red oxide of iron, hematite, Fe_2O_3. Such oxide particles are easily recognized in the microscope using transmitted white light and are even more striking using transmitted polarized light with crossed polars. They are the result of rusting in the machine and generally indicate the presence of moisture or moist conditions which permit the rusting to occur. The rust is usually not generated at the wearing surface, but is simply material flaked off of shafts, the insides of pipes, and many other places.

The oxides of other metals may be white, blue, green, or yellow, depending on the metal.

Dark Metallo-Oxide Particles

Another category consists of dark metallo-oxide particles which are thought to be principally Fe_3O_4 (magnetite). These particles are non-stoichiometric oxides and may be thought of as oxides with iron dissolved in them. They are surprisingly more opaque than would be expected from pure Fe_3O_4. These particles appear as black or very dark chunk-like particles, similar to pieces of hard coal. It is postulated that they are sufficiently hard to cause surface denting and subsequent micro-cracking of the surfaces of rubbing elements in bearings.

A second type of dark chunk-like particle has been found recently, usually accompanied by dark flat platelets with straight sides. They appear to be the wear product from carbon seals or separators. The chunk-like particles do not have the sharp edges characteristic of magnetite; the fracture surfaces are concoidal, similar to that of glass.

Cutting Wear Particles

Cutting wear particles have the appearance of tiny lathe chips or coils of fine wire. Such particles are the result of the failure of the boundary layer lubrication and are usually associated with high surface contact forces. They may also be generated by the presence of abrasives. An independent investigator has proposed that these abrasives can be synthesized on wearing surfaces.

Fatigue Chunks

Another type of particle is the fatigue chunk or grain. They are composed of free metal, usually ferrous and show crystalline faces containing considerable detail. They are approximately as long as they are wide and are often several microns thick. Such particles are generated by certain types of gear wear and are seen in other situations where cracking perpendicular to the surface can develop.

Laminar Particles

Laminar particles are found in connection with gear and rolling bearing wear. They are exceedingly bright free metal particles most frequently seen in connection with rolling bearing wear. The particles are thin, typically 3/4 µm thick, and generally have holes in their surface. They appear to be the result of rolling out of the metal as could occur in the shear mixed layer on the ball bearing track or near the pitch line of gears.

Spherical Particles (Free Metal Spheres)

Spherical particles are generated by the thousands in cases where micro-cracks are present in rolling bearings, such as ball bearings and roller bearings, lubricated by either oil or grease. They range in size from less than 1 µm to more than 10 µm. The smaller sizes are much more numerous. Up to several million spheres can be generated in the course of a bearing fatigue failure.

These spherical particles are not to be confused with polymer spheres or oxide spheres. The polymer spheres are thought to be the result of polymerization of oil around wear particles which serve as a nucleating catalyst.

Oxide spheres are produced in a variety of ways, but probably the most common is fretting of steel surfaces. The non-free metal spheres are easily distinguished from free metal spheres by virtue of the reflectivity and opacity of the free metal. In bichromatic illumination, free metal spheres appear red and the non-metallic or oxide spheres appear green.

Corrosive Wear Particles

Corrosive wear particles are those particles which have been digested by the lubricant. They are distinguished from red and black oxides of iron because they are generally colorless and much more transparent. They may be chlorides of the wearing material.

Non-ferrous Metallic Particles

These particles may belong to any of the first five classes.

Hybrid Particles

Hybrid particles are composed of non-ferrous material which also contain some iron. They result from the wearing of some non-ferrous alloy, such as bronze, against steel.

Non-metallic Crystalline Particles

Non-metallic crystalline particles are common, the most familiar example being sand. However, other oxides and carbides, such as silicon carbide, are also frequently seen. The significance of such particles depends on local conditions. The presence of sand, for example, can indicate an air filter failure or a bearing seal that is leaking.

Amorphous Material

Amorphous material usually consists of deposits of material which does not have a specific shape. The material is usually translucent but often contains thousands of metal particles. Various contaminant polymers such as gasket material and plasticizers are the major sources of this material.

The above two efforts constituted the bulk of the work performed under the data base program phase. Except for revisions, this phase has been completed.

(2) Laboratory Study

The laboratory study phase of the program involves the bench testing of prime oil wetted components. The objective of this phase is to monitor both the component surface wear condition and the respective generated wear particle characteristics and parameters. Correlations can then be drawn between surface wear progression and particle characteristic/parameter trends. Trend analysis will serve to identify critical particle characteristics which reflect the wear state of oil wetted components.

Under this phase, bench testing has been instituted for ball bearings, roller bearings, gears and sliding contacts. These components have previously been identified as prime wear components in oil wetted systems. Component test parameters reflect field operating conditions to the greatest extent possible. Examples of these parameters are presented in Figure III. Each component is operated in an individual closed-loop lubrication system. Oil specimens are periodically sampled from the lubricant system and subjected to a battery of particulate analysis techniques. These techniques include the following:

- Ferrographic Analysis
- Millipore Patch Analysis
- SEM Microscopy
- Optical Microscopy
- Densitometer Analysis
- Particulate Counts
- Acidity Measurements
- Viscosity Measurements
- Colorimeter Analysis
- Spectrometric Analysis
- TEM Microscopy

The above techniques serve to classify wear particle, size, size distribution, shape, color, density, and concentration among others.

In addition to oil specimen sampling, the component wear surface is monitored at predetermined intervals during testing. Both

	6309 Deep-Groove Ball Bearing	LM102949/LM102910 Tapered-Roller Bearing
1. Bore diameter (D, mm)	45	45.2
2. Speed (N, rpm)	9,700	2,900
3. D x N x 10^{-6}	0.44	0.13
4. Lube	MIL-L-23699	MIL-L-23699
5. Lube viscosity at 38/100°C	25/5.1	25/5.1
6. Radial Load (kN)	18.7	18.4
7. Axial Load (kN)	0	5.74
8. Bearing Capacity (kN)	39.63	47.62
9. Theoretical L_{10} Life:		
10^6 revolutions	10	10
10^6 stress cycles	50	130
10. Theoretical L_{50} Life:		
10^6 revolutions	50	50
10^6 stress cycles	250	650

BEARING TEST PARAMETERS
Figure III

optical and scanning electron microscopy are utilized in this surface monitoring effort.

Particulate analysis trend results are then compared and correlated with respective wear surface monitoring results. This correlation effort serves to identify critical particulate characteristics and/or parameters.

Component bench testing has been initiated for ball and roller bearings, as well as sliding contact. Gear bench testing is imminent. As a result of this early test stage, it would be premature at this time to draw any conclusions from the above described correlation efforts.

Although correlation results have not been firmly established, several significant findings have evolved from this laboratory study program phase. The first area of findings involves oil sample storage. In order to insure viable test results, representative oil specimens must be taken from test systems. These samples when subjected to analytical techniques, after various storage periods, must remain representative of the test system lubricant. Under the oil analysis program, a study was initiated to investigate the storage characteristics of oil samples. The following findings, some still not fully explained, were uncovered.

- Different lubricants exhibit significantly different abilities to retain particles in suspension.
- The particle agglomeration characteristics of different lubricants exhibit much variance.
- The longer an oil specimen is stored, the more difficult it is to redisperse the contained particles.
- Mild heating (72°C) followed by manual shaking has been determined to be the most effective method to thoroughly redisperse stored oil samples.
- Analysis of heated oil samples in contact with tygon exhibits deposits of plastic gels. This plastic material tends to coalesce near or around wear particles.
- Accelerated heat aging of oil samples in polypropylene bottles results in the migration of components of the plastic into the oil.

The most significant finding to result from this program has been the full realization of what a truly clean lubrication system can mean in extending the life of operating components. Ultra clean lubrication systems, utilized in ball bearing bench testing, have consistently resulted in the extension of bearing operational life in excess of 40 times their calculated expected life. This life extension dramatically illustrates the major influence oil particulate contaminants exert on the wear rate of a lubricated component.

The above efforts and resulting initial findings constitute a brief overview of the work performed under the laboratory study program phase. This phase is expected to be completed within the next six months.

(3) System Application

The third and final phase of the oil analysis program involves the application of laboratory findings to field operating systems. The objective of this phase is to verify laboratory component test results and conclusions.

Under this phase various field control groups have been organized. Oil samples are collected from respective equipment that fall within these groups. Each time a sampled piece of equipment experiences an oil wetted component replacement, the worn or broken part, as well as any pertinent reports, are collected. This process creates a repository of failed parts and respective series of preceding oil samples. A respository of this type serves as an excellent system application test for laboratory developed results and conclusions. The application of laboratory monitoring methodologies to repository oil sample failure series will serve to verify the applied methodologies.

Control groups that have been organized under this phase consist of landbase, shipboard, and airborne equipment. Oil wetted systems of the F4 aircraft, UH-1 helicopter, M60 tank, and nuclear submarines are presently being monitored. At the conclusion of the laboratory study program phase, results will be verified by application to these field control groups. This phase will be completed within the next eighteen months.

The above described three phase program approach will serve to bridge the technological gap that exists with respect to oil analysis technique development. Expected results to be derived from this program can be summarized as follows:

- Definition of Wear Components.
- Identification of Critical Wear Modes.
- Feasibility of Identifying Critical Wear Mode Parameters.
- Feasibility of Correlating Critical Wear Mode Parameter Monitoring to Wear Component Failure.
- Definition of Monitoring Criteria.

These results will serve to explain the variations in effectiveness of existing oil analysis techniques as well as serve as a firm technical basis for the development of a more sophisticated technique.

WEAR MODE MATRICES

APPENDIX I

Table 1. Sliding Surface Failure Modes

	(15) Smearing and Scuffing in the Sliding Direction, Adhesion	(1) Spalling of a Bearing Surface, Fatigue	(8) Roughened Microdented Surfaces, Abrasion, Erosion	(9) Pitted, Stained Surfaces, Corrosion	(11) Fretting Corrosion	(13) Nicks, Dents and Score Marks	(16) Cavitation gouging of surfaces
B) Shock load		Can cause fatigue damage to a surface subjected to repeated loading					
D) Vibration					Welding, shearing and subsequent oxidation can occur; ex. splines		
F) Deficient lubrication	Inadequate film strength may result in metal-to-metal sliding contact			Corrosive agents and oxidized products can attack surfaces	May allow metal-to-metal contact		
C) Misalignment	May prevent localized film separation				Can contribute to fretting corrosion in splines		
H) Incomplete sealing			Metal contamination can cause abrasive wear; also erosion of surfaces from flow of lubricant	Can allow corrosion from contaminants including water			
P) Destructive operating environment			Products of internal combustion such as carbon, sulfides will damage surfaces	Combustion products will form acids which attack surfaces			Below atmos. pressures will cause oil bubble collapse and impingement
M) High environmental temperatures	May prevent adequate film strength and cause oil breakdown			Will increase chemical activity of products in lubricant and from combustion			
I) Manufacturing and material deficiencies	Improper surface finish may prevent film separation	Material may have inadequate strength to resist fatigue cracking					
J) Incorrect design	Surface geometry may prevent adequate lube. film development	System may not have sufficient strength to withstand shock load					System should be designed to prevent cavitation conditions
L) Improper handling						Abuse and mis-handling can cause damage	

Table 2. Roller Bearing Failure Modes

	(1) Roller and Raceway Spalling	(2) Spalling at Roller and Raceway Edge of Contact	(3) Extensive Glazing, Frosting, Microspalling of Stressed Surfaces	(4) Heavy Smear Tracks and Discoloration on Raceways and Rollers	(5) Oblong Dents and Flat Spots on Rollers and Raceways Brinnelling	(6) Pattern of Oblong Scuff and Fret Marks on Raceways False Brinnelling	(7) Heavy Cage Wear and Breakage
A) Heavy, prolonged load	May greatly accelerate fatigue damage		May cause a break through of a thin film		Load exceeds static capacity		
B) Shock load					May cause permanent denting		
C) Misalignment		Heavy edge loading will greatly increase contact stresses	Can cause film breakdown at edges	Can cause sliding and skewing of rollers			Can impose damaging loads on cage
D) Vibration						May occur with int. clr. and poor film damping	
E) Very light load				Insufficient traction can cause roller skidding			
F) Inadequate or poor quality lubricant			Can cause a loss of film strength with metal-to-metal contact	Rollers may not slide on film of oil			May not have film separation on land riding surface
G) Excessive speed	Increase in stress cycles which accelerates fatiguing of surfaces			Increases the tendency to skid with light load			Land guided cage required to withstand centrifugal forces
H) Incomplete sealing							
I) Manufacturing or material deficiencies	Soft metal, bad grain flow and size can increase fatigue likelihood		Poor surface finish can cause surface distress				
J) Incorrect bearing design	Insufficient load carrying capacity can cause fatigue damage	May result from an inadequate crown on rollers and raceways		Too much internal play can contribute to skidding	Inadequate capacity to resist brinnelling		
K) Improper mounting							
L) Improper handling							
M) High environmental temperatures			May cause lube breakdown with loss of film strength				
N) Presence of electric currents							

Table 2 continued. Roller Bearing Failure Modes

	(14) Excessive Tapered Roller End Wear at the Cone Rib	(8) Roughened, Microdented Surfaces with Increased Internal Play, Abrasion	(9) Pits, Stains on Raceways and Rollers, Corrosion	(10) Thermal Growth, Discoloration and Seizure of Bearing Burnout	(11) Bands of Rust, Discoloration + Glazing of Fitted Surfaces, Fretting	(12) Crack Formation on Rings and Rollers	(13) Nicks, Dents and Score Marks on Bearings
A) Heavy, prolonged load							
B) Shock load						Can occur with thru-hardened steels	
C) Misalignment							
D) Vibration							
E) Very light load							
F) Inadequate or poor quality lubricant	Can cause metal-to-metal sliding contact		Damage may be caused by corrosive agents and oxidized products in oil	Inadequate heat removal capability			
G) Excessive speed				Can increase heat generation			
R) Incomplete sealing		Metal contamination may cause abrasive damage to surfaces	Corrosive agents such as water may destroy surfaces				
I) Manufacturing or material deficiencies						Improper heat treat can cause cracking	
J) Incorrect bearing design	An incorrectly specified fitup to control end play or preload						
K) Improper mounting	Incorrect fitup can increase roller end load				A loose fit may cause creep and fretting corrosion	Too tight a fit may cause ring cracking	
L) Improper handling							Abuse and rough handling may result in damage
M) High environmental temperatures				Prevents adequate heat removal from bearing			
N) Presence of electric currents			Electric current may cause extensive pitting of surfaces				

Table 3. Gear Failure Modes

	(1) Spalling of Tooth Surface	(15) Scoring Lines in Direction of Sliding	(16) Fatigue Fracture of Tooth with Focal Pt. and Contour Lines	(17) Fracture of Corner Tip of Tooth	(18) Crack Formation on Gear	(19) Crushing and Distortion Inward of the Case
A) Heavy, prolonged load	Increased contact stress promotes fatigue					
B) Shock load			May exceed bending stress limit			May damage case if severe enough
C) Misalignment	Can increase probability of fatigue damage			Can cause very heavy localized bending stress		
F) Deficient lubrication		Inadequate film strength may result in metal-metal sliding contact				
H) Incomplete sealing						
I) Manufacturing and material deficiencies	Soft metal, bad grain flow and size can cause spalling out of the surfaces	A rough surface finish may result in lack of film separation			Can result from bad heat treatment	Damage due to too thin a case and too soft a core
J) Incorrect gear design	Poor gear geometry may result in high stress levels		Bending stress may be insufficient for operating conditions			Required case depth may be insufficient
L) Improper handling						
K) Improper mounting		Inadequate backlash can cause gears to run hot		Can result in a misaligned gear		
M) High environmental temperatures		May result in lubricant film breakdown				

Table 3 continued. Gear Failure Modes

	(20) Rolling, Peening with Rippling and Ridging Lines on the Teeth	(8) Roughened, Micro-dented Surface with Increased Backlash Abrasion	(9) Pits, Stains on Tooth Surface Corrosion	(10) Thermal Growth Discoloration and Softening of the Gear	(13) Nicks, Dents, Score Marks
A) Heavy, prolonged load	May produce plastic flow				
B) Shock load					
C) Misalignment	Possible localized plastic flow				
F) Deficient lubrication			Corrosive agents and oxidized products in can attack surfaces	May have inadequate heat removal capability	
H) Incomplete sealing		Metal contaminants can cause abrasive wear of teeth	Corrosion due to contaminants such as water can destroy surfaces		
I) Manufacturing and material deficiencies					
J) Incorrect gear design					
L) Improper handling					Abuse and mishandling may cause damage
K) Improper mounting					
M) High environmental temperatures				May prevent sufficient heat removal	

Table 4. Ball Bearing Failure Modes

	(1) Ball + Raceway Spalling	(2) Peening + Spalling at Race Shoulder	(3) Extensive Glazing, Frosting, Micro-spalling of Stressed Surfaces	(4) Heavy Smear Tracks and Discoloration on Raceways and Balls	(5) Oblong Dents and Flat Spots on Balls and Raceways Brinnelling	(6) Pattern of Oblong Scuff and Fret Marks on Raceways False Brinnelling	(7) Heavy Cage Wear and Breakage
A) Heavy, prolonged load	Heavy load can increase incidence of fatigue damage	Very heavy thrust load can cause ball to ride over shoulder	A heavy load may cause a break through of a thin film		Permanent deformations may occur if load exceeds static capacity		
B) Shock load					Can cause permanent denting		
C) Misalignment	May impose heavier loads	Wear track may run close to shoulder					Can impose heavy loads on cage pockets and land riding surfaces
D) Vibration						May cause damage when there is a lot of play and poor film damping	
E) Very light load				Insufficient tractive force can cause ball skidding			
F) Inadequate lubrication or poor quality lubricant			May result in lack of film separation of contacting surfaces	When balls skid they may not slide on a film of oil			May prevent film separation of land riding surfaces
G) Excessive speed	Will increase stress cycles which accelerates fatiguing of surfaces			Increases the tendency to skid with light load			Cage must be balanced and land guided to withstand centrifugal forces
H) Incomplete sealing							
I) Manufacturing or material inadequacies	Soft metal, bad grain flow or size can cause spalling out of the surfaces		A rough surface finish may prevent film separation of the surfaces				
J) Incorrect design	Inadequate load carrying capacity can increase fatigue damage	Shoulder height may be inadequate for load conditions		Too much internal play can contribute to skidding	Inadequate static load capacity		Cage may have inadequate strength for operating conditions
K) Improper mounting							
L) Improper handling							
M) High environmental temperatures			May cause lubricant breakdown				
N) Presence of electric currents							

Table 4 continued. Ball Bearing Failure Modes

	(8) Roughened, Micro-dented Surfaces with Increased Internal Play Abrasion	(9) Pits and Stains on Raceways and Balls Corrosion	(10) Thermal Growth, Discoloration and Seizure of Bearing Burnout	(11) Bands of Rust, Discoloration + Some Glazing on Fitted Surfaces Fretting	(12) Crack Formation on Rings and Balls	(13) Nicks, Dents and Score Marks on Bearing
A) Heavy, prolonged load						
B) Shock load					Can cause cracking with thru-hardened steels	
C) Misalignment						
D) Vibration						
E) Very light load						
F) Inadequate lubrication or poor quality lubricant		Can result in corrosive and oxidized products attacking surfaces	Inadequate heat removal capability			
G) Excessive speed			Can greatly increase heat generation			
H) Incomplete sealing	Metal contamination may cause abrasive damage to contacting surfaces	Corrosive agents such as water can destroy surfaces				
I) Manufacturing or material inadequacies					Improper heat treat can cause cracking	
J) Incorrect design						
K) Improper mounting				Too loose a fit can cause creep and fretting corrosion	Too tight a fit may cause cracking	
L) Improper handling						Abuse and rough handling may result in damage which shortens life
M) High environmental temperatures			Prevents adequate heat removal from bearing			
N) Presence of electric currents		Electric current may cause extensive pitting of surface				

DISCUSSION

C. R. Garbett, Shell Development Company: Did you carry out any studies in relation to journal-type bearings? I should think that would be of interest in nuclear submarines. It is certainly of interest to us in a lot of our industrial turbine compressor equipment.

P. B. Senholzi: All we consider right now are ball bearings and roller bearings.

T. Tauber, Tedeco: In addition to oil samples, do you look at sediment in the test rigs, transmissions, or gear boxes?

P. B. Senholzi: Our test rigs are built to have "no sediment." The oil sumps were funnel shaped. The pump was located at the bottom of the funnel. So supposedly, there was nowhere that particles could get trapped. Even so, there were a lot of particles in the beginning but they seemed to peter out and go somewhere. We do have all the oil that we saved from machines and that which was washed out from the sumps. We have two gallons of oil from each of 28 systems, and we are going to look at what is left.

T. Tauber: Can you also describe your sampling technique?

P. B. Senholzi: The technique for the bearings utilized a syringe-type sampler that was injected in the top of the funnel. We withdrew oil samples just before it went into the pump.

T. Tauber: Was this after shutoff?

P. B. Senholzi: No, this is while the machine is on. It had a port in the top of the cylinder.

T. Tauber: You mentioned the formation of gels due to the use of plastics in the sampling bottles. What kinds of materials were subject to that in addition to Tygon?

P. B. Senholzi: Polypropylene was the other one we tested, because that was what the bottles were made of, and a lot of the seals on the caps of oil sampling bottles were made of the same polypropylene or Tygon.

T. Tauber: Basically it does not interfere with SOAP analysis. That is probably why nobody has picked it up.

P. B. Senholzi: The particles agglomerate in this plastic gel and act as one big particle and fall to the bottom. They wouldn't be picked up in SOAP analysis if they were laying on the bottom of the bottle. Because SOAP does not agitate the particles to any great extent, the mixture is not homogeneous.

S. Pinel, Industrial Tectonics, Inc.: Would you describe the filtration process for your test rig?

P. B. Senholzi: There was no filter.

S. Pinel: You mentioned that the low number of particles contributed to the long life of your system. Could you expand on that a minute?

P. B. Senholzi: Well, before we ran any bearing we kept flushing the system and making ferrograms of the flushing solution to see how many particles were there. We didn't start until the system was thoroughly clean. There weren't any particles in the system, above and beyond those generated by the ball bearings themselves. Since there were Teflon impellers in the pumps, anything the pump would generate we would be able to see as a Teflon particle as opposed to a metal particle. There wasn't anything initially to dent the races, and this is what contributed to the long life.

R. J. Salvinski, TRW Systems Group: There are some theories that suggest that surface energy of the medium may have an effect on wear particle size. Does wetability have any significance in your work?

P. B. Senholzi: We didn't consider that effect at all.

G. J. Philips, Naval Ship Research and Development Center: You mentioned you put two defects on the inner race of the bearing. One ended as a fatigue spall. What happened to the other?

P. B. Senholzi: We did this on 14 bearings and a good percentage of the 14 spalled at one of the indents. The other defects ended with the leading end normal and the lagging end extruded.

G. J. Philips: At what point did you dent the bearings? How long did the bearings last with the dents in them?

P. B. Senholzi: They lasted about 200 million revolutions on the average. We ran bearings without dents up to 250-300 million revolutions without failure. We put dents in them and they failed within a matter of maybe 30 million revolutions. Some of the new ones that we put dents in lasted over 200 million revolutions, so it seems a new bearing is less vulnerable to a dent in the race than a bearing that has already been run.

T. Tauber: Did you have a full design load on these bearings?

P. B. Senholzi: They were overloaded to the extent that we couldn't get them to fail to begin with so we kept raising the load and the RPMs. We got these 6309 bearings up to 9700 RPMs and we still couldn't get them to fail even in a high speed condition. We had started them at 2700 RPMs.

J. W. Forest, Ontario Hydro: It looks like your program has got a terrific byproduct - you keep the oil clean and go on forever.

P. B. Senholzi: If the oil is kept clean, one wear mode may be eliminated, but you still have other wear modes that may cause the bearing to fail.

U. Sela, Exxon Company, USA: We find much reluctance to get the system clean. Normally, operations people are happy having it 50 percent clean. Data to show that a clean system improves bearing life are very important.

P. B. Senholzi: We are looking at a whole program initiated by that result - the effect of the contaminants on the wear life of the component.

O. E. Compton, Northrop Corporation, Aircraft Division: Did you vary the temperature of the oil?

P. B. Senholzi: No, all constant temperature, constant load, constant speed.

DEVELOPMENT OF INSPECTION AND DIAGNOSTIC EQUIPMENT FOR MOTOR VEHICLE EQUIPMENT FOR MOTOR VEHICLE INSPECTION

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I. Program Overview and Philosophy

Motor Vehicle Inspection (MVI), as practiced in 34 of our States and territories, is primarily limited to those items which are easy to inspect and is a cursory examination of the most critical safety systems and degradation modes. Inspection equipment used in most inspections is not automated, is not necessarily suited for its intended use, and does not reduce defects on vehicles-in-use to the desired degree. To improve MVI, it is necessary to develop new equipment, which in addition to addressing the most safety critical defects, is thorough, comprehensive, objective, and has a high throughput. Automated equipment must include the essentials of control of the test sequence and automatic comparison of inspection equipment output to inspection criteria.

While automated inspection equipment can overcome most of the problems of existing inspection relative to items inspected and objectivity, most states will rely on private garage/gas station/dealership inspections for the foreseeable future. For this reason, there is a need to improve this basically manual form of inspection. The first step in this process is to recommend to the states only the most safety critical defects as the basis for MVI programs. The second step is to develop techniques, simple equipment and hand tools, and procedures to improve manual inspection.

Regardless of whether it is automated equipment or manual techniques and procedures, a deliberate development process must be followed. MVI has been pursued in the U. S. since 1926 in a variety of ways with as many different objectives. Thus, a review of past accomplishments must be made before proceeding to a solution. It is first necessary to identify and justify any existing MVI deficiencies and current needs to those, who through years of experience, have developed a reliance on existing techniques and equipment. This is not an easy task, but is necessary to either justify further research and development or to identify, evaluate, and verify the satisfactory existing approaches. The last twenty-five years have resulted in a large and varied generation of inspection equipment and techniques, and even a slight change in the area could neither be accomplished in a short time nor be accepted by the total following, regardless of the justification. Therefore, all conclusions and recommendations must be carefully supported and verified.

Once the current climate has been evaluated, development of inspection techniques and equipment may systematically proceed. Primary objectives will relate to suitability, accuracy, objectivity, etc. This will insure that the final product, if it can be developed, will not have the deficiencies of existing techniques and procedures. New techniques and equipment must be subjected to the rigorous evaluation that bore their need. Although this is not the final proof or justification, it stands as a major milestone to be satisfactorily completed. Perhaps the major evaluation measurement will be the practicality of the techniques or equipment in an MVI environment. Then the evaluation results will not only verify that a correctly identified problem is solved, but that the solution is not an "overkill".

Another constraint on the development of improved MVI techniques and equipment is the consumer related aspect of motor vehicle safety and MVI. The growth of engine diagnostic facilities has shown that consumers are interested in the performance condition of their vehicles. On the other hand, they are unsatisfied with the attempts to repair them. A goal of the program to develop MVI techniques and equipment is the proper identification of specific safety-critical vehicle subsystem degradation and vehicle repair needs in a rigorous manner that results in consumer satisfaction. It is in their interest that the identification of vehicle repair needs not only be correctly identified, but limited to only those subsystems or components specifically needing repair, replacement, or adjustment.

A final goal of MVI technique and equipment development is the overall streamlining and efficiency of the total MVI environment. Probably the most important considerations are equipment integration, inspection time, equipment cost, and operator skill level requirements. In the long run, the overall effectiveness of new techniques and equipment will have to be weighed against possible negative factors caused by the development of new inspection techniques and equipment for specific vehicle subsystems in separate development projects.

Research results in the areas of (1) the role of vehicle defects in accident causation and (2) the relationship of vehicle defects and degradation to vehicle performance degradation have determined the following vehicle systems as being safety critical in the priority listed:

a) Braking systems
b) Tires
c) Steering and suspension systems

Research to evaluate existing inspection techniques and equipment and to develop new techniques and equipment have been conducted in each of the three areas. Current and future research will also concentrate on these three systems.

II. Past and Current Research Activities

A. Automated Brake Inspection

The first effort to evaluate and develop inspection techniques and equipment began in June 1972, with a research project whose primary objective was to operationally demonstrate a cost-effective (in relation to other systems) brake inspection system that is capable of detecting and measuring safety critical defects and degradation of brake systems. The work performed in this project consisted of the following:

1) determination of present brake inspection methods,
2) development of a methodology for evaluating available brake inspection equipment,
3) evaluation of available brake system inspection methods and equipment,
4) design and construction of single-station inspection systems, and
5) physical verification of inspection system performance.

The developed brake inspection procedures had to be able to determine current brake system performance capabilities and to determine any defects or degradation existing in a particular brake system that would lead to near-future catastrophic failures or sub-level performance. The primary measures of brake performance considered to be important are effectiveness and stability. Vehicle brake system design and performance characteristics that greatly influence the vehicle braking performance are:

1) brake system gain,
2) brake system response,
3) brake force proportioning, front to rear,
4) brake force uniformity from side-to-side, and
5) friction material characteristics.

The above discussion concerns primarily brake defects and degradation leading to immediate changes in vehicle performance. Degradation leading to eventual catastrophic failures cannot always be detected in performance tests, therefore, inspection techniques complementary to performance tests must be utilized. Brake components which are subject to this type of degradation or deterioration are:

1) friction materials,
2) drum or rotors,
3) hydraulic system (leakage),
4) brake fluid (water contamination), and
5) actuation system (pedal reserve).

Project results have included the following:

1) Current brake inspection, as conducted in various States, involves the use of various combinations of three inspection techniques. These techniques are visual inspection, low speed road stopping test (20 mph), and low speed (5 mph) platform tester.

2) Visual inspection is the only state-of-the-art technique for detecting such items as worn friction materials, oversize drums, broken or missing parts, etc. However, these inspections tend to be very subjective.

3) The low speed road and platform tester stopping tests serve to show that the inspected brake system has the ability to stop the vehicle at low speeds and nothing more. These tests are manually controlled and the results are visually observed. This type of test and inspection control has inherent repeatability problems from test to test and from operator to operator.

4) The brake analyzer and brake dynamometer are also used in brake inspections. These machines use either electric motors or inertia weights to supply energy to the test vehicle brakes through a set of wheel rollers. All of these machines test either the front or rear axle set of brakes at a time, although one costly machine using inertia weights has the ability to test all four vehicle brakes at one time.

5) Test data analysis indicated the dynamic brake analyzer to be far superior to the platform tester in capability, repeatability, and sensitivity to vehicle brake performance levels. Also, higher energy levels to the vehicle brakes and continuous performance readouts are available. Platform brake testers give only an instantaneous low-speed readout of brake proportioning which is not usually repeatable. The platform test cannot indicate brake system gain and possesses a high brake force threshold.

6) The dynamic brake analyzer has proven itself capable of accurately detecting outages in vehicle brake system performance with good repeatability.

A visual inspection of the brake system for component condition combined with a dynamic brake test now appears to represent the most practical approach to brake inspection where high throughput is desired.

The above results, when combined with the results of other research to develop inspection items and criteria, resulted in the development of a specification for a dynamic brake tester. The brake tester has been built, evaluated, and will shortly be available for further, long-term evaluation. The most significant features of the machine are:

a) low speed - high force capabilities,
b) automated input control, and
c) automated printout and defect decision making in the dynamic mode.

B. Shock Absorber Inspection

A research project was initiated in June 1973, whose objectives were:

1) Through analysis, an extensive literature review, and a shock absorber survey, determine the important shock absorber parameters with respect to safety and the range of these parameters in the passenger vehicle shock absorber population.

2) Physically test each type of shock absorber test machine that is available and determine its effectiveness with respect to the above safety critical shock absorber parameters.

3) Recommend an approach and equipment for shock absorber inspection that includes the appropriate features of the evaluated equipment.

The contract has been completed with the basic finding that no existing shock absorber inspection equipment is suitable for state MVI use. The deficiencies range from inappropriate tests to lack of capacity. A common deficiency is that vehicle performance with original equipment shock absorbers must be known.

A recommendation for new equipment development was made which is based on the fact that the primary shock absorber failure mode is loss of fluid and that shock absorbers with low fluid levels result in aerated fluid when exercised. The inspection philosophy then, would be to design a machine which would exercise the wheel, spring, shock absorber, and suspension system at various frequencies (or a frequency sweep) at a fixed amplitude and would compare system damping at the start of the test to later in the test. If the fluid level is low, it will aerate and the damping will change. What is particularly desirable about this approach is that no new-vehicle information is needed.

C. Tire Inspection

A research effort is currently underway to develop a means of inspecting tires for inflation pressure, tread depth, and carcass integrity on an automated basis. The basis for the carcass integrity inspection is that carcass flaws (separations, chunking, delaminations, voids, etc.) disrupt one of the symmetric modes of tire vibration. An exciter is placed at the center of the tread with one pick-up on each sidewall. The system is tuned to a symmetric resonance mode about 400 Hz and the tire rotated and examined for defects by observations of the change in resonance amplitude and frequency. This research is covered extensively in the paper "Resonance Tire Inspection for Motor Vehicle Inspection" given at this symposium and will not be covered further here.

D. Brake Component Inspection

In the previous section on brake dynamometer development it was stated that a visual inspection of brake condition is required as a supplement to the performance test of a brake dynamometer. However, a visual inspection of brake condition is time consuming and inappropriate in a high throughput, automated inspection. Therefore, a research effort was begun in June 1974, to develop a "static" brake inspection technique, equipment, and procedures to perform an inspection of brake components without wheel removal. The objectives of the project are:

1) Conduct a systematic state-of-the-art survey into existing static brake inspection systems, proposed designs, inspection criteria,

techniques, and related literature.

2) Determine basic performance objectives of static brake inspection systems, alternatives, evaluation criteria/weighting requirements, test methodology for evaluation of alternatives, and preliminary analysis of potential approaches.

3) Analyze and evaluate the more promising approaches and determine the optimum static brake inspection system.

4) Construct and evaluate two prototype static brake inspection systems based on related useable portions of the evaluated equipment and/or new design requirements as needed, and develop the related inspection criteria and techniques.

5) Demonstrate and verify both the operational capabilities of the equipment and the validity of the inspection criteria and techniques to detect and assess the condition of automotive braking systems in the static state.

This project is still in process but some results are available. It was hoped that a technique such as ultrasonics could be used to determine brake lining thickness in drum brakes by placing a transducer on the drum directed radially inward toward the lining. It was also hoped that similar advanced techniques could be used for the inspection of other brake components. It appears, however, that the most promising approach is a modification of the braking system to facilitate the use of mirrors, fiberoptics, etc., in viewing the components; and component modifications which indicate when wear limits are reached. An example of the latter area would be a blind hole drilled in the friction surface of a brake disc that would be worn away when the disc wear limit is reached. The only state-of-the-art technique which appears to have application is the use of gas chromotography for detecting brake fluid leakage.

III. Future Research Activities

Since most state MVI programs will use low throughput private garages, gas stations, and dealerships for the inspecting authority, it is appropriate and essential that techniques, procedures, and equipment for this type of program be developed. In some cases the equipment developed for automated inspection can be simplified for such use.

During the second quarter of calendar year 1975, two research projects will be initiated to respectively develop manual brake inspection techniques and to determine the requirements and state-of-the-art of on-board vehicle sensors. The latter effort is being conducted to indicate to vehicle manufacturers our interests in this area. On-board sensors are viewed as a complement to MVI in terms of both easing the inspection task and providing real-time safety critical outage information to the driver.

The objectives of the manual brake inspection research are to systematically investigate, develop, and verify objective, manual inspection criteria (replacement) techniques, procedures, and equipment aids to replace 1) dynamic brake testing and 2) existing subjective brake inspection procedures. Results from this project are expected by the end of 1976.

The objectives of the on-board sensor research are to assess the state-of-the-art and potential areas of future development of on-board vehicle sensors and to derive the applicability of on-board vehicle sensors to brakes, steering, suspension, tire, lighting, and signaling systems. Results from this project are expected in mid-1976.

In the near future (FY 1976-77), research will focus on developing or improving manual inspection techniques for the remaining vehicle systems requiring inspection. This effort will be keyed at increasing the effectiveness of MVI when implemented by licensed private garages, gas stations, and dealerships. A minimum amount of low-cost equipment aids will be developed and combined with refined and objective inspection criteria. This will improve test accuracy and acceptance at both the inspector and consumer levels.

In the years FY 1977-80, research will focus on developing automated, high throughput inspection equipment for passenger car steering and suspension systems. Work on identifying or developing inspection techniques for trucks, buses, and motorcycles will begin in the same time period. It is difficult at this time to envision the results of this effort since an MVI program for these vehicles has not been developed. One possible approach might be self inspection by fleets combined with sampling or random inspection by State authorities.

IV. Diagnostic Equipment Development

A philosophy of the research to date is that diagnostic capabilities are included in inspection techniques and equipment if their inclusion does not significantly increase the time/cost of inspection. In other words, the primary determination of these techniques are go-no go decisions. Of course, many inspections are basically diagnostic in nature, such as the inspection of brake components. However, performance tests tend not to be diagnostic. For example, steering system lash inspection is not diagnostic.

The 1974 amendments to Title III of the "Motor Vehicle Information and Cost Savings Act," P.L. 92-513, require the Department of Transportation to conduct demonstration projects that will aid in the development and evaluation of advanced inspection, analysis, and diagnostic equipment. An assessment of the capabilities of small repair garages is also included in the requirements. In order to satisfy the provisions of the act, as amended, a research program should be conducted to develop the advanced equipment. The primary reason for this is that existing equipment is not compatible with the high throughput, mass diagnosis intent of the demonstrations and the Act. Existing equipment is designed for use by garages, dealerships, and diagnostic centers with low or, at most, medium throughput. Medium throughput can only be obtained with a labor intensive operation which increases the cost of inspection and diagnosis radically. As an example, using today's equipment for mass inspection results in an estimated 82 percent of total costs for labor and labor overhead and 7 percent of total costs for equipment.

It is also known that existing equipment is not objective, complete, nor accurate. Certain types of equipment provide a measurement means but interpretation is left to the diagnostician. Other types of equipment make inappropriate tests or tests limited in range. Furthermore, the lack of automation means that vehicle specifications applicable to specific tests must be listed in reference books or sheets and used for each test or diagnosis.

Research is needed, therefore, to develop advanced inspection, analysis, and diagnostics equipment. This equipment must be thorough, accurate, complete, objective, reliable, and allow for high throughput, non-labor intensive vehicle inspection and diagnosis. In this way the spirit and letter of P.L. 92-513 will be met, and the basis will exist for effective demonstrations of an advanced approach to the diagnosis and repair problem.

DISCUSSION

R. W. Adamson, California Polytechnic State University: We started out our meeting this morning in connection with determining the effectiveness of any test program. Are studies being made to come up with the data that would permit you to know where the problem areas are?

L. H. Emery: Yes, there are 10 to 15 extensive accident investigation programs under way throughout the United States where trained accident investigation teams try to determine the causes of accidents; i.e., whether they were due to a component failure, driver error, or environment. Also there have been extensive research programs to determine the safety status of the nation's vehicles. The results of these programs indicate that approximately 5 to 7 percent of the accidents are either caused by or influenced by component degradation and catastrophic failure.

J. K. O'Connor, Consumer Product Safety Commission: You said that the shock absorber test was not going to depend on new vehicle performance, but simply on a change of performance between the beginning of the test and the end of the test. Then I thought you said that's predicated on partially filled shock absorbers and the oil aerated. Suppose you had no shock absorbers and just had the mass damping of the system, then would you get a change?

L. H. Emery: No. We conducted a research program to look at the major modes of shock absorber degradation and to look at the existing shock absorber inspection equipment, the majority of which is produced and used in Europe. It was determined that 99 percent of the shock absorber failures are due to loss of fluid. We discovered that the technique used by one of the existing inspection machines in Europe is able to detect a loss of fluid due to a change in dampening as the shock absorber is exercised. The loss of fluid encourages a quick aeration of the fluid and dampening is lost. We think that loss of fluid in shock absorbers is the thing to look for in a shock absorber inspection machine, and there is an existing technique. However, there are no existing machines suitable for MVI use.

J. K. O'Connor: If you lost all the fluid you wouldn't get the change.

L. H. Emery: That's true but, it would be obvious that the car didn't have any dampening.

O. E. Compton, Northrop Corporation, Aircraft Division: Is a loss of fluid recognizable by a visual means - by looking at a shock absorber itself - or do you need a piece of diagnostic equipment?

L. H. Emery: I don't know that it is always recognizable. In any case, for a high through-put type of inspection it is desirable to minimize the labor involved. I am not recommending my machine over a visual inspection. Our objective was to look at the problem and develop some technology.

ON VEHICLE MOBILITY MEASUREMENT & RECORDING SYSTEM

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ABSTRACT

A prime long term goal of the U. S. Army is to field maintenance-oriented diagnostic equipment which will improve the reliability and reduce the cost associated with keeping vehicles operational. An important part of making diagnostic equipment viable is the establishment of base-line levels on a well operating vehicle so an adequate automatic judgement of the operational status of a vehicle under test can be made. This paper describes an on-going U. S. Army Tank Automotive Command, Maintenance/ Product Assurance Directorate program directed at establishing such levels for the M35 (Figure 1). The program uses technology previously developed for the M151 vehicle. The current work involves instrumenting an M35A2, 2-1/2 Ton Truck with on-board transducers, signal processing, and tape recording equipment, and running the vehicle 20,000 miles with various "seeded" and "unseeded" components in both idle and running modes. The data will be computer analyzed to establish "good" and "bad" levels for diagnostic reference purposes. In addition to the actual measurements made and the test program outline, the needs and objectives of the user--the Maintenance Directorate of TACOM--will be discussed in terms of how the current program relates to the general diagnostic goals of the Army.

INTRODUCTION

Modern maintenance procedures make use of sophisticated instrumentation in order to analyze vehicle performance for indications of component failure, imminent failure, or need for adjustment. Often this analysis is conducted with the vehicle idling in a maintenance facility. Since it is desirable to minimize repair time, analysis time requirements are minimized. The resulting situation is one of sometimes performing a brief, indoor idle test in order to assess the integrity of a heavy duty vehicle designed for extended use in severe environment. In order to define or refine appropriate maintenance analysis procedures and failure indicating threshold levels, supportive operational base-line data is required to correlate the brief idle test data with mobility data obtained over a wide variety of operating situations representative of the vehicle's full design environment.

The mobility testing a vehicle undergoes during the preproduction and production phases of its life-cycle is used to validate the vehicle's performance capability. It is important to know during this testing, whether a particular vehicle was subject to under-testing, over-testing, or the testing desired because the ability of a vehicle to pass its performance tests depends on how well the stresses generated during testing correlate with the stresses estimated during the vehicle design phase.

The above types of information, if available, can help maintenance people who are responsible for keeping vehicles operational, quality assurance personnel responsible for vehicle test implementation, and engineering personnel responsible for vehicle design. Ultimately quantized mobility information from vehicle performance tests will help insure optimal vehicle cost, life, and service.

A system (MO/MARS) has been developed for a data gathering and reduction system which will allow efficient generation and analysis of data for the above applications. This MO/MARS is centered around a small, rugged instrumentation and recording system mounted on-board the vehicle under test (Figure 2). The system operates unattended for prolonged periods of time in the vehicle operational environment. The data acquired is stored on tape in the vehicle until it can be carried to an off-board playback and reduction station. In order to reduce data storage requirements as well as data reduction time, data is not stored continuously. As an integral element of the on-board system, a data processor analyzes critical data for deviations from normal conditions or changes of state. When a deviation or change occurs, a recording trigger is generated which causes a complete scan or sample of each channel to be recorded in a digital format on magnetic tape. In the event that one of these triggers does not occur in five minutes, a trigger is generated so that "normal" performance is recorded. After tape completion, it is removed and taken to a data reduction center for detailed analysis and correlation on a commercial computer.

TECHNICAL DISCUSSION

The MO/MARS concept was implemented with a composite of off-the-shelf and custom hardware constructed as a network of subsystems. Individual subsystems must operate under varying constraints depending on their function, their physical location, and their relationship to other subsystems. One of the more varied requirements is that imposed by the local environment. Transducers are fully exposed to rain, mud, snow, and ice as provided by nature as well as vehicle dynamics (e.g., splashing and submersion). The remainder of the on-board equipment is protected from direct effects by an environmental case shown in Figure 3 with the front cover removed. Mild shock and vibration as well as temperature extremes must still be accommodated. Off-board systems are housed in the usual temperature and humidity-controlled computer environment. Details of the transduction scheme and processing electronics are presented in the following sections.

Transducers

The various transducers used to monitor the parameters, listed in Table 1, are subjected to the most severe environment. In general, transducers are exposed to local shock, water, electrical noise, temperature, and solid impediments encountered on the test course. As a result, all transducers operate over wide temperature ranges with minimal error. Transducers mounted beneath the vehicle body are waterproof, while those above the body are splashproof. In order to reduce the effects of electrical noise, all outputs are high level (±1 V, typical) and low impedance (1Ω, typical). Modest shock/vibration tolerance as well as physical ruggedness are included as well. The following subsections discuss individual transducer groups.

Pressure Transduction

The Robinson-Halpern pressure transducers selected use LVDT's. They were selected for their good record of transduction for TACOM and railroad locomotive pressure monitoring. They also have a military prescribed calculated failure rate of 0.34 failures per million hours. Their rugged construction has been qualified to specifications MIL-S-901 for high impact shock and MIL-STD-167 for vibration. The housing meets weatherproof and water-proof Class IV NEMA standards and is designed for Class I, Division 1, Group D explosion-proof service. Operating temperature range is: -65°F to $> +165^\circ$F. These pressure transducers have quoted accuracy capability to 0.15%.

MO/MARS recordable accuracy is dependent on the pressure monitoring points. For example, differential pressure across an oil filter is measured as close to the inlet and outlet ports of the filter as is practicable to eliminate the influence of pressure drops or turbulence in associated components such as hoses. The selection of sensing points was based on these considerations as well as those of accessibility, ease of calibration, and protection from damage. Specific locations of the various pressure monitoring points are given in Table 1.

All five transducers are mounted on a contoured plate, shown in Figure 4, which in turn is mounted on the left engine compartment, side cover. In this location, the transducers are protected from physical damage and extreme temperature as well as being accessible for bleeding and calibration. Transducers are connected to pressure monitoring points by various adapters, fittings, and hoses. The hoses used on the project have a working pressure rating of 500 psi, a temperature rating of 300°F and are compounded of oil and fuel resistant synthetic rubber. Wherever possible, suitable commercial fittings are used. Specially designed fittings are as simple as possible and made to interface commercial fittings.

Temperature Transduction

The selection of temperature monitoring points is of utmost importance.

Temperature sensors are located so they are always submerged or surrounded by fluid which is not stagnant, and monitor the fluid at a known, critical point. This can be illustrated by considering the measurement of coolant and oil temperatures. Coolers are used in both circuits, and maximum or minimum temperatures of the circulating fluid could be measured and related to normal operating temperatures. However, an analysis of the relationship between the measured variable and the overall system results in the best choice of sensing points. The main purpose of the engine coolant is to maintain cylinder wall temperatures well below 500°F to prevent overheating and breakdown of the piston-cylinder lubrication film. The system sensitivity to overheating is greater at the inlet port. For the oil circuit, the same reasoning applies. In addition, the temperature of the oil is critical. Below 200°F, a properly refined oil will not oxidize excessively, but oxidation becomes appreciable above 250°F. Therefore, knowing the maximum oil temperature is of value, and the sensor is located at the inlet to the cooler.

All temperature measurement was accomplished with a GARD-developed transducer. It is an operational amplifier-augmented resistive bridge with one active element. The active element is a platinum resistance bulb.

A precision reference voltage is derived from a temperature-compensated zener diode. The circuit output is approximately ±1 V @ 0.1Ω for 0°F to 300°F. The circuit itself is also designed to operate over the full temperature range. Typically, output voltage error due to circuit temperature was found to be within 0.3°F over the range 0°F to 300°F. The circuit is constructed on a 1.0" x 1.2" printed circuit board and housed in a cylindrical, stainless steel case. Typical of this transducer installation is that for transmission oil temperature shown in Figure 5.

Speed Transduction, Clutch Slip, Odometer Transduction Consideration

The speed transduction design has evolved from a sequence of theoretical considerations and on-board experimental tests. It was decided that speed would be measured by counting gear teeth per unit time. Some of the initial design considerations were tachometers, encoders, electronic gear tooth counters, or electro-mechanical counters possibly driven by adaptive gearing or pulley systems. Electronic gear tooth counters were found to be satisfactory in the M151A2 MO/MARS. Gears on the truck were found for indicating the respective speeds with minimal retrofitting.

On-board examinations of axle and gear structures corroborated by TACOM-supplied vehicle drawings showed that the electronic gear tooth counters could be satisfactorily applied for all required speed transduction. Vehicle speed is monitored by counting teeth of the rear axle ring gear. Engine rpm is measured by counting fly wheel ring gear teeth. Clutch slippage is a measurement that compares shaft speed at the input of the clutch to that at the clutch output. Since shaft speed at the clutch input is already derived by the engine rpm transducer, it is only necessary to monitor clutch output speed for the comparative measurement. A transmission gear was selected whose speed relative to the engine is invariant with transmission gear selection including neutral.

Experience with the M151A2 MO/MARS indicated that a time varying magnetic flux density change (dB/dt) sensitive transducer works well with magnetically permeable material, such as steel, which is used for all gears monitored. Experience and specifications indicated that gapping and alignment problems would be minimal with this transducer.

An Electro, 5/8" diameter, digital magnetic transducer was selected for speed transduction. The probe is modified mechanically to facilitate mounting and adjustment, and a standard JT connector was added. Mounting and adjustment is accomplished by screwing the transducer body into an appropriately tapped hole and securing it with a locking nut. For engine speed, a probe monitors gear teeth through a modified inspection port on the flywheel housing (Figure 6). The transmission gear is monitored from an accessory plate on the side of the transmission housing. The rear axle ring gear is monitored from a top inspection plate on the rear axle housing.

Battery Voltage Transduction

The magnitude of the battery voltage is indicative of the condition or well-being of the electrical system. Further, the condition or identification of electrical equipment or accessories may be determined from a monitor's indication of their effect on battery voltage.

The transduction accuracy or reliability could be affected by the choice of sensing point. Transient or steady state currents from electrical equipment, if allowed to flow through the measurement circuit, could grossly affect the monitor's reliability. Thus, the transducer is electrically tied directly to the battery posts with twisted pair wires to eliminate electromagnetic interference, thereby obtaining the most minimal path possible for interfering currents in the measurement circuit.

Battery voltage is monitored by a GARD-designed instrumentation type input circuit. Tests of the characteristics of the voltage have shown that spikes due to inductive switching and ripple due to generator charging will be present and must be contended with. A combination of low pass filters and surge protectors protect monitoring electronics from transient destruction while accurately measuring battery voltage.

Time/Date Transduction

To facilitate a time correlation of data, a precision reference oscillator is used to generate time of day and date information in digital accumulators. The accumulators are kept in the self-powered monitor, thus time is kept continually beginning with time zero at the start of the test program. The time accumulator is quite similar to an electronic wristwatch. Low power, CMOS family of digital logic is implemented in the monitor. Time of day is recorded as elapsed time since midnight in hours, minutes, and seconds. Date is recorded in a Julian-like calendar form as day of year.

Elapsed time is also sensed for recorder triggers. That is, if 5 minutes, ±1/2 minute, has elapsed since a recorder trigger, the recorder accumulates a data record.

Tape Status

MO/MARS is designed to be a self-initializing and sustaining system requiring minimal interaction from operator or test supervisor. However, because of the finite data capacity of the magnetic tape and the desire to accumulate all meaningful data, the tape supply will require periodic refreshing.

An aid for evaluating tape supply is the tape status indicator. The tape status indicator signals the driver when the tape has reached a predetermined data capacity short of full. The capacity level for signalling refresh is internally programmable from 75% to 90%, with a final value best determined empirically.

Data Handling

All on-board data processing and recording is handled by a network of processing elements shown in Figures 7, 8. The processor assembly is the principal control operating the recorder and accessing the monitor as required. It contains analog signal processing, digital signal processing, monitor interfacing, and recorder control. The monitor is unique in MO/MARS since it has a self-contained source of power, i.e., its battery. In combination with low-power CMOS logic, extended operation is possible independent of the vehicle electrical system. Thus, the monitor is capable of generating and/or storing long term data, typically date, time-of-day, distance (odometer), and recorder tape supply status. It also uses the vehicle accessory switch to sequence MO/MARS on when the vehicle is running. The recorder is charged with recording data on magnetic tape which will eventually be removed from the vehicle for data reduction. Analog data channels interface directly with the recorder which contains a signal multiplexer and an analog-to-digital converter both under program control. The recorder also contains a wide variety of operational clocks ranging in frequency from 1 MHz to 0.028 MHz which are brought out for use in the processor. A controller within the recorder coordinates all functions (internal and external) including the actual writing of magnetic tape and electro-mechanical control of the tape transport. Also contained in the processor, is the clutch slippage detection and analysis circuitry. It operates in a separate mode independently of the other subsystems, although it is integrated with existing logic where compatible. Clutch slippage requirements are so demanding that the processor incorporates electronic FIFO memory to buffer data for recording and then record data in a unique, variable word-length pattern .

Trigger Detection

The triggering events which initiate recording are presented in Table 2.

Most triggers are derived by comparing a signal with some preset threshold level. The level is bounded by a hysteresis band to minimize repeated triggering when the signal level is relatively stable and at approximately the threshold value. Both analog and digital threshold plus hysteresis circuits are used. Analog circuits are implemented on the input/output (I/O) cards with integrated circuit comparators on analog voltage levels. Triggers derived in this manner include all differential pressures and temperature. Digital circuits are implemented with integrated circuit digital comparators and digital levels extended via DIP switches. Digital triggers are derived for speed, time, and clutch slippage. Each circuit (analog and digital), results in a trigger signal which is sent to a trigger handler. The trigger handler alerts the controller to initiate a recording cycle, then formats the trigger information for entry as data. The format includes identification of the triggering event as well as the status of all triggers. Since wheel speed can trigger multiple levels, the level-to-level transition resulting in a trigger is uniquely identified and recorded. Instantaneous clutch slippage data is recorded in a separate, distinct mode of operation.

Time/Date Processing

Both of these data are derived from a low-power oscillator operated as part of the monitor from the monitor battery. The oscillator will be counted down to 1 Hz with standard CMOS logic. The 1 Hz signal drives a "seconds" counter which presets at 59 seconds. The seconds counter reset also drives a minutes counter which resets at 59 minutes driving an hours counter limited to 23 hours. The hours reset drives the day or date counter which is programmably reset at 365 or 366 days. A higher frequency can be injected at any stage for the purpose of initializing the clocks under manual control.

Tape Status and Odometer Storage

The total number of records recorded on a tape will be used as a measure of tape available or tape used. Since it is anticipated that multiple operational periods will be stored on a given tape, it is necessary to keep track of tape status even when MO/MARS power is off. Since the monitor is always powered, it is appropriate to include some form of low-power memory within the monitor for maintaining the total-records count between MO/MARS operations. The odometer or distance record has similar data maintenance requirements and is also stored in the monitor.

Wheel Speed/Engine Speed

These speeds are measured by counting pulses in the pulse trains derived from sensing teeth on appropriate gears. These pulse trains enter through I/O modules which serve to filter noise, isolate the transducer lines from the processor network, and shift the signal to TTL logic levels. The logic level pulses are then counted for a programmable counting period. The number remaining in the counter at the end of a counting period is proportional to the average speed over the counting period. The number is recorded as a count and converted to engineering units during data reduction.

Clutch Slippage

The method of measuring clutch slippage involves detecting relative displacement of the two sides of the clutch. A nonrotating tooth sensor is mounted to sense the passing of teeth on each gear. Tooth counters are connected to each sensor. When the clutch is engaged and rotated, the gears are synchronized and the two counters count exactly together. When there is some form of partial disengagement present, the two gears do not rotate precisely together. They are said to slip. As a matter of convention, the transmission-side of the clutch is the reference. The procedure for measuring slippage consists of counting a fixed number of teeth on the transmission side and comparing the number of teeth counted on the engine side in the same time interval to that fixed number. For example, start both counters initially cleared at the same instant. When the transmission-side counter reaches 100, read the engine-side counter. If it too reads 100, there was no slip. If it reads 110, then the engine-side rotated 10 teeth more than the transmission side.

In studying clutch slippage, it seems desirable to detect not only the presence or absence of slippage, but nature of the slippage. Is it a smooth phenomena uniformly distributed over several revolutions? Or is it irregular, occurring in some non-uniform, perhaps discontinuous manner? To answer these questions, the data required must project high magnitude sensitivity, coupled with precise location. The only readily-varied parameter available is the number of teeth included in the reference. As the reference increases in size, sensitivity increases, but locational accuracy decreases. Decreasing the reference leads to better location, but less sensitivity.

The method chosen was to simultaneously measure slip with several different references.

The actual numbers of teeth available for counting are not as easily handled as those in the above discussion. The engine-side gear has 138 while the transmission side must be observed through a compound gear which appears to have 16.57 teeth. However, four distinct levels of reference equal approximately to 1/16 rev, 1 rev, 8 rev, and 64 rev are used. Triggers are based on bands about the no-slip reference for each level.

Four similar circuits for each level are implemented. The interaction of the four simultaneously operating circuits is quite complex and is not presented within this report. The four-level network forms a string of data which includes trigger level and trigger location with respect to the previous trigger. At no slip intervals, engine vehicle speeds are recorded as well as all the other normally measured parameters.

This amounts to a large amount of data relative to the recording rate of the recorder. Thus, it is necessary to use a buffer memory within the processor to permit data compaction and data speed averaging. A variable word length, self-identifying data stream is used to make the system compatible with the recorder.

Data Buffers

The data buffers are used to format data prior to entry into the recorder. All of the required digital data is shifted into the buffer from the various processing elements. After data is assembled in an appropriate form for recording, the recorder control is notified that the data is ready for transfer to the recorder. Then the recorder control transmits appropriate strobes to load the data through the recorder onto magnetic tape.

Controls

Each major group of elements has some control all under command of the main processor control. The monitor has adequate control to accomplish timing, clock up-dating, and vehicle status sensing. The recorder control sequences the tape transport on, sequences the signal multiplexer, generates appropriate control characters and coordinates the writing of digital and analog data on magnetic tape. The master controller within the processor coordinates the monitor and recorder through their respective controls in order to respond to triggers and process data.

Power System

All power used in the on-board system is taken from the vehicle's 24 VDC electrical system. Isolation from vehicle ground is achieved by converting the 24 VDC to standard 120 VAC which is easily transformer isolated. This DC to AC conversion was accomplished with a Topaz Model 250-GW static inverter. The AC voltage was used to power the recorder directly. Various precision DC voltages for transducers and the processor were produced in the Power Module shown in Figure 3. All DC voltages were produced with commercially available power supplies.

Data Recorder

The recorder used is a Metrodata Model 620A shown in Figure 3. The unit has been modified to record in both the digital and analog data input modes on all of its twenty channels. In the normal data mode, eleven channels from transducers are analog, and the remaining nine are direct digital from digital type transducers. The digital channels are formatted so that actually twenty-eight channels of unique data are available. The recorder also records all channels in direct digital in the instantaneous clutch slip and the compression balance modes. All recording is in a four-track binary coded decimal (BCD) format on 1/4 inch magnetic tape housed in an endless loop cartridge. Analog signals in the range of ±1 volt are fed to the recorder where they are internally analog to digital converted. The unit was chosen for its ruggedness and performs well. Recording time is dependent on the event oriented parameters measured. Nominally over fourteen thousand records are recordable which provides a capacity of weeks without requiring a fresh tape supply.

Data Reduction

The data was reduced at GARD on the GA 1830 computer. A metrodata model 622 tape reader was interfaced to the 1830 through the computer's I/O channel. It was controlled with an interrupt driver assembly language subroutine. The data reduction program was implemented with the GA 1830 Fortran IV subset. Magnetic tape cartridges recorded with the on-board system are read with the tape reader under computer control. As the raw data enters the computer for processing, it is stored on disk files for analysis. All data from tape is thereby directly accessible with normal Fortran mainline programs and subroutines. Raw data is converted to engineering units through the calibration data entered initially as case data. Conversion is done before processing to eliminate errors due to transduction non-linearity. Converted data is stored on a disk file for eventual use in tables. The maximum and minimum values of each parameter are determined in a straightforward manner. The averages, standard deviations and the maximum/minimum values for each parameter are printed as a data summary as shown in Figures 9, 10, & 11. Idle and operating summaries are illustrated. A listing in engineering units of all data acquired comprises the data listing shown in Figure 12.

Summary and Conclusions

A total system comprised of hardware and software has been designed, developed, and installed on an M35A2 cargo truck. Hardware consists of on-board transduction elements and associated processing and recording systems. Software consists of all Fortran and assembler level routines required to read and analyze the data that is recorded on magnetic tape. All measurement points are calibrated by traceable standards from the point of transduction through the recorder. A continuing calibration program shall be implemented. Data is provided for hot and cold idle and motive vehicle operation. Data is also provided for clutch slip, compression balance, and engine power measurements. The vehicle, with the MO/MARS system installed, is presently undergoing road testing over highway, secondary and cross country terrain. All measured parameters shall be uniquely observable over the entire length of the test.

Acknowledgment

The results presented are based on work sponsored by the United States Army Tank Automotive Command, Warren, Michigan. The authors wish to acknowledge the contribution of Messrs. N. F. Muelleman of GARD and B. Emerson and D. L. Gamache of TACOM to the design and development of the MO/MARS system.

Key Word Index

Mobile Vehicle Testing
Transduction
Recorder
Magnetic Tape
On-Board

Table 1 - TRANSDUCTION SUMMARY

Parameter		Monitoring Site of Sensor	Range
Differential pressure across oil filter		Oil filter housing	0 to +15 psid
Differential pressure across fuel filter		Inlet to primary filter Outlet of final filter	0 to +30 psid
Differential pressure across air filter		Air filter housing	0 to -1 psid
Pressure of oil at outlet of filter		Oil filter housing	0 to +100 psig
Pressure of fuel at inlet of primary filter		Inlet to primary filter	0 to +10 psig
Engine coolant temperature		Inlet to radiator	0 to +300°F
Engine oil temperature		Oil filter housing	0 to +300°F
Ambient temperature of air		Rear of front bumper	0 to +300°F
Transmission oil temperature		Drain plug	0 to +300°F
Transfer oil temperature		Drain plug	0 to +300°F
Engine speed		Flywheel housing	0 to 3000 RPM
Wheel speed		Top of rear axle	0 to 80 MPH
Clutch Slippage	Instantaneous	Side plate on transmission case	± 0.12 rad/rad to ± 120 rad/rad
	Average		± 0.00012 rad/rad to ± 120 rad/rad
Distance		Top of rear axle	0 to 99,999 miles
Time	Time of day	Reference clock	00:00 to 23:59:59 hours, minutes, sec.
	Time of year		0 to 365 days

Table 2 - TRIGGERING EVENTS

Parameter	Triggering Condition
1) Differential Pressure	
a) Oil filter	over 12 psid ± 2 psid
b) Fuel filter	over 15 psid ± 2 psid
c) Air filter	under 27 in H_2O ± 15%
2) Temperature, coolant, engine	over 225°F ± 5°F
3) Speed	
a) Engine	over 2500 RPM ± 100 RPM
b) Wheel (four speed ranges with transitions identified) range limits	0, 2, 15, 30, 50 MPH
4) Time	over 5 minutes since previous trigger
5) Instantaneous Clutch Slippage	over E rad/T rad, E and T programmable

FIGURE 1 M35A2 2-1/2 TON CARGO TRUCK

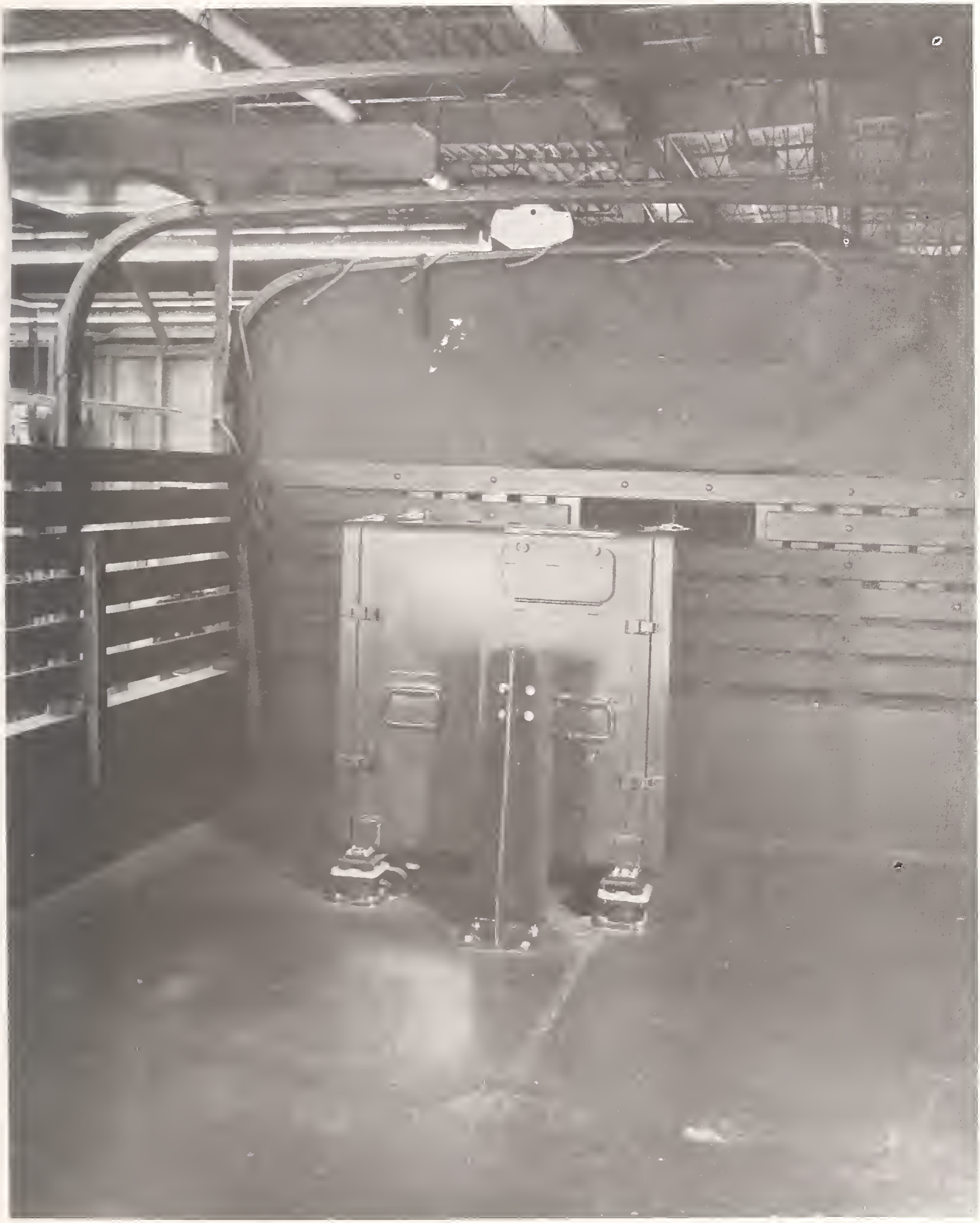

FIGURE 2 MO/MARS CABINET IN PLACE - FRONT AND REAR COVERS ATTACHED

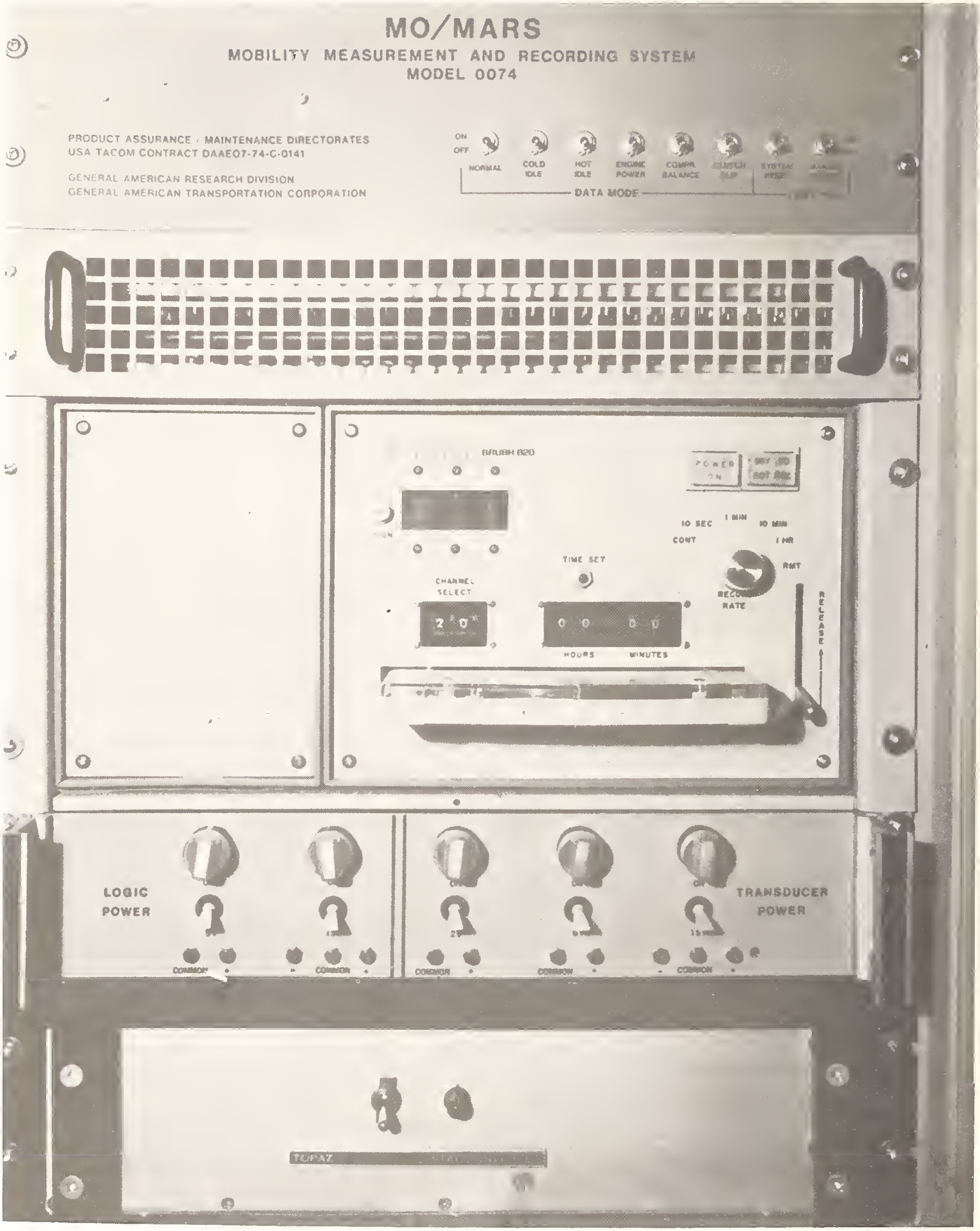

FIGURE 3 CONTROL AND INDICATOR PANEL

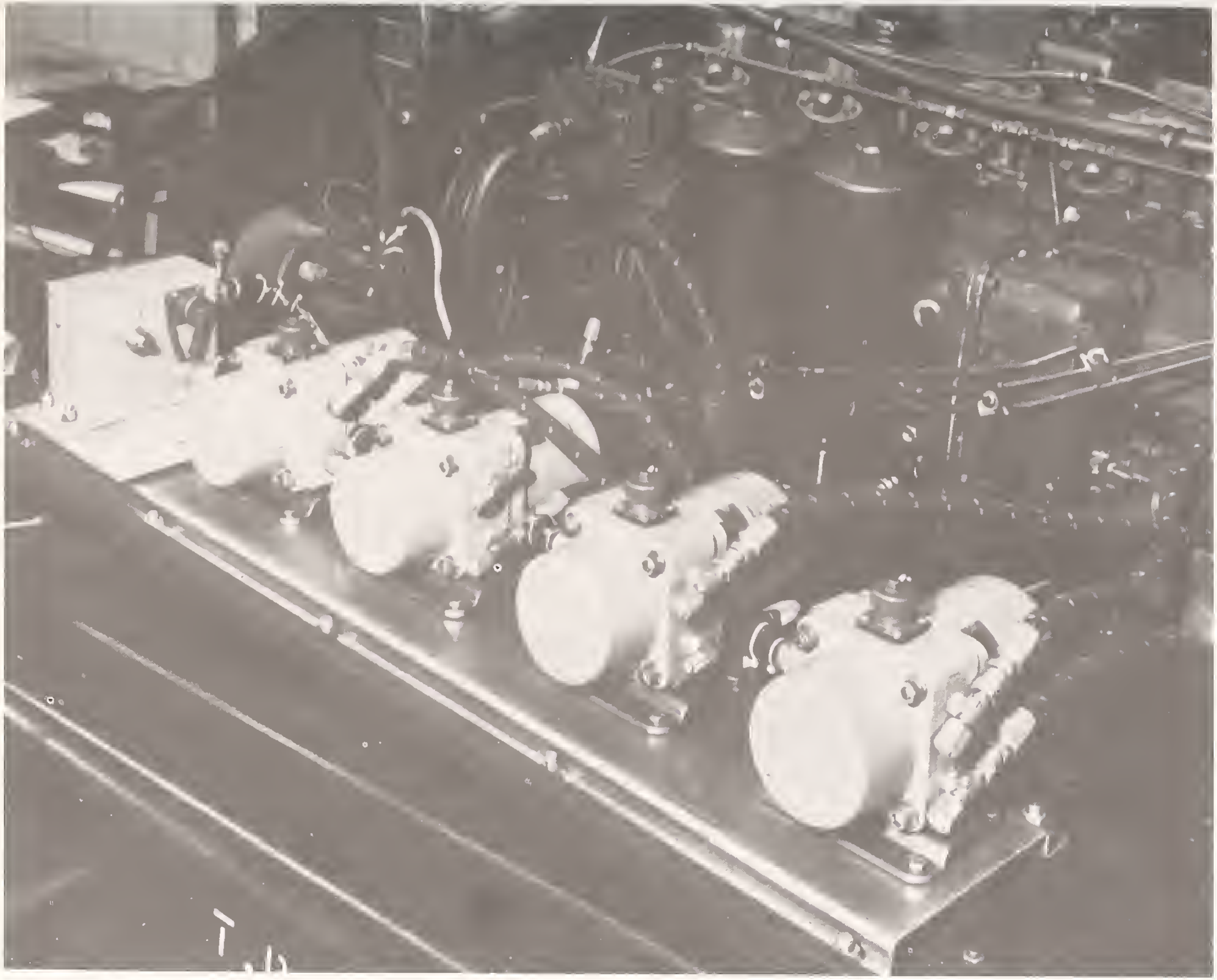

FIGURE 4 PRESSURE TRANSDUCERS - INSTALLED IN ENGINE COMPARTMENT

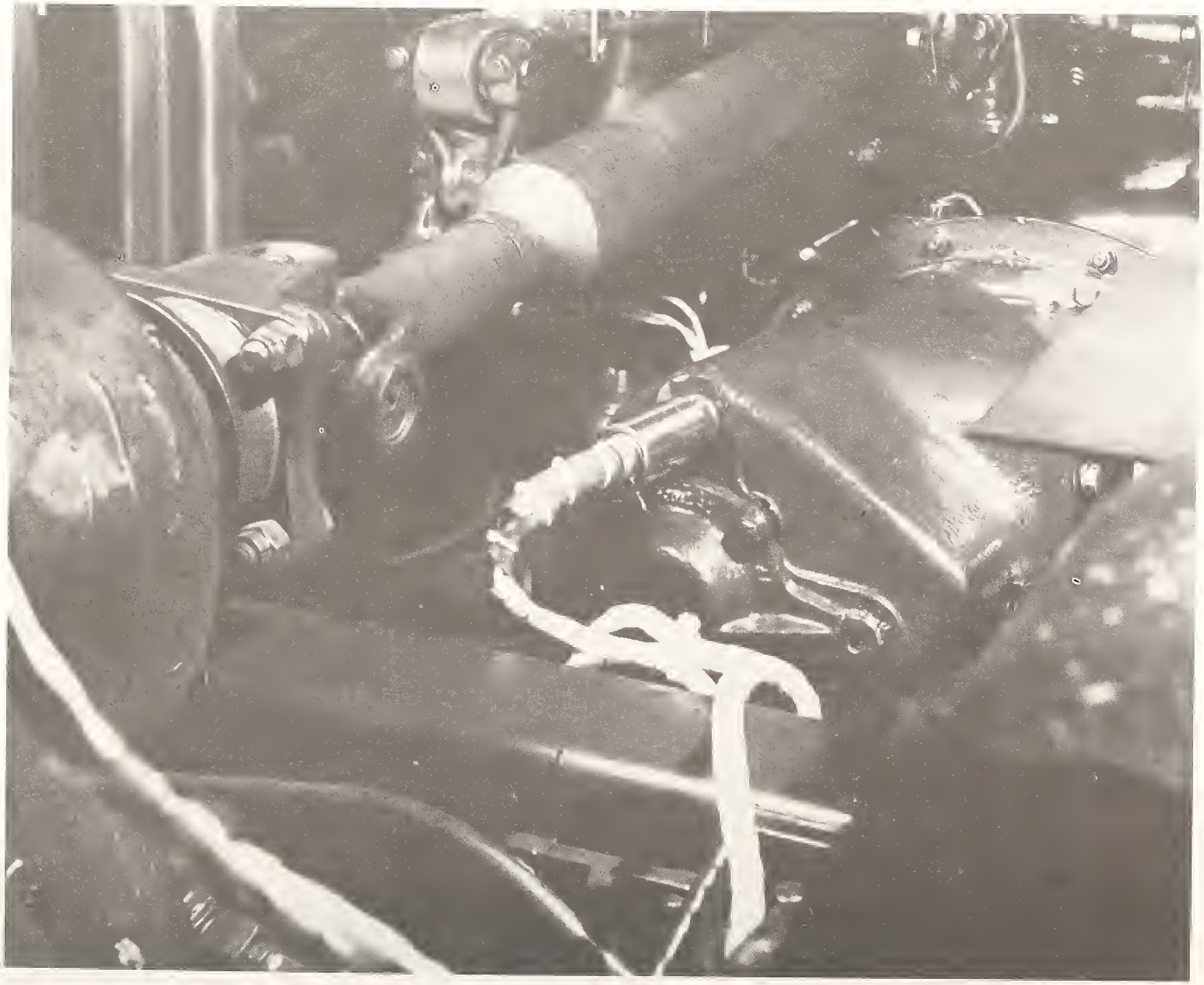

FIGURE 5 TRANSMISSION OIL TEMPERATURE TRANSDUCER

FIGURE 6 ENGINE FLYWHEEL SPEED TRANSDUCER

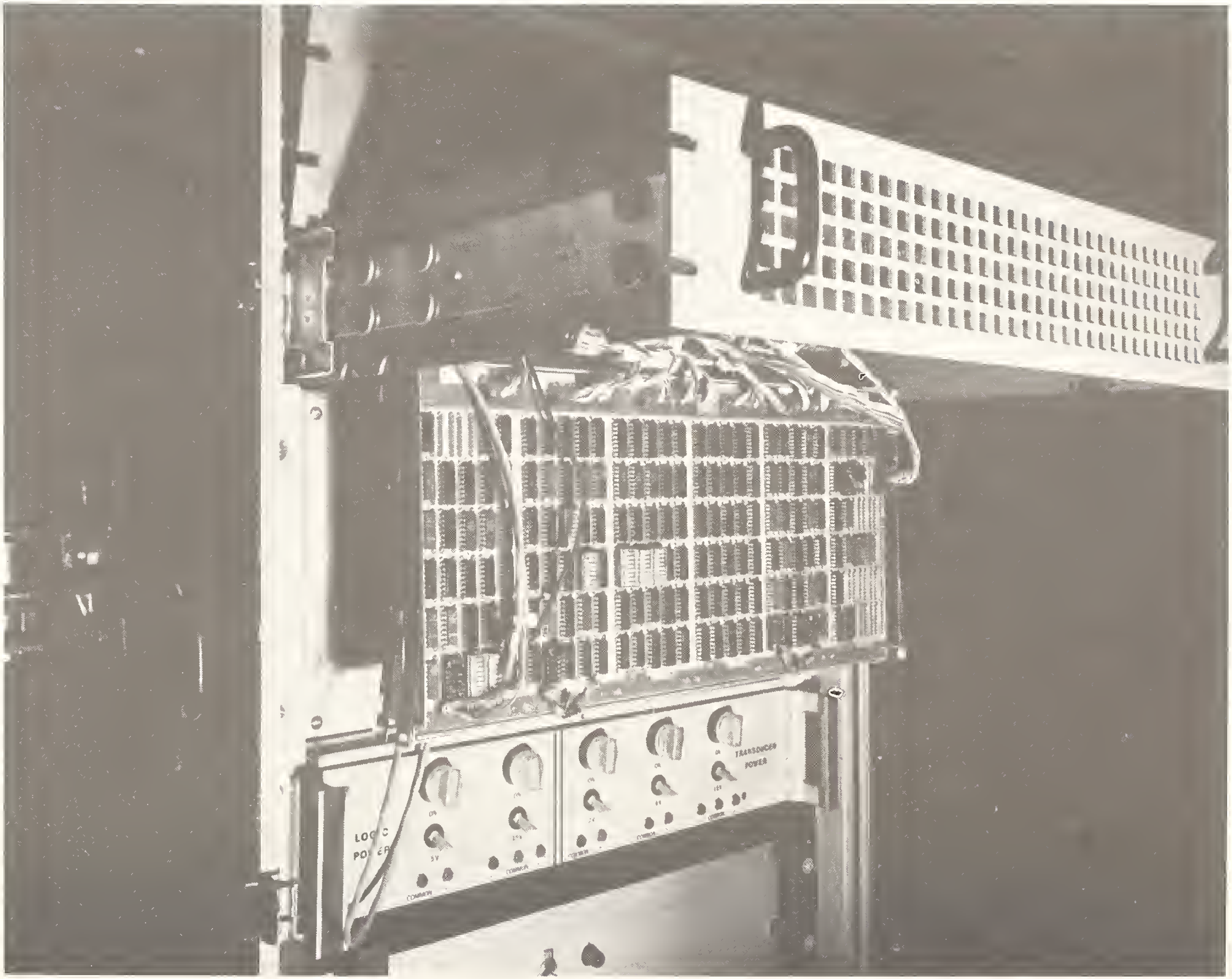

FIGURE 7 PROCESSOR LOGIC PANEL - TILTED FOR SERVICE

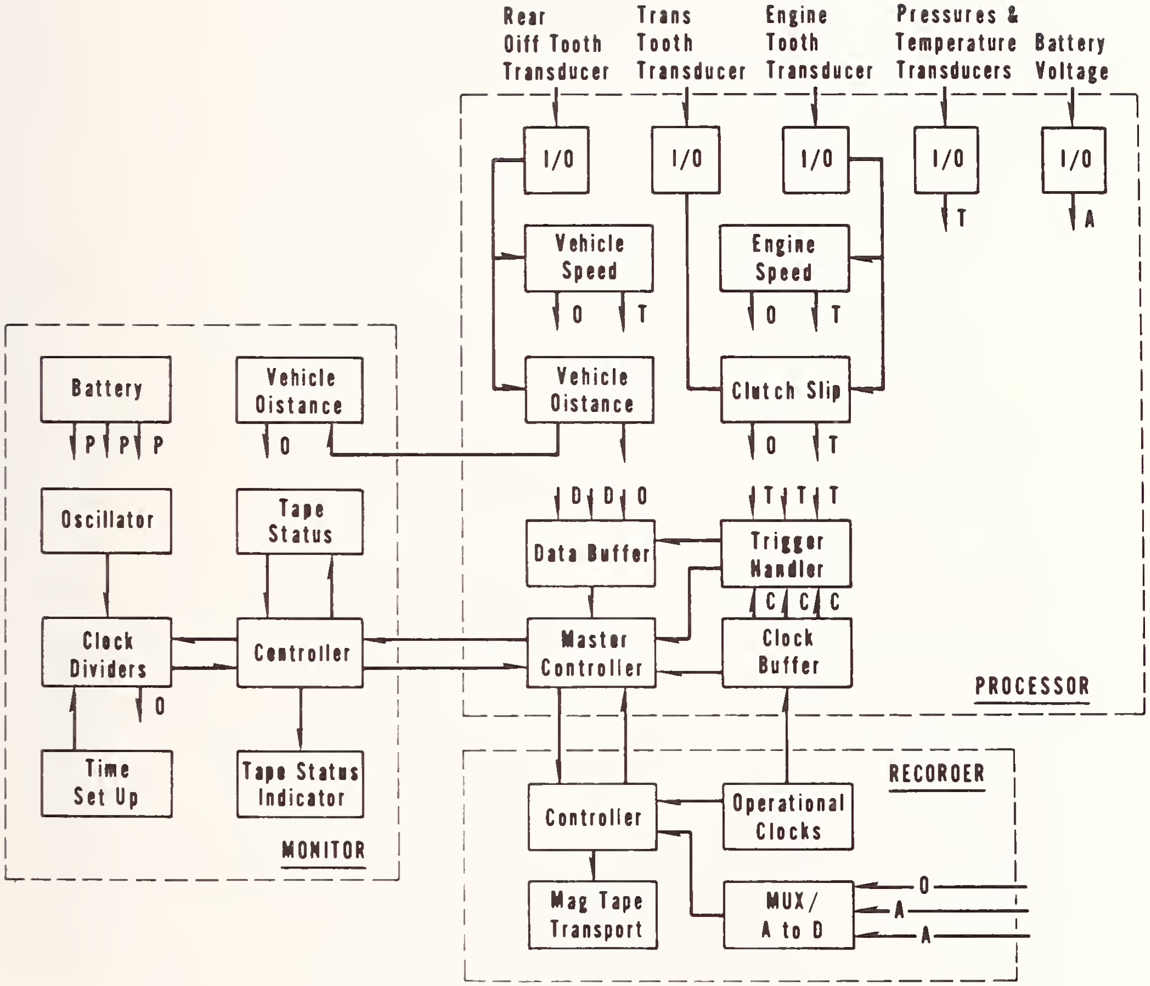

FIGURE 8 NETWORK SUBSYSTEMS BLOCK DIAGRAM

```
                                                          MO/MARS M35 DATA SUMMARY
GENERAL AMERICAN RESEARCH DIVISION                                                                    TACOM CONTRACT NO. DAAE07-74-C-0141
GENERAL AMERICAN TRANSPORTATION CORPORATION                                                           PRODUCT ASSURANCE/MAINTENANCE DIRECTORATES
RUN DESCRIPTION HWY/SECONDARY/CROSS COUNTRY                                                           NO. DATA SAMPLES-  621-OPER,HOT+COLD IDLE

OPERATING VEHICLE DATA SUMMARY-NO.DATA SAMPLES    553-----------------------------------------------------------------------------

PR 1         PR 2         PR 3         PR 4         PR 5         PR 6         PR 7         PR 8         PR 9
VEHICLE      ENGINE       AIR FIL      FUEL FIL     OIL FIL      COOLANT      OIL FIL      FUEL FIL     AMB AIR
SPEED        SPEED        PRESSURE     PRESSURE     PRESSURE     TEMP         PRES OUT     PRES IN      TEMP
MPH          RPM          PSID         PSID         PSID         DEG F        PSIG         PSIG         DEG F

58.          2583.          0.2          0.6          2.4          179.        68.5          7.5            69.  (HIGH)

 0.             0.          0.0         -1.0         -5.1           72.         7.4          3.9            26.  (LOW)

26.          1571.          0.1          0.1          0.2          163.        45.5          5.4            32.  (AVE.)

18.           558.          0.0          0.1          0.5           14.        12.9          0.8             7.  (S.DV)

*****************************************************************************************************************

      PR 10        PR 11        PR 12        PR 13        PR 14        PR 15        PR 16                    PR 18
      OIL TEMP     OIL TEMP     BATTERY      ENG OIL      ODOMTR       DAY OF       TIME                     AVE CLUTCH
      TRANSMIS     TRANSFER     VOLTAGE      TEMP                      YEAR                                  SLIP
      DEG F        DEG F        VOLT DC      DEG F        MILES        DAY          MINUT                    RADIAN

(HIGH)   146.         161.       28.6           194.      1657.1        18.          924.78                    0.000

(LOW)     65.          61.       28.2            68.      1230.1        16.          528.75                    0.000

(AVE.)   118.         122.       28.4           173.      XXXXXXX       XXXXX                                  0.000

(S.DV)    20.          28.        0.0            18.      XXXXXXX       XXXXX                                  0.000

*****************************************************************************************************************

TRG CON 1    TRG CON 2    TRG CON 3    TRG CON 4    TRG CON 5    TRG CON 6    TRG CON 7    TRG CON 8    TRG CON 9    TRG CON 10
0/2          2/15         15/30        30/50        50/80        2500         27 IN H20    15 PSID      12 PSID      225 DEG F
MPH          MPH          MPH          MPH          MPH          RPM          AIR FILT     FUEL FILT    OIL FILT     COOLANT

   51.          132.         137.         136.          80.           4.           0.           0.           0.        0.(TOT.TRG)

*****************************************************************************************************************

LEGEND  1)--(HIGH)--MAXIMUM VALUE OF DATA SET
        2)--(LOW)--MINIMUM VALUE OF DATA SET
        3)--(AVE.)--AVERAGE VALUE OF DATA SET
        4)--(S.DV)--STANDARD DEVIATION VALUE OF DATA SET
        5)--(TOT.TRG)--TOTAL TRIGGER VALUE PER CONDITION OVER THE DATA SET
```

FIGURE 9 DATA SUMMARY - OPERATING VEHICLE

```
                                                    MO/MARS M35 DATA SUMMARY
GENERAL AMERICAN RESEARCH DIVISION                                                 TACOM CONTRACT NO. DAAE07-74-C-0141
GENERAL AMERICAN TRANSPORTATION CORPORATION                                        PRODUCT ASSURANCE/MAINTENANCE DIRECTORATES
RUN DESCRIPTION HWY/SECONDARY/CROSS COUNTRY                                        NO.  DATA SAMPLES-  161-OPER,HOT+COLD IDLE

COLD IDLE DATA SUMMARY-NO.DATA SAMPLES     38    -------------------------------------------------------------------------------

PR 1        PR 2        PR 3        PR 4        PR 5        PR 6        PR 7        PR 8        PR 9
VEHICLE     ENGINE      AIR FIL     FUEL FIL    OIL FIL     COOLANT     OIL FIL     FUEL FIL    AMB AIR
SPEED       SPEED       PRESSURE    PRESSURE    PRESSURE    TEMP        PRES OUT    PRES IN     TEMP
MPH         RPM         PSID        PSID        PSID        DEG F       PSIG        PSIG        DEG F

 0.          721.         0.0         0.1        -0.4         170.        57.4        6.7          67.  (HIGH)

 0.            0.         0.0         0.1        -1.0          70.         0.2        5.5          65.  (LOW)

 0.          690.         0.0         0.1         0.1         131.        43.0        6.6          66.  (AVE.)

 0.          114.         0.0         0.0         0.2          29.        11.9        0.1           0.  (S.DV)

*****************************************************************************************************************************

        PR 10       PR 11       PR 12       PR 13       PR 14       PR 15       PR 16                   PR 18
        OIL TEMP    OIL TEMP    BATTERY     ENG OIL     ODOMTR      DAY OF      TIME                    AVE CLUTCH
        TRANSMIS    TRANSFER    VOLTAGE     TEMP                    YEAR                                SLIP
        DEG F       DEG F       VOLT DC     DEG F       MILES       DAY         MINUT                   RADIAN

(HIGH)    86.         64.       28.4         156.       1634.7       18.        874.15                       0.000

(LOW)     65.         63.       24.5          67.       1634.7       18.        843.56                       0.000

(AVE.)    77.         63.       28.2         116.       XXXXXXX     XXXXX                                    0.000

(S.DV)     6.          0.        0.6          28.       XXXXXXX     XXXXX                                    0.000

*****************************************************************************************************************************

TRG CON 1   TRG CON 2   TRG CON 3   TRG CON 4   TRG CON 5   TRG CON 6   TRG CON 7   TRG CON 8   TRG CON 9   TRG CON 10
0/2         2/15        15/30       30/50       50/80       2500        27 IN H20   15 PSID     12 PSID     225 DEG F
MPH         MPH         MPH         MPH         MPH         RPM         AIR FILT    FUEL FILT   OIL FILT    COOLANT

    0.          0.          0.          0.          0.          0.          0.          0.          0.          0.(TOT.TRG)

*****************************************************************************************************************************

LEGEND  1)--(HIGH)--MAXIMUM VALUE OF DATA SET
        2)--(LOW)--MINIMUM VALUE OF DATA SET
        3)--(AVE.)--AVERAGE VALUE OF DATA SET
        4)--(S.DV)--STANDARD DEVIATION VALUE OF DATA SET
        5)--(TOT.TRG)--TOTAL TRIGGER VALUE PER CONDITION OVER THE DATA SET
```

FIGURE 10 DATA SUMMARY - COLD IDLE VEHICLE

```
                                                  MO/MARS M35 DATA SUMMARY
GENERAL AMERICAN RESEARCH DIVISION                                              TACOM CONTRACT NO. DAAE07-74-C-0141
GENERAL AMERICAN TRANSPORTATION CORPORATION                                     PRODUCT ASSURANCE/MAINTENANCE DIRECTORATES
RUN DESCRIPTION HWY/SECONDARY/CROSS COUNTRY                                     NO.  DATA SAMPLES-  161-OPER,HOT+COLD IDLE

HOT IDLE DATA SUMMARY-NO.DATA SAMPLES      35       ----------------------------------------------------------------------------

PR 1          PR 2          PR 3          PR 4          PR 5          PR 6          PR 7          PR 8          PR 9
VEHICLE       ENGINE        AIR FIL       FUEL FIL      OIL FIL       COOLANT       OIL FIL       FUEL FIL      AMB AIR
SPEED         SPEED         PRESSURE      PRESSURE      PRESSURF      TEMP          PRES OUT      PRES IN       TEMP
MPH           RPM           PSID          PSID          PSID          DEG F         PSIG          PSIG          DEG F

 0.            708.           0.0          0.1           0.2           155.          40.5          6.5              55.  (HIGH)

 0.            699.           0.0          0.1          -0.1           127.          25.6          6.3              33.  (LOW)

 0.            704.           0.0          0.1           0.0           137.          34.5          6.4              34.  (AVE.)

 0.              2.           0.0          0.0           0.0             8.           4.5          0.0               0.  (S.DV)

*******************************************************************************************************************************

       PR 10         PR 11         PR 12         PR 13         PR 14         PR 15         PR 16                        PR 18
       OIL TEMP      OIL TEMP      BATTERY       ENG OIL       ODOMTR        DAY OF        TIME                         AVE CLUTCH
       TRANSMIS      TRANSFER      VOLTAGE       TEMP                        YEAR                                       SLIP
       DEG F         DEG F         VOLT DC       DEG F         MILES         DAY           MINUT                        RADIAN

(HIGH)   129.          122.        28.4           169.         1657.1         18.           954.66                          0.000

(LOW)    110.           84.        28.3           135.         1657.1         18.           926.33                          0.000

(AVE.)   120.          100.        28.3           148.         XXXXXXX       XXXXX                                          0.000

(S.DV)     6.           10.         0.0            10.         XXXXXXX       XXXXX                                          0.000

*******************************************************************************************************************************

TRG CON 1     TRG CON 2     TRG CON 3     TRG CON 4     TRG CON 5     TRG CON 6     TRG CON 7     TRG CON 8     TRG CON 9     TRG CON 10
0/2           2/15          15/30         30/50         50/80         2500          27 IN H2O     15 PSID       12 PSID       225 DEG F
MPH           MPH           MPH           MPH           MPH           RPM           AIR FILT      FUEL FILT     OIL FILT      COOLANT

    0.            0.            0.            0.            0.            0.            0.            0.            0.            0.(TOT.TRG)

*******************************************************************************************************************************

LEGEND  1)--(HIGH)--MAXIMUM VALUE OF DATA SET
        2)--(LOW)--MINIMUM VALUE OF DATA SET
        3)--(AVE.)--AVERAGE VALUE OF DATA SET
        4)--(S.DV)--STANDARD DEVIATION VALUE OF DATA SET
        5)--(TOT.TRG)--TOTAL TRIGGER VALUE PER CONDITION OVER THE DATA SET
```

FIGURE 11 DATA SUMMARY - HOT IDLE VEHICLE

```
                                                MO/MARS M35 DATA LISTING
GENERAL AMERICAN RESEARCH DIVISION                                                        TACOM CONTRACT NO. DAAE07-74-C-0141
GENERAL AMERICAN TRANSPORTATION CORPORATION                                               PRODUCT ASSURANCE/MAINTENANCE DIRECTORATES
RUN DESCRIPTION HWY/SECONDARY/CROSS COUNTRY                                               NO.  DATA SAMPLES-  161

PR 1        PR 2        PR 3        PR 4        PR 5        PR 6        PR 7        PR 8        PR 9
VEHICLE     ENGINE      AIR FIL     FUEL FIL    OIL FIL     COOLANT     OIL FIL     FUEL FIL    AMB AIR
SPEED       SPEED       PRESSURE    PRESSURE    PRESSURE    TEMP        PRES OUT    PRES IN     TEMP
MPH         RPM         PSID        PSID        PSID        DEG F       PSIG        PSIG        DEG F

      PR 10       PR 11       PR 12       PR 13       PR 14       PR 15       PR 16       PR 17       PR 18
      OIL TEMP    OIL TEMP    BATTERY     ENG OIL     ODOMTR      DAY OF      TIME        EVENT       AVE CLUTCH
      TRANSMIS    TRANSFER    VOLTAGE     TEMP                    YEAR                    TRIGGER     SLIP
      DEG F       DEG F       VOLT DC     DEG F       MILES       DAY         HXMXS       NUMBER      RADIAN

TRG CON 1   TRG CON 2   TRG CON 3   TRG CON 4   TRG CON 5   TRG CON 6   TRG CON 7   TRG CON 8   TRG CON 9   TRG CON 10
0/2         2/15        15/30       30/50       50/80       2500        27 IN H20   15 PSID     12 PSID     225 DEG F
MPH         MPH         MPH         MPH         MPH         RPM         AIR FILT    FUEL FILT   OIL FILT    COOLANT

 0.            0.         -0.002       0.1        -0.3         70.71       0.2         5.5          65.08

       65.61       63.74       24.5          69.64       1634.7      18         14  3 34     8            0.000

0           0           0           0           0           0           0           0           0           0
*****************************************************************************************************************

 0.           660.         0.011       0.1        -1.0         71.78       52.4        6.5          65.08

       66.15       63.74       27.9          67.76       1634.7      18         14  4 13     12           0.000

0           0           0           0           0           0           0           0           0           0
*****************************************************************************************************************

 0.           686.         0.013       0.1         0.3         76.61       55.2        6.7          65.08

       66.95       63.74       28.4          70.44       1634.7      18         14  4 59     8            0.000

0           0           0           0           0           0           0           0           0           0
*****************************************************************************************************************

 0.           699.         0.013       0.1         0.4         82.51       55.2        6.7          65.08

       68.03       63.74       28.4          72.59       1634.7      18         14  5 49     8            0.000
```

FIGURE 12 DATA LISTINGS - TYPICAL

DISCUSSION

D. N. Fry, Oak Ridge National Laboratory: Are you going to use this data for design purposes or for maintenance purposes?

F. K. Chin: We see it right now as being for both.

D. N. Fry: Are you going to have an active program of evaluating this data and scheduling maintenance?

F. K. Chin: We are going to perform normal maintenance for 10,000 miles, and then nothing - just drive the truck into the ground.

R. Lenich, Caterpillar Tractor Company: Is there an indicator for the driver to stop the truck in case there is a malfunction or is this strictly for data acquisition?

F. K. Chin: Basically, it is for data acquisition.

R. Lenich: If a truck component was not operating properly, the driver would not know it at that point.

F. K. Chin: No, he wouldn't.

VIDEC SHIP PROPULSION SYSTEM PERFORMANCE MONITOR*

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Raytheon Company, Portsmouth, Rhode Island 02871
William L. McCarthy
McCarthy Marine & Ocean Engineering Associates
Great Neck, New York 11023

INTRODUCTION

The Vibration Analysis and Deviation Concept (VIDEC) is an effort directed and sponsored by the US Maritime Administration (MARAD) to develop an effective performance monitoring system for main and auxiliary marine machinery plants. The project encompasses, within three phases, concept development, performance specification, design and fabrication, installation, operation and evaluation. It spans nearly five years and involves six major participants from the maritime community.

Historically, the Deviation Concept was conceived by J.K. Salisbury under contract to the Bailey Meter Company for applications in heat cycle analysis in large shoreside power generating plants[1]. The VIDEC Phase I contract was a program sponsored by the US Maritime Administration's Office of Commercial Development (MARAD-OCD) and performed by a multidisciplined team at the State University of New York Maritime College (SUNYMC) with the purpose of applying this concept to the maritime industry. This work was performed during 1971 and 1972 and resulted in the formulation of a set of mathematical, thermodynamic and vibration processing expressions which were designed for a computer-based realtime shipboard monitoring system[2]. A set of performance specifications was also developed during Phase I for such a computer-based system.

The Phase II effort was initiated in early 1972 with separate contract awards to Raytheon Company and Ingalls Shipbuilding Division of Litton Industries for the respective tasks of system integration and shipboard installation aboard a

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*Original version of this paper presented at meeting of Society of Naval Architects and Marine Engineers, New England Section, at Portsmouth, R.I., 24 January 1975.

[1] Dickinson, C.E., "A Method for Propulsion Plant Performance Evaluation for Marine Application," IEEE Transactions on Industry Applications, Volume IA-10, No. 2, March/April 1974.

[2] Gleicher, N., Kramer, A.R., Mathieson, J., and Pergament, S., "The Deviation Concept: A Tool for Preventive Maintenance of Marine Power Plants," Marine Technology, October 1972.

newly constructed American President Lines' (APL) vessel. MARAD was assisted in technical liaison and coordination by the National Maritime Research Center in Kings Point, NY (NMRC-KP). Consultation was provided by SUNYMC during the transition from Phase I through the Phase II effort. The culmination of Phase II was the computerized real-time machinery monitoring and display system installed on board the SS PRESIDENT JOHNSON in January 1974.

Finally, the Phase III portion of the VIDEC project includes those constituents which are required to fully evaluate the effectiveness of a system of this magnitude and potential. The major participants under MARAD direction include Raytheon, NMRC and APL. The objectives of Phase III include technical and economic feasibility analysis of the VIDEC system in a two-year operational evaluation.

This paper discusses the Phase II and Phase III program evolution with interim findings one year after ship delivery.

SYSTEM DESCRIPTION

The Deviation Concept is simply a method of performance analysis of the propulsion plant whereby representative parameters are closely watched for departure from a reference figure of merit (Baseline). Continued observation of these variances should lead to certain deductions beneficial in effecting maintenance scheduling, efficiency regulation, manning improvements and increase in overall ship availability. A properly chosen set of measurement parameters can provide performance analysis to determine:

- Machinery deterioration trends
- The contribution of performance degradation of an individual machine to the overall plant efficiency
- Predicted time to failure estimates.

The VIDEC system contains the essential ingredients to put into practice this Deviation Concept on board the American President Lines' containership SS PRESIDENT JOHNSON. The key to successfully implementing this concept is determining just what a "deviation" is. The characteristics of the marine steam propulsion plant vary considerably depending on sea state and other operating conditions. The resulting variations of these normal operating ranges and conditions are numerous and as many different modes of variation exist as there are parameters to be monitored. Therefore, a major requirement of the VIDEC system was to provide the ability to ensure highly repeatable measurements with comparison to precise reference operating conditions. In order to facilitate control of such an intricate task, as well as to execute realtime thermodynamic and vibration processing algorithms, VIDEC was developed as an automated digital computer-based system.

This process of establishing the reference values for all monitored parameters and providing the means for normalizing this data for operating conditions has been designated "Baseline Mode". With a propulsion plant running at an optimum performance level (presumably during the maiden voyage) a complete data set is acquired, processed and stored for several (five) operating load points of shaft horsepower spanning approximately 80 percent SHP through 100 percent SHP where the heat cycle remains relatively constant. When the five load points have been stored, further processing takes place to produce coefficients of an equation which represents a best fit curve for each parameter. It is to this curve that subsequent data will be referenced.

The system analysis is partitioned into two distinct categories: Vibration Analysis and Thermal Analysis.

Vibration Analysis—Vibration analysis consists of maintaining surveillance over 25 pieces of rotating machinery plus the line shaft bearing for deviations in vibration levels measured by 104 fixed accelerometer sensors. Each vibration "channel" is examined over a broad spectral range of frequencies with 1/3 octave resolution totalling 30 bands. In addition, combinations of these bands are assembled together to form regions (four regions per channel). Regions are tailored to the specific natural vibration forces of each channel; i.e., RPM, blade count, electrical frequency. Thus for each of the 104 channels, there are 30 bands plus four regions which are processed for amplitude deviation from a reference containing over 3500 separate baseline curves. During the baseline procedure several RMS samples are measured for each point and, based on a statistical computation, the baseline level arrived at includes the sample variance and allows for a 99 percent probability factor.

The 30 bands have assigned upper "alarm" limits which if exceeded actually initiate an audible/visual alarm with a printed description of the deviation. The four regions have assigned upper limits also but for another reason. The regions, being representative of the specific machinery excitation forces, are maintained for trending purposes. The upper limits for the regions are used for a reference to which a time to alarm prediction is computed based on a least squares curve fit of a collection of past and current measurements. This information can facilitate maintenance scheduling by making maximum use of machinery history.

Thermal Analysis—Thermal analysis involves a determination of performance deviation for the main and auxiliary machines within the steam cycle. The performance measurement is based on a set of 73 calculations called "macro" parameters which are indicators of the condition of 17 different components within the propulsion plant. These calculations are based on the measured "micro" values of 99 discrete parameters and 22 on/off monitors including eight different types of measurements:

1) Temperature	5) RPM
2) Pressure	6) Valve position
3) Flow rate	7) Kilowatts
4) Torque	8) On/Off

The reference or baseline for the thermal analysis is established in a manner similar to vibration and at the same time. There are 99 "micro" and 73 "macro" baseline curves produced to which subsequent data are compared and the deviation recorded. Alarm limits (upper and lower) are assigned to each macro parameter and, if exceeded, cause an audible and visual alarm and printed description of all measured and calculated values for the respective plant component (Figure 1). All thermal values (micro and macro) are retained for trending whereby the data history is presented in graphic form.

In addition to the micro and macro values processed in the Thermal Analysis portion of the system, a set of 25 special computations called "Dollar Deviations" are made to estimate the respective penalty associated with a degradation

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                                                          FEED PUMP 2

                                                     PARAMETER   DEVIATION
       *** 54        TURB STEAMRATE                     28.5      20.18294
       *** 55              PUMP EFF                      .502       .26077
       *** 56              WATER HP                    264.        74.07727
           57                   RPM                   4472.       115.97852
  90   MN FD PUMP FD WTR FLOW RATE2    LBS/HR        179386.    120906.90625
  91   PORT MN FD PUMP SUCTION PRESS     PSIG            53.6        7.33070
  92   PORT MN FD PUMP SUCTION TEMP     DEG F           296.        27.28949
  93   PORT MN FD PUMP DISCHARGE PRESS   PSIG          1132.        80.60327
  94   PORT MN FD PUMP DISCHARGE TEMP   DEG F           301.        28.26068
  95   MN FD PUMP TURB STM FLOW RATE   LBS/HR         15000.     14335.70703
  96   PORT MN FD PUMP RPM                RPM          4472.      1665.66602
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Thermal alarm deviations are presented on the line printer with all associated parameter values and deviations from baseline. For each report all macro and micro parameters for the affected machine are presented.

Figure 1. Typical Thermal Deviation Report

of efficiency. The calculation appraises the total additional fuel consumption effect contributed by each machine and the "dollar" deviation refers to a unit value per barrel of fuel oil.

Once the Baseline Mode has been completed, the VIDEC system functions automatically by completely scanning all data once per hour in an Operate Mode, logging and alarming any deviation which exceeds set alarm limits. At the end of the day a complete report of all parameters is printed for hard copy history. Prior to each Operate Mode, the system exercises a thorough equipment calibration and self-test routine reporting any errors along with a fault isolation code. This code represents the result of a systematic troubleshooting analysis performed by the computer, and when used with the technical manual describes the most logical problem area with identification of the failed module(s).

Several additional modes of operation are available to an operator via the console control panel to retrieve data over and above that which is printed regularly.

These operator modes include the following:

1) Calibrate Mode
2) Demand Mode
3) Standby Mode
4) Baseline Mode
5) Self-Test Mode
6) In-Port Mode.

- Calibrate Mode—provides a repetitive readout, via cathode ray tube (CRT) display, of a selected thermal channel in engineering units for the purpose of span adjustment and calibration of sensor signal conditioners.

- Demand Mode—allows the operator to select, via keyboard, 10 special request operations from a CRT-displayed menu. These requests include the following:

    - Vibration trend graphic display of a four-region history over the past 24 hours or past 30 days on a selected channel (Figure 2).

    - Thermal trend graphic display of any micro or macro parameter history over the past 24 hours or past 30 days (Figure 3).

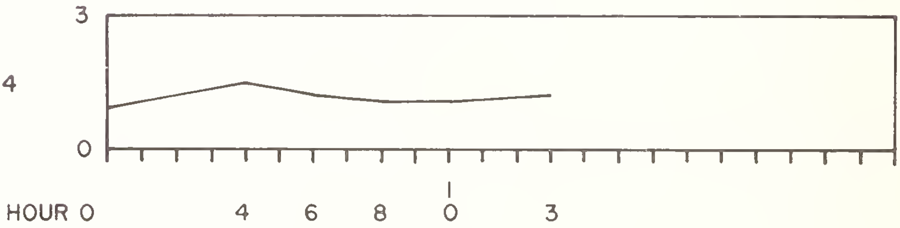
    - An up-to-date elapsed running time count (hours) for each of 22 pieces of machinery.

    - Automatic initiation of an analog tape recording of 13 preselected vibration channels for use in off-line narrowband analysis.

    - Graphic vibration display, 1/3 octave, frequency vs amplitude spectrum for a selected channel (Figure 4).

CHANNEL 1

LINE SHAFT BRG NO. 1 (FWD END)
DAY 1

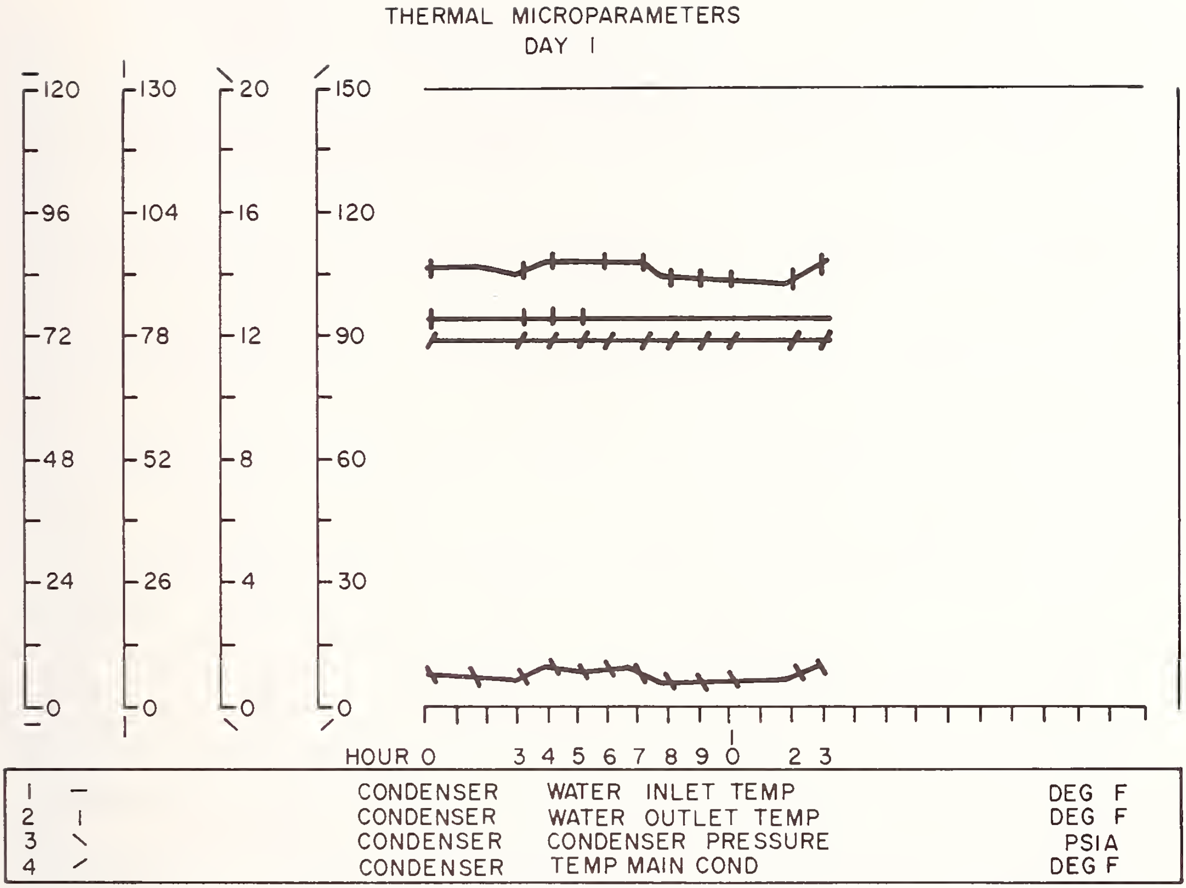
REGION		TIME TO ALARM HOURS
	NSC	> 900.0
2	NSC	> 900.0
3	NSC	> 900.0
4		331.1

The vibration trending function uses a graphic representation of time versus vibration within each of four regions for a specified sensor address. The regions displayed are those bounds preselected for each particular channel and include the total signal summation of all bands (groups) within the defined bounds. The deviation presented is a ratio of the measured data to the baseline data. A time-to-alarm estimate is printed to the right of each region plot and is based on a linear least-squares curve fit.

The operator options available include:

1) Trend by hour for 24 hours
    a) Previous day
    b) Present day
2) Trend by day for up to the last 30 days.

Figure 2. Typical Vibration Trends Presentation

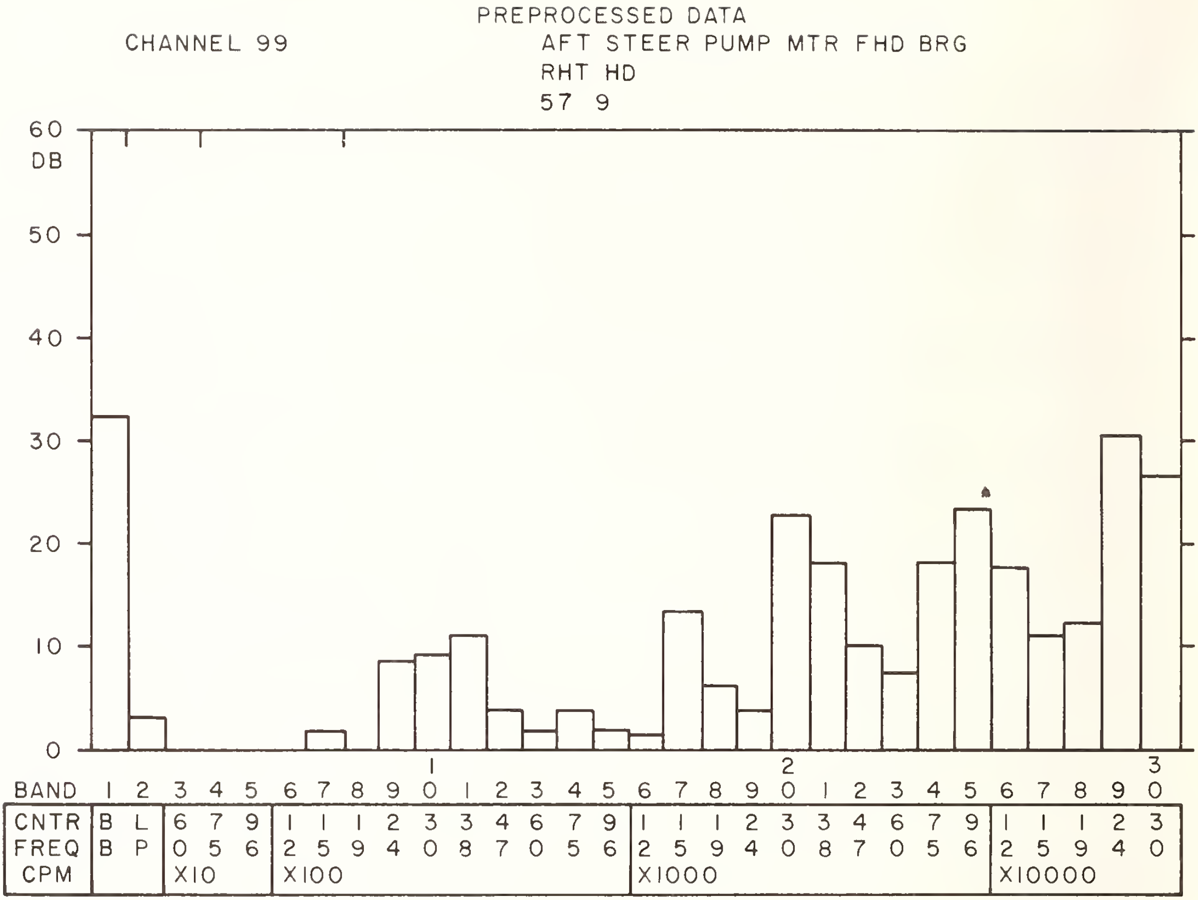


Thermal trends of multiple microparameters are available on a graphic representation of time versus thermal values for four channels simultaneously. Included in the display are the legends with engineering units with respective measured values taken at the indicated times.

The operator options available include:

1) Trend by hour for 24 hours
    a) Previous day
    b) Present day
2) Trend by day for the last 30 days.

Figure 3. Typical Thermal Trends (Multiple Microparameter) Presentations



An on-line graphic plot of vibration level versus frequency for any selected vibration channel is available. The amplitude level axis (vertical) is scaled in dB reference 1 millivolt RMS. The frequency axis (horizontal) is segmented in 1/3 octave bands with the exception of the first two. These two bands represent broadband and low pass (1.25 to 9 Hz) respectively. The frequency axis is labeled in unit of cycles-per-minute for direct RPM correlation. The assigned regions are shown at the top of the graph in tick marks.

Figure 4. Typical Vibration Channel Preprocessor Presentation

    - Graphic vibration display, broadband amplitude vs time over a 10-minute period for a selected channel.
    - A printout of past 30-day record for all daily averages at end of the current day.

  Also available via the Demand Mode is another menu which can be accessed for the purpose of changing thermal and vibration constants stored in the computer memory; e.g., alarm limits, region allocation, thermodynamic constants, etc.

- Standby Mode—when initiated, places the VIDEC system in an idle condition whereby no processing takes place.
- Baseline Mode—allows entry to stored data at any time to reestablish a new reference if major overhaul or replacement of a machine takes place.
- Self-Test Mode—allows initiation of the system diagnostics at any time in addition to that which automatically takes place once per hour.
- In-Port Mode—extends vibration surveillance to include the period when rotating machinery remains in operation while the propulsion plant is either running below 80 percent SHP or secured.

The system configuration consists of 13 Signal Acquisition Stations, 203 sensors, an engineroom console, two signal processing cabinets, ASR-35 teletype, and an analog tape recorder (Figures 5, 6 and 7).

The purpose of the Acquisition Stations is to consolidate those sensor cables within a local area and route them via a single (multiple pair) cable to the signal processing units. No processing takes place in the stations with the exception of signal conditioning needed to convert some sensor output signals to a form suitable for reliable transmission over long distances.

A complete list of system sensors is included in the appendix. All of the 104 vibration sensors are of the accelerometer type. The thermal sensors include various types, each chosen for a specific application. A description of these sensors follows:

- Temperature: All channels—platinum Resistance Temperature Detectors (RTD)
- Pressure: All channels—capacitance element
- Flowmeters:
    - Condensate, steam—Δ pressure (orifice/nozzle)
    - Fuel oil, saltwater—turbine
    - Distillate—variable area

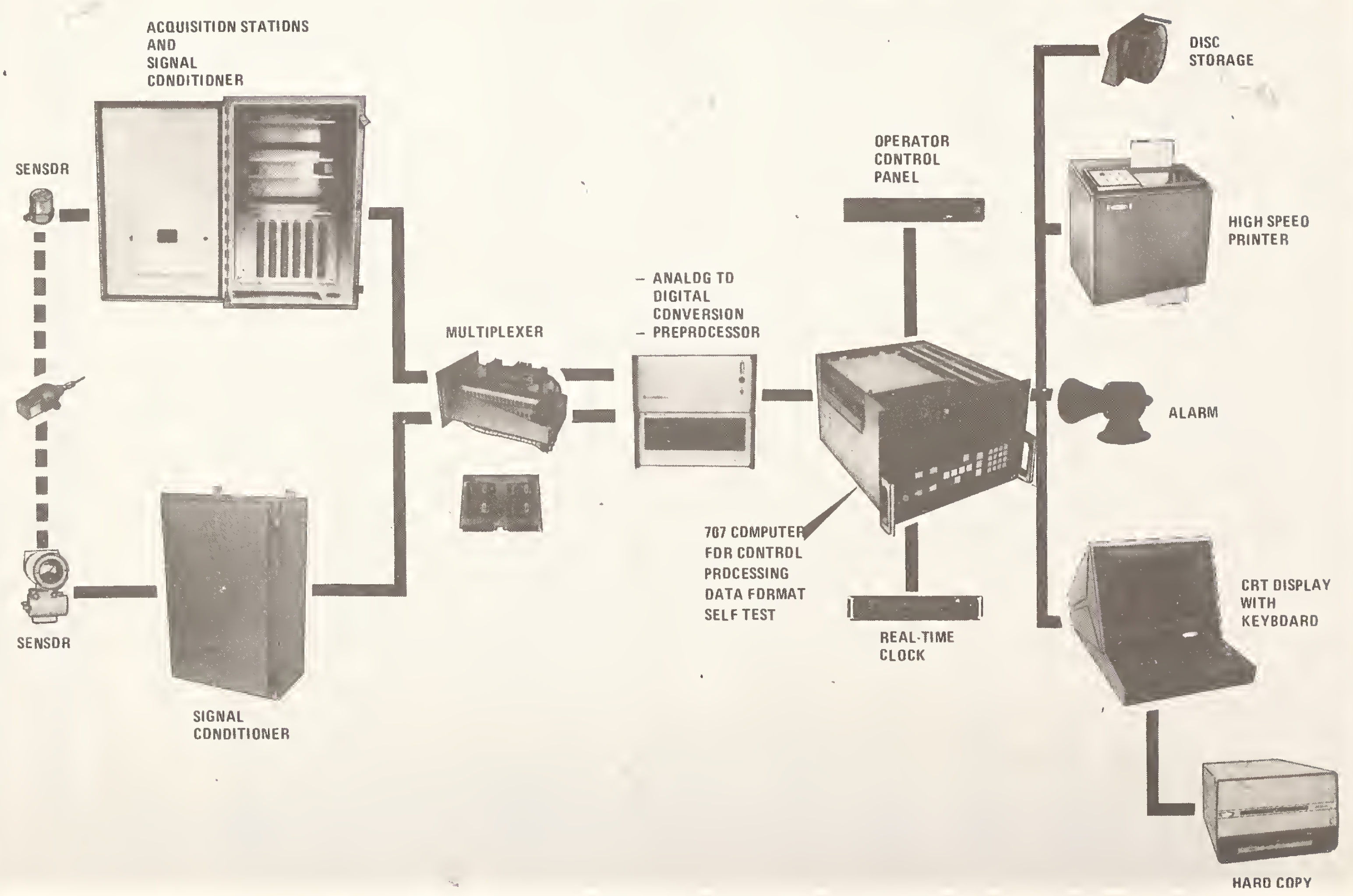


Figure 5. VIDEC Functional Pictorial

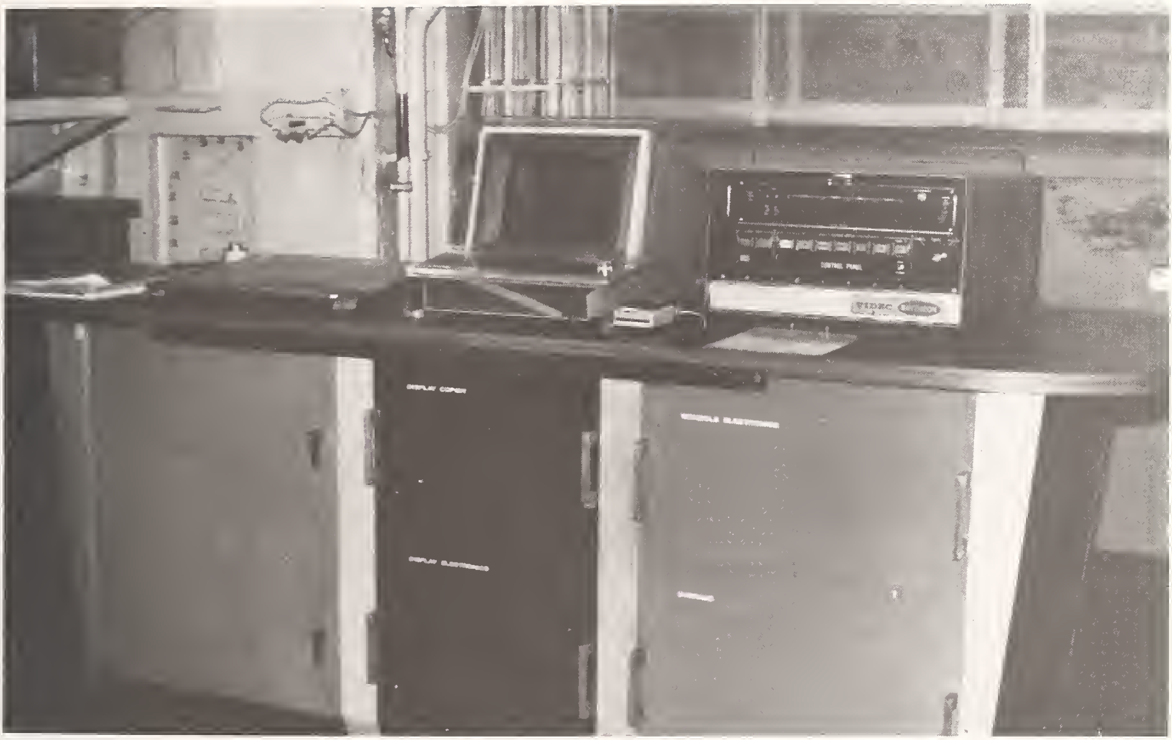


Figure 6. VIDEC Console

Figure 7. VIDEC Analog and Digital Processors

- RPM:
  - Feed pump—Magnetic pulse pickup
  - Main shaft—Torductor
- Valve Position: All channels—Linear Variable Differential Transformer (LVDT)
- Kilowatt: All channels—Hall effect transducer (current transformer pickup).

The Signal Processing Units contain all of the analog scanning and preprocessing hardware, system control hardware, computer, disc memory unit, digital cassette recorder and power supplies. This portion of the system functions under complete software control via a Raytheon 707 digital computer and every hardware processing function is dependent on a computer program instruction. All of these programs reside on the disc memory and are "called up" to core memory when needed. The disc also serves to retain all historical and baseline data. A cassette unit provides a means to load new program changes and also record historical data from the disc for permanent retention.

The Console, located in the engineroom, contains the following equipments:

- High speed line printer for logging of daily reports, alarm descriptions and 30 day reports
- CRT display and keyboard for presentation of graphic trends, parameter values, demand request menus and operator communications
- Hard copier to reproduce CRT presentation
- Time of day clock which acts to control the system time-dependent functions
- Control panel to allow selection of system modes.

Other units include an ASR-35 teletype used for baseline operation only, and an analog tape recorder to make recordings of unfiltered vibration data for off-line narrowband analysis.

SYSTEM IMPLEMENTATION

VIDEC implementation, Phase II, called for hardware and software design, fabrication and installation of a fully integrated system applying the system equations and performance specifications developed during Phase I. The primary objective of Phase II was to produce a system which would evaluate the VIDEC concept using present day technology with minimum operator intervention.

The principal considerations included:

- Instrumentation data integrity
- Maximum use of proven, off-the-shelf hardware
- Equipment reliability
- Ease of accessibility and repair
- Ease in operator-system interface
- Flexibility of operation, expansion, etc.
- Rapid installation at minimum costs
- System simulation test
- Training.

During the initial system definition period several modifications were made to the VIDEC sensor specifications involving deletions and reassignments of sensors, for reasons of optimization. The final system sensor list which was implemented is shown in the appendix. Other modifications to the system specification were made throughout the project development to improve operator interface and increase data collection. During these periods of redefinition which affected all participating parties, the technical coordination of NMRC was substantial and quite beneficial.

A proper selection of sensor and transmission techniques is paramount in achieving accurate, stable, and reliable measurement data over an extended time period. To this end the following actions were taken:

- Numerous sensor manufacturers were surveyed in order to acquire sensors of proven reliability
- Susceptibility to EMI/RFI was minimized by using integral signal conditioners on each sensor wherever possible
- For those sensors requiring non-integral electronics, the cable distance between primary element and signal conditioner was minimized by use of the local acquisition stations
- An all-encompassing grounding and shielding design standard was developed for the entire system to suppress external signals generated by shipboard machinery
- A special software-controlled treatment of sampled data was employed to eliminate noise transients.

The application of commercial off-the-shelf hardware was a major goal for the VIDEC program. This presented no significant problems. Equipment trade-off studies had shown that for each function required, there were several candidates which, with only minor ruggedization, could perform satisfactorily within the shipboard environment specified. The fact that the processing equipment was to be installed in an air-conditioned space allowed usage of the ASR-35 teletype, analog tape recorder and commercial vibration analyzer directly with only shock and vibration isolation added. Both the 707 computer and disc bulk storage unit, crucial to the system operation, were chosen specifically because they were designed for a harsh shipboard environment. The engineroom console required considerable attention with respect to temperature, humidity, dirt, vibration, etc. The commercial equipments (i.e., line printer, CRT terminal, real time clock and hard copier) were repackaged to withstand the vibration and shock; oil and moisture seals were placed on exposed switches and indicators; air circulation was provided around all heat dissipating equipment; cooling air was provided at the filter/blower inlet from a ventilation duct; and quick access to all electronics was made via slide-mounted pull-out drawers with latching handles.

The system was designed to provide complete "hands-off" operation for normal watchkeeping functions, the basis being that, to be consistent with the Deviation Concept, only degradation from baseline should require attention. However, when a deviation causes an alarm, and a closer look at data is necessary, a simple operator interface is provided using a concise conversational mode. The subject of operator interface was of concern from the outset. Because of the prototype nature of the VIDEC system, there are numerous display types, system variables, and data printouts intended primarily for system performance analysis and not necessarily useful to the engineroom operator. The conversational type operator interface via CRT terminal was chosen as the best means to implement system flexibility and at the same time provide access to operator demand modes. Through a displayed menu, the operator may choose one of the graphic trend displays, a vibration signature, or alter system parameters; e.g., alarm limits, sensor range, higher heating value for fuel oil, etc. System flexibility is inherent to the software-controlled nature of the VIDEC which makes use of a powerful minicomputer software system.

A major concern associated with a system like VIDEC is how to thoroughly test it before delivery. With the many modes, calculations, displays and parameter interrelations, the only practical method suitable was to develop a simulator to provide a programmable representation of every system parameter. The simulator hardware was developed and a test program prepared to test the system at the factory and again on board the ship as an installation checkout prior to connecting actual sensors.

The simulator proved itself invaluable during factory test and also in the training course which was held to familiarize the ship's engineering personnel with the system. The training course included a mixture of theory, operation, and hands-on working sessions. The attendees and lecturers included the ship's Chief Engineer, First Assistant Engineer, Operations personnel and representatives from all of the participating agencies and firms.

INSTALLATION

As part of their contribution to the program, American President Lines (APL) made the machinery plant of the SS PRESIDENT JOHNSON available for integration with the VIDEC system. The vessel is the last of four PACESETTER class containerships built for APL by Ingalls Shipbuilding Division of Litton Industries, Pascagoula, Mississippi. She was delivered on 4 January 1974. She is 680 feet long overall, displaces 22,000 tons dwt, and has a maximum service speed of 25 knots. Her power plant consists of a cross-compounded single plane steam turbine main engine and reduction gear set, two boilers and four stages of feed heating. She is equipped with a GE Central Operating System (COS) for propulsion control. The vessel is presently employed in APL's US East Coast-West Coast-Far East run.

PROGRAM MANAGEMENT

In view of the great physical distances separating the parties involved in this project and their varying operational philosophies, the coordination and management became a formidable task. The responsibility therefore was shared between MARAD-OCD in Washington DC and the NMRC-KP. The OCD Program Officer was responsible for the overall management of the project while NMRC-KP was assigned certain technical review and coordination aspects. As the program moved into the fabrication and shipboard installation phase, the program management function became critical and more demanding. The occurrence of changes in design, delivery of critical items to the yard, and other last minute events that seem to accompany a project of this nature became paramount as the vessel neared completion. In many instances solutions were worked out with a verbal agreement. The cooperation and involvement which was instilled in all parties proved to be indispensable in achieving the system completion without any major deviations in program schedule.

VESSEL DELIVERY SCHEDULES

The original schedule called for equipment delivery by January 1973 and installation completion by June. Many long lead delivery items were involved and procurement could not be initiated until ship piping design was completed and these sensor specifications defined. However, the VIDEC installation contract negotiations between MARAD and the shipbuilder were not complete until July 1972 and a specific hull was not defined until January 1973. The immediate effects of these delays prevented the timely commencement of:

- Specifying sensors for procurement
- Development of interface specifications for shaft RPM and torque (supplied via COS unit)
- Defining sensor cable lengths for procurement
- Defining cable lengths for cabinet interconnections
- Finalization of software equations as affected by sensor specifications
- Flowmeter orifice plate design and procurement.

A work-around schedule was implemented that minimized the effect of these items on equipment delivery.

The system was designed for rapid installation so that equipment delivery could take place at the last possible moment and not interfere with normal shipyard tasks. The installation plan called for: a) Early delivery of the acquisition stations requiring shipyard wiring to terminals; b) connectorized cabinets with the cables being made up in advance by the yard; and c) a parallel effort of sensor installation. System checkout was to consist of mounting of the cabinets, plugging in the prefabricated cables, and repeating the simulator test previously run in the factory. In this manner the equipment checkout could proceed without the need for all sensors to be installed or the steam plant to be fired up. All went well with the exception that the simulation could not be accomplished. The feverish activity in the engineroom prohibited the complete assembly of the console for an extended period of time. There were two 12-hour shifts working due to the tight delivery schedule. The CRT terminal and control panel turret, if left assembled, would have been damaged. Also, the disc unit was damaged during installation handling and the full program loading could not be implemented.

During the fabrication and installation phase, there were other activities of interest taking place. To better define the signal levels anticipated and assist in choosing exact placements for vibration sensors on typical machines, early in the program a portable instrumentation package was taken on a sister ship, the Farrell Lines' SS AUSTRAL ENVOY. The equipment included accelerometers, the necessary amplifiers, and a tape recorder. Vibration data were recorded from several machines in various locations and the tape played back through the in-house VIDEC system for analysis and verification.

All equipments underwent a 40-day (24 hour/day) burn-in period in order to minimize failures due to infant mortality. This burn-in applied to the entire system including those electronic signal conditioners which were delivered to the ship directly from the vendors. The VIDEC system was subject to US Coast Guard and American Bureau of Shipping approval. Special Coast Guard approval was extended for the use of a connectorized installation and unarmored low noise vibration Triax cable.

The installation experience identified several considerations applicable to future systems of this nature. The most severe conditions encountered by the VIDEC system occurred during handling in the shipyard installation phase. It is felt that shipboard simulation is the ideal method for installation checkout. Were it not for the various difficulties described earlier, a very rapid and effective system checkout would have been accomplished. The placement of the console in an open area on the main engineroom deck probably subjected it to more potential damage than if it were an integral part of the engineroom console complement. Temporary protection during this installation phase should be provided for all equipment subject to physical damage. The disc unit, as an operational device, running at its normal speed, is capable of withstanding large shock and vibration conditions. However, during installation and handling it becomes more vulnerable as the sensitive pickup heads are resting on the disc platter. Special equipment such as this should be shipped separately from the main cabinets and handled with special care.

EARLY DESIGN CONSIDERATIONS AND RESTRICTIONS

It has been the general policy of MARAD-OCD during early negotiations with ship operators, for the shipboard installation and operation of a prototype system, to ensure that a given system would in no way impact design, development, construction, or operation of the vessel. Each system must incorporate the ability to be quickly isolated from the particular subsystem being monitored or controlled or must be designed so that its function is totally independent of actual vessel operation. There was also an agreement with the ship owner which called for equipment removal if the system proved unsatisfactory. It is within this basic framework that Raytheon's application of Phase I results to the propulsion plant of the SS PRESIDENT JOHNSON was undertaken. All of the VIDEC's instrumentation and therefore, all of its signal inputs were completely independent of existing sensors except for torque and RPM signals which were supplied via COS.

These ground rules naturally created a situation where redundant instrumentation was required. VIDEC instrumentation duplicates and supplements the COS sensor configuration for major engineroom machinery components. Other aspects of VIDEC's design and installation were also impacted by these considerations. Orifice design and installation is a good example. Proper operation of an orifice or flow nozzle for mass flow determination requires that sufficient straight pipe be available both upstream and downstream. These lengths generally are based on the expected pressure drop across the orifice, steam line pressure, pipe diameter, and other factors. Those familiar with marine power plant design know that relatively long straight runs of high pressure steam piping are at best uncommon on ships due to space, expansion, and other considerations. Therefore, situations arose where the unavailability of straight pipe runs and significant pressure drops across an orifice plate made flow measurement unacceptable. Superheated steam flow rates from the port and starboard boilers and steam flow to the main engine are examples. These signals are critical to the thermal analysis of the boilers and turbine set. By relocating certain flow transmitters and making use of VIDEC's computer software flexibility to insert a mass flow summation to derive these critical values, the resulting elimination of these orifice plates had little impact on the thermal analysis portion of the system.

Another critical area for design consideration was cable length between various system components. Integrity of signal transmission from sensors to data processing components to display console was a major concern in determining maximum cable lengths. Excessive runs could cause signal degradation and/or excessive noise pickup. Although certain system components were located outside the engine spaces their location was limited due to cable length. Generally, the course taken throughout system design and installation was one of altering VIDEC to fit the ship rather than attempting to alter the ship to fit VIDEC, with minimum effect on the resulting data.

Integration of a complex electronic system with a newly built vessel is certain to impact the contractual guarantee of the ship's construction. VIDEC was no exception. The 104 vibration sensors, for best results, should have been attached directly to the various machinery by drilling and tapping holes in the casings and attaching the accelerometers directly with cap screws. However, this technique was found to be unacceptable as the drilling and tapping of machinery casings constitute an alteration to the equipment and therefore, would negate the warranty on these machines. The initial solution consisted of attaching drilled and tapped stainless steel mounting pads to the machinery with high strength and high temperature epoxy. The vibration sensors were then secured to these pads with cap screws. With the end of the six-month warranty period, these sensors are now being attached directly to the machinery.

Inclusion of the VIDEC installation on board the new construction vessel brought to view a unique situation. The VIDEC system, being an additional and highly sensitive fault detection instrument, could significantly increase the number of initial machinery faults not normally detected within the ship's warranty period. If utilized in this manner, the VIDEC system could affect warranty liability. A settlement was reached in which the owner agreed not to use VIDEC data for warranty purposes during the guarantee period.

SYSTEM OPERATION, VOYAGES 1-4

A series of management decisions made late in the vessel's construction schedule affected the initial checkout and operation of VIDEC. In mid-December 1973 the ship owner requested delivery of the vessel as soon as practicable. In an effort to meet this request the shipbuilder assigned every available worker in all trades to this vessel. In keeping with the ground rules discussed earlier for the implementation of prototype shipboard hardware systems, virtually all work on the VIDEC installation was stopped as all personnel working on VIDEC were reassigned to other ship systems. VIDEC was not critical to vessel operation and in no way could impact delivery schedules or schedule changes. Thus plans for initial system lightoff, sensor checks, etc., planned for sea trials had to be modified. When the ship departed Pascagoula on 5 January 1974, VIDEC installation was partially completed with system startup, checkout, and calibration still remaining to be performed.

Voyages 1 and 2 saw the completion of the system installation and initial operation at sea. Items completed consisted of the sensor and signal conditioner installation, pressure and differential pressure sensor taps into the piping, welding of various high pressure sensor flange adapters, and correction of installation faults. Fortunately, support personnel on board during this period, through jury rigging and part swapping, were able to bring the system to an operational status. Data processing, equipment installation hookup, and checkout went smoothly except for two instances. As previously mentioned, the rotating disc storage device was damaged during shipment or installation. When the data processing equipment sub-loop was energized, the disc would not function and had to be removed and shipped back to the manufacturer for repairs. By loading a temporary program into core memory, checkout of signal continuity from sensor to CPU could continue until the disc was reinstalled. The second hardware failure in the data processing sub-loop was the programmable gain amplifier located before the 1/3 octave spectrum analyzer. This component was taken back to the plant, repaired and reinstalled in a matter of a few days. Additionally, although not a hardware failure, the late arrival of the cassette tape unit presented some difficulty in system debugging. The flexibility that this device provides for troubleshooting, system modification and data collection is invaluable.

Prior to loading the data base or "Baseline", a thorough check of all 203 vibration and thermal channels was made. Calibration was performed on those sensors that required it. The majority of sensors had been factory calibrated prior to delivery to the yard. Thermal sensor readings were cross-referenced with local instrument and COS remote readings whenever possible as a check for accuracy and repeatability. The following is a description of the actual procedure for baseline loading performed on 7-8 March 1974. It is typical of the baselines loaded prior to and after this date.

The procedure for loading baseline is a simple one. However, complete baseline involves a considerable amount of time. The three baselines loaded during voyage 1 averaged 27 to 30 hours in length. An initial baseline is taken for all sensors whether the components they monitor are on line or not. Data is gathered at five operating points (100, 95, 90, 85 and 80 percent SHP). At the end of the final run a curve fit is performed. During this curve fit, the redundant main and machinery components are transferred. At the end of the first curve fit, a baseline of the redundant equipment is performed as above. The curve fit is repeated and at the end of this curve fit the system is ready for normal operation. Each run, with all components included, required four hours to complete. Of this time, vibration data gathering and processing took about 3 hours and 45 minutes. Thermal data processing required only 15 minutes. Initially it was felt that one hour between runs was required to let the plant stabilize at each new power level. This was especially important for thermal data. However, this hour was not needed. Since vibration data was gathered first, the plant had already run at a steady load for 3-3/4 hours. Ten hours were cut from the time required for a full baseline by eliminating this one hour warmup at each power level. Table 1 describes the baseline format followed for the baseline taken on 7-8 March 1974.

From Table 1 it can be seen that a considerable amount of time must be allotted for baseline operations. Although baseline could have been performed by 2 February 1974, vessel schedule and operational considerations took priority. Loss of data due to main power frequency and voltage fluctuations caused by a turbogenerator governor malfunction in one instance and by VIDEC operator error in another instance made it necessary to acquire two additional baseline runs. Although neither of these difficulties has recurred, an investigation into the need for an uninterruptable power source (UPS) is underway and modifications to the software have been implemented to prevent similar operator error.

OPERATION, VOYAGES 2-4

A major factor which affected both the vibration and thermal subsystem was that, due to the energy shortage, the ship's operating speed was reduced to 20

Table 1. Baseline Loading Procedure 7-8 March 1974
All Channels

<table>
<tr><th>Run No.</th><th>SHP (Meter)</th><th>1st STG Press. (HP Turbine)</th><th>Start</th><th>Complete</th></tr>
<tr><td>5</td><td>28,500</td><td>370 psig</td><td>1510 (3/7)</td><td>1915</td></tr>
<tr><td>4</td><td>27,100</td><td>350 psig</td><td>1920</td><td>2320</td></tr>
<tr><td>3</td><td>25,600</td><td>330 psig</td><td>2330</td><td>0435 (3/8)</td></tr>
<tr><td>2</td><td>24,200</td><td>310 psig</td><td>0445</td><td>0830</td></tr>
<tr><td>1</td><td>22,800</td><td>290 psig</td><td>0840</td><td>1230</td></tr>
<tr><td colspan="5">Curve Fit 1 1230-1330</td></tr>
<tr><td colspan="5">Redundant Component
Update</td></tr>
<tr><td>1</td><td>22,800</td><td>290 psig</td><td>1335</td><td>1420</td></tr>
<tr><td>2</td><td>24,200</td><td>310 psig</td><td>1425</td><td>1510</td></tr>
<tr><td>3</td><td>25,600</td><td>330 psig</td><td>1515</td><td>1600</td></tr>
<tr><td>4</td><td>27,100</td><td>360 psig</td><td>1700</td><td>1745</td></tr>
<tr><td>5</td><td>28,500</td><td>370 psig</td><td>1755</td><td>1840</td></tr>
<tr><td colspan="5">Curve Fit 2 1840-1940</td></tr>
</table>

knots which corresponds to approximately 75 percent SHP load. This meant that the VIDEC system would seldom function in a normal operating mode (automatically cutting out below 80 percent SHP). Therefore, the system was placed in In-Port mode, collecting vibration data only.

It was not until the second voyage (19 March to 9 June) that data of any consequence was obtained. A preliminary review of this first data set showed that there were several questionable areas requiring investigation. The vibration analysis data revealed a high number of false alarms and the thermal data was sparse.

Prior to voyage 3 the ship's engineering officers were occupied with the problems associated with new vessel adjustment. During this period there was little confidence inspired due to the high false alarm rate and minimal thermal data available for use. Following consultation, a decision was made to extend the lower limit for the Operate mode to 70 percent SHP where it was felt that the plant operating conditions would still be fairly stable.

Prior to voyage 4, both software and hardware modifications were incorporated. The 70 percent SHP mode change proved to be instrumental not only in permitting collection of thermal data but also in drastically reducing vibration false alarms. There was no baseline taken below 80 percent SHP due to data storage limitations and it was decided to use the 80 percent load data as a reference for all In-Port mode conditions. This proved to be erroneous for variable speed machinery where the vibration signature changes with speed and contributed greatly to the false alarms observed. Efforts are under way at this time to investigate the possible addition of a separate In-Port baseline reference below 70 percent SHP. During voyage number 4 (22 August to 1 November), the Chief Engineer was able to become more involved with the system and contributed valuable criticism defining potential benefits as well as system weak points.

During these first voyages, the VIDEC system has been supported with one and two engineers full time. This effort has been necessary due to the many problems involved with incomplete installation, debugging, improvements and unavailability of ship's engineering force due to their involvement in new vessel operation. There was a contractual arrangement with APL during this period for MARAD and Raytheon to supply support until operating personnel were in a position to assume responsibility for the system. VIDEC has reached a point in its development where this full-time support should no longer be needed and the intent at this time is to turn over operation to the ship's engineering officers during voyage 6, scheduled to begin 5 February.

FINDINGS TO DATE

It is premature to report on overall system performance analysis. However, several findings have been identified at this point in the program. These findings have been determined from the data collected, system reports, and discussions with shipboard personnel.

The ability to make system revisions, modifications, etc., has been facilitated through the inherent flexibility of this modular system being completely software-controlled. The modifications incorporated would not have been possible in a hard-wired system without major rework. The advantages for having a software-controlled design for a first of a kind program are rather obvious. However, other benefits of this flexibility have become apparent with the ease with which operational changes may be made, such as sensor rescaling, demand display requests, thermal parameter changes, rescheduling of events and the addition of channels.

There is a definite impact on the data collected from the engineroom due to shipboard operating conditions such as displacement, trim, sea state and shallow water squat. These conditions affect both vibration and thermal measurements. Frequent monitoring of such data has revealed periodic variances in vibration levels and pressures related to the rolling of the ship and impact during heavy seas.

Sensor relocations, rescaling and equation modifications became necessary as a result of last-minute ship design changes and evaluation of the first data set. Owing to the flexibility within VIDEC, this trimming of the measurement system to the ship was made possible.

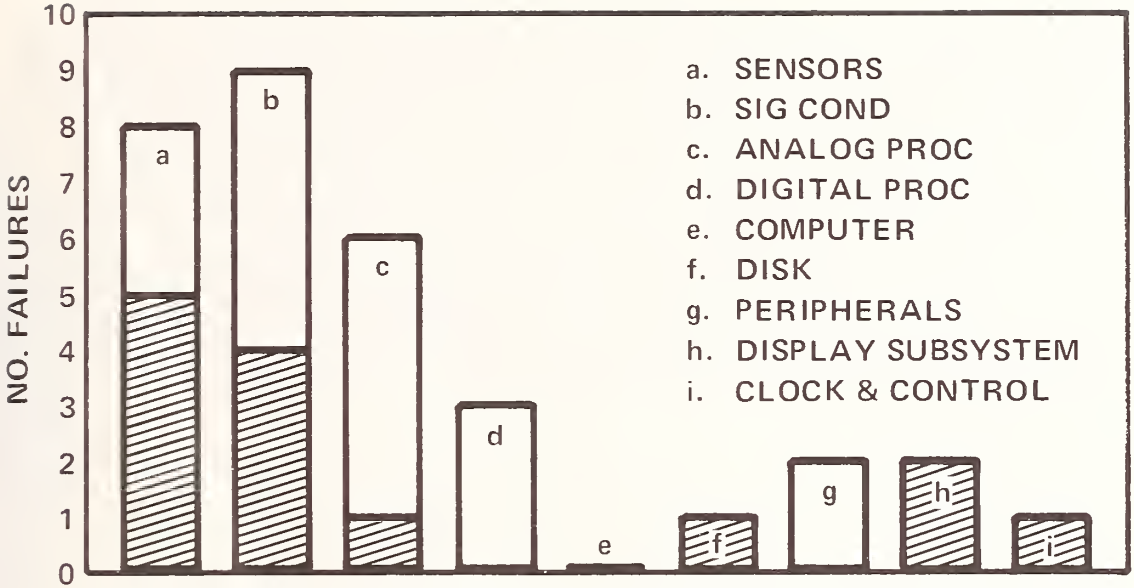
System maintenance has not posed significant problems thus far and appears to be well within the capability of the ship's engineering officers. This characteristic is very important and is facilitated by the automatic system self-test, modular design, software-controlled hardware functions, hardware accessibility, available diagnostics and realtime sensor display features such as calibrate mode and vibration preprocessor display.

The VIDEC system configuration is not the optimum from an operator's standpoint. Much of the data displayed is intended for further analysis and does not provide immediate answers as to what the machinery problems are. In order to better serve as a performance monitoring system, improvements will have to be made in this area to display more useful information for the machinery problems which occur.

The continuous operation of a computer-based monitoring system is proving to be a highly practical concept with respect to reliability. The most sophisticated components of the system (i.e., computer, disc, digital processing and display equipment) have been the most reliable elements of the system. Figure 8 shows the distribution of system failures. To further qualify the chart, 20 percent of the failures were caused during the shipyard installation phase as a result of miswires or handling, including the single disc failure. All of the failures indicated under the "digital processing ","clock and control" and "display subsystem" were caused by loss of cooling air at the engineroom console. The air duct installed for the purpose of directing outside air to the console blower intake was inadvertently cut off.

Investigation into the cause of the failures which were experienced resulted in several determinations.

Five of the sensor failures indicated constitute the same component, a turbine flow meter magnetic pickup probe. Vendor analysis of the failed parts revealed a discrepancy in the manufacturing process which was subsequently corrected.



FAILURE OCCURRENCES SHADED REPRESENT INSTALLATION, INFANT MORTALITY AND OPERATOR ERROR PROBLEMS.

Figure 8. VIDEC Failure Distribution

The turbine type flow meter used for measuring the mass flow rate of circulating water outlet of the main condenser was found to be susceptible to being jammed with foreign matter. This type of sensor seems to be unsuitable for the application.

Two of the signal conditioner failures which occurred were traced directly to the operating temperature environment. The actual ambient temperature experienced was greater than that expected. Once relocated, these units never failed again.

VIDEC YEAR II

The continuing effort with the VIDEC program for the next year is concentrated on evaluation with the objective being a qualitative determination of both technical feasibility and economic value. The basis for this evaluation is an objective analysis of data. The data includes system outputs, machinery logs, deck logs, operations cost data (from the PRESIDENT JOHNSON as well as sister ships) and evaluations by shipboard personnel. A common failing usually associated with programs of this nature is that the large volumes of data collected surpass the ability to analyze it. The VIDEC Phase III program was designed to handle vast quantities of data. The entire set of system parameters needed for evaluation is recorded on digital cassettes as part of the normal VIDEC functions. Each cassette contains a complete set of data for two days of operation. Machinery log information (repairs, preventive maintenance, chemical water analysis, fuel oil characteristics, etc.) and deck log information (sea state, draft, speed, etc.) are recorded daily on preformatted forms. Retrieved once per voyage, the tapes and forms are merged in a chronological format on computer tape reels via a sorting process. Hard copy reports and printouts serve only as reference material if needed. Cost information including operating, manning, repairs, etc., will also be entered in a similar manner where recall and analysis are accomplished under the control of a large data processing system.

The evaluation process includes correlation of data to determine:

- comparison of short term vs long term trends
- validity of system failure prediction
- effect of VIDEC-induced plant adjustments on overall fuel consumption
- effect of ship operating conditions on plant efficiency
- thermal/vibration deviation correlation
- most cost effective plant performance indicators
- accuracy of steam plant performance calculations
- vibration failure modes for various machines.

The Phase III program is a well-coordinated effort under the direction of MARAD with direct involvement by NMRC, Raytheon, and APL. In addition, several notable specialists are assisting in the areas of thermodynamics, machinery vibration, and economic analysis.

SYSTEM FUTURE

VIDEC is an integral part of MARAD-OCD's Unmanned Machinery Space Development Program. It is a steppingstone in the development of an automated closed loop monitoring and control system for engineroom applications suitable for adaption to all types of vessels and power plants. At the end of FY '76 an optimum condition and performance monitoring system will be defined incorporating all of the desirable concepts in VIDEC. Once the optimum monitoring system has been configured from the evaluation along with other inputs, development of a closed loop control system can be continued. Additionally, during this period, data generated by VIDEC is made available to other related ongoing MARAD-OCD R & D programs, such as the Integrated Ship System (ISS), specifically as it applies to condition and performance monitoring areas. This is done in accordance with MARAD's policy of cross-fertilization between related R & D programs and to prevent duplication of effort. Finally, VIDEC will be evaluated in a stand-alone aspect as a condition and performance monitoring system from which a standard specification for such systems can be developed for inclusion in specifications for future MARAD-subsidized vessel construction.

Based on discussions with a number of ship operators to date, we believe that there is a definite and increasing need aboard modern ships for a system capable of reliable, automatic continuous monitoring of machinery status and condition. The primary interest of these ship operators, at this time, is the reduction of vessel downtime. The capability to detect imminent failures, to accurately diagnose the cause of machinery degradation and to predict future deterioration and failures through trend analysis of monitored data will all contribute to reducing vessel downtime. Therefore, Raytheon is committed to the design of software-oriented, modular monitoring systems employing the methods and techniques utilized in the implementation of VIDEC.

By using digital microprocessor technology and modular architecture the scope of such systems can be configured to the particular needs of the vessel's machinery plant and the owner's budget, and readily modified or expanded as the need arises. It is fully expected that the ultimate results of the VIDEC operational evaluation will demonstrate the usefulness of such monitoring and diagnostic systems.

CONCLUSIONS AND RECOMMENDATIONS

- During the first year of operation, problems with the data processing and display hardware were very minor. Sensor heat failures made up most of the component failures.
- The system software functioned very reliably; only minor changes were required.
- The operation and maintenance of this system is not beyond the capability of responsible operating marine engineers.
- From the experience to date, it would appear that the shipboard installation and operation of a high powered process control minicomputer and a sophisticated software package are feasible.
- From initial inspection of the vibration levels taken from the three baselines loaded during the first three months of operation, vibration appears to be closely related to draft, displacement, sea state, and wind as well as shaft horsepower. Other operating phenomena, such as squat that

occurs in shallow water passages, also appear to have an influence on vibration levels.

- Judicious equipment selection and location of key components in environmentally controlled spaces has significantly reduced casualties caused by the harsh seagoing environment.
- The 40-day burn-in period for all system data processing and display components, a detailed system simulation to debug VIDEC software, and the inclusion of a sophisticated self-test routine contributed greatly in minimizing failures and problems encountered during operation.
- Vibration failure detection is capable of detecting failures that occur from actual physical changes within a component; e.g., when a balance weight in a forced draft fan impeller flew off and when a feed pump packing retainer ring backed out of its housing.
- Improved system displays are required to present machinery diagnostic data in a more suitable form for immediate operator evaluation.

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3) VIDEC Training Course Manual, Raytheon Company, Submarine Signal Division, Portsmouth, Rhode Island, September 1973.

APPENDIX

- Vibration Sensor List
- Thermal Micro and Macro List
- Operator Demand Requests
- Operator Parameter Update List
- Adjustable Thermal Constants.

VIBRATION SENSOR LIST

CHANNEL NUMBER	SENSOR LOCATION	SENSITIVITY
1	Line Shaft Brg No. 1 (FWD End)	Radial
2	Line Shaft Brg No. 1 (AFT End)	Radial
3	Line Shaft Brg No. 2 (Top End)	Radial
4	Line Shaft Brg No. 2 (Side End)	Radial
5	Line Shaft Brg No. 3 (Top End)	Radial
6	Line Shaft Brg No. 3 (Side End)	Radial
7	Port L.O. Serv Pump Motor Upper Brg	Radial
8	Port L.O. Serv Pump Motor Lower Brg	Radial
9	HP Turbine 1st Red Pin FWD Brg	Radial
10	HP Turbine 1st Red Pin AFT Brg	Radial
11	HP Turbine 1st Red Gear FWD Brg	Radial
12	HP Turbine 1st Red Gear AFT Brg	Radial
13	HP Turbine 2nd Red Pin AFT Brg	Radial
14	LP Turbine 1st Red Pin FWD Brg	Radial
15	LP Turbine 1st Red Pin AFT Brg	Radial
16	LP Turbine 1st Red Gear FWD Brg	Radial
17	LP Turbine 1st Red Gear AFT Brg	Radial
18	LP Turbine 2nd Red Pin AFT Brg	Radial
19	Line Shaft Thrust Brg	Radial
20	HP Turbine FWD Brg	Radial
21	HP Turbine AFT Brg	Radial
22	LP Turbine FWD Brg	Radial
23	LP Turbine Aft Brg	Radial
24	Stbd L.O. Serv Pump Motor Upper Brg	Radial
25	Stbd L.O. Serv Pump Motor Lower Brg	Radial
26	Stbd L.O. Serv Pump Brgs	Radial
27	Main Circ Pump Motor Upper Brg	Radial
28	Main Circ Pump Motor Lower Brg	Radial
29	Main Circ Pump Brg Upper	Radial
30	Main Circ Pump Brg Lower	Axial
31	STBD Cond Pump Motor Upper Brg	Radial
32	STBD Cond Pump Motor Lower Brg	Radial
33	STBD Cond Pump Brgs	Radial
34	STBD Cond Pump Brgs	Axial
35	Port Cond Pump Motor Upper Brg	Radial
36	Port Cond Pump Motor Lower Brg	Radial
37	Port Cond Pump Brgs	Radial
38	Port Cond Pump Brgs	Axial
39	SSTG Turbine FWD Brg	Radial
40	SSTG Turbine AFT Brg	Radial

VIBRATION SENSOR LIST (Cont)

CHANNEL NUMBER	SENSOR LOCATION	SENSITIVITY
41	SSTG Pinion AFT Brg	Radial
42	B.B. & S.W. Serv Pump Motor Upper Brg	Radial
43	SSTG Gear AFT Brg	Radial
44	SSTG AFT Brg	Radial
45	SBDG Engine FWD Brg	Radial
46	SBDG Engine AFT Brg	Radial
47	SBDG AFT Brg	Radial
48	B.B. & S.W. Serv Pump Motor Lower Brg	Radial
49	B.B. & S.W. Serv Pump Brgs	Radial
50	STBD Main Feed Pump FRD Brg	Radial
51	STBD Main Feed Pump AFT Brg	Radial
52	STBD Main Feed Pump Thrust Brg	Radial
53	B.B. & S.W. Feed Pump Brgs	Axial
54	Port Main Feed Pump FWD Brg	Radial
55	Port Main Feed Pump AFT Brg	Radial
56	Port Main Feed Pump Thrust Brg	Radial
57	Port Feed Pump Motor FWD Brg	Radial
58	Port Feed Pump Motor AFT Brg	Radial
59	Port Feed Pump FWD Brg	Radial
60	Port Feed Pump AFT Brg	Radial
61	STBD F. D. Blower Motor STBD Brg	Radial
62	STBD F. D. Blower Motor Port Brg	Radial
63	STBD F. D. Blower STBD Shaft Brg	Radial
64	STBD F. D. Blower Port Shaft Brg	Radial
65	Port F. D. Blower Motor Port Brg	Radial
66	Port F. D. Blower Motor STBD Brg	Radial
67	Port F. D. Blower Port Shaft Brg	Radial
68	Port F. D. Blower STBD Shaft Brg	Radial
69	STBD F. O. Serv Pump Motor Upper Brg	Radial
70	STBD F. O. Serv Pump Motor Lower Brg	Radial
71	STBD F. O. Serv Pump Brgs	Radial
72	Port Atmos Drain Pump Brg	Radial
73	Port F. O. Serv Pump Motor Upper Brg	Radial
74	Port F. O. Serv Pump Motor Lower Brg	Radial
75	Port F. O. Serv Pump Brgs	Radial
76	STBD Atmos Drain Pump Brg	Radial
77	Port Cond Exh Vac Pump Motor STBD Brg	Radial

VIBRATION SENSOR LIST (Cont)

CHANNEL NUMBER	SENSOR LOCATION	SENSITIVITY
78	Port Cond Exh Vac Pump Motor Port Brg	Radial
79	Port Cond Exh Vac Pump STBD Brg	Radial
80	Port Cond Exh Vac Pump Port Brg	Radial
81	Salt Water Serv Pump Motor Upper Brg	Radial
82	Salt Water Serv Pump Motor Lower Brg	Radial
83	Salt Water Serv Pump Brgs Upper	Radial
84	Salt Water Serv Pump Brgs Lower	Axial
85	STBD Air Comp Motor STBD Brg	Radial
86	STBD Air Comp Motor Port Brg	Radial
87	STBD Air Comp STBD Brg	Radial
88	STBD Air Comp Port Brg	Radial
89	Port L.O. Serv Pump Brgs	Radial
90	Control Air Comp Motor FWD Brg	Radial
91	Control Air Comp Motor AFT Brg	Radial
92	Control Air Comp Brg	Radial
93	FWD Steer Pump Motor FWD Brg	Radial
94	FWD Steer Pump Motor AFT Brg	Radial
95	FWD Steer Pump FWD Brg	Radial
96	FWD Steer Pump AFT Brg	Radial
97	AFT Steer Pump FWD Brg	Radial
98	AFT Steer Pump AFT Brg	Radial
99	AFT Steer Pump Motor FWD Brg	Radial
100	AFT Steer Pump Motor AFT Brg	Radial
101	STBD Cond Exh Vac Pump Motor STBD Brg	Radial
102	STBD Cond Exh Vac Pump Motor Port Brg	Radial
103	STBD Cond Exh Vac Pump STBD Brg	Radial
104	STBD Cond Exh Vac Pump Port Brg	Radial

THERMAL MICRO AND MACRO LIST

SENSOR NO.	ADDRESS NO.	MICROPARAMETERS	OP.	MACROPARAMETERS
		-1 Condenser-		-1 Condenser-
105	1	Temp Seawater	1	Condenser Sat Temp
106	2	Temp Circ Water Outlet	2	Temp Circ Wtr Outlet
107	3	Condenser Sat Temp	3	Condenser Film Coeff
108	4	Temp Main Condensate	4	Pct Ht Rej
109	5	Flowrate Circ Water		
		-2 H.P. Turbine-		-2 H.P. Turbine-
110	6	Flowrate H.P. Turbine Inlet*	5	Cor 1st Stg Press
111	7	Flowrate H.P. Bld	6	H.P. Turb Eff
112	8	Flowrate I.P. Bld		
113	9	Temp H.P. Turb Inlet		
114	10	Press H.P. Turb Inlet		
115	11	Temp H.P. Bld		
116	12	Press H.P. Bld		
117	13	Temp I.P. Bld		
118	14	Press I.P. Bld		
119	15	Temp Crossover Bld		
120	16	Press Crossover Bld		
121	17	First Stg Press		
		-3 L.P. Turbine-		-3 L.P. Turbine-
122	18	Flowrate Crossover Bld	7	L.P. Turb Eff
123	19	Flowrate Drns L.P. Htr	8	Exhaust Loss
124	20	Press L.P. Bld		
125	21	Temp L.P. Bld		
		-4 H.P.&L.P.Turbine-		-4 H.P.&L.P.Turbine-
126	22	Shaft Horsepower*	9	Pct Pwr in H.P. Turb
127	23	Line Shaft RPM	10	Mech & Ext Efficiency
128	24	Line Shaft Torque		
		-5 H.P.&L.P. Heater-		-5 H.P.&L.P. Heater-
129	25	Shell Press H.P. Htr	11	Pump 1 Flowrate
130	26	Temp Drns H.P. Clr	12	Pump 2 Flowrate
131	27	Temp Fd Wtr Outlet H.P. Htr	13	4th Stg Coeff
132	28	Temp Fd Wtr Inlet I.P. Clr	14	Effectiveness
133	29	Press Fd Wtr Inlet I.P. Clr	15	Steam Flo/Feed Flo
134	30	Shell Press I.P. Htr	16	3rd Stg Coeff
135	31	Temp Fd Wtr Outlet I.P. Htr	17	Effectiveness
136	32	Temp Drns I.P. Clr	18	Steam Flo/Feed Flo
			19	3rd Stg Inlet Temp
			20	3rd Stg Outlet Temp
			21	4th Stg Outlet Temp
		-6 D.F.T. Heater-		-6 D.F.T. Heater-
137	33	Temp Outlet DFT	22	Effectiveness
138	34	Temp Condensate Inlet DFT	23	Diff Saturation Temp
139	35	Temp Outlet Primary Sect DFT		
140	36	Shell Press DFT		

THERMAL MICRO AND MACRO LIST (Cont)

SENSOR NO.	ADDRESS NO.	MICROPARAMETERS	OP.	MACROPARAMETERS
		-7 L.P. Heater-		-7 L.P. Heater-
141	37	Temp Condensate Outlet L.P.Ht	24	Steam Flo/Cond Flo
142	38	Temp Condensate Inlet Drn Clr	25	Effectiveness
143	39	Shell Press L.P. Heater		
144	40	Flowrate Mn Condensate		
		-8 Boiler 1-		-8 Boiler 1-
145	41	Temp Fd Wtr Inlet Stm Drm	26	Efficiency
146	42	Press Suphtd Stm	27	Feedwater Temp
147	43	Tot Temp Suphtd Stm	28	Slag Formation
148	44	Press Desuphtd Stm	30	Soot Formation
149	45	Temp Desuphtd Stm	31	Flowrate Difference
150	46	Temp Gas Outlet Mn Bank	32	Tot Steam Flowrate
153	49	Pct Open Control Desuphtr		
154	50	Flowrate Desuphtd Stm		
155	51	Flowrate Suphtd Stm*		
156	52	Flowrate Fuel Oil Burners		
157	53	Temp Fuel Oil Burners		
		-9 Boiler 2-		-9 Boiler 2-
159	55	Temp Fd Wtr Inlet Stm Drm	33	Efficiency
160	56	Press Suphtd Stm	34	Feedwater Temp
161	57	Tot Temp Suphtd Stm	35	Slag Formation
162	58	Press Desuphtd Stm	37	Soot Formation
163	59	Temp Desuphtd Stm	38	Flowrate Difference
164	60	Temp Gas Outlet Mn Bank	39	Tot Steam Flowrate
167	63	Pct Open Control Desuphtr		
168	64	Flowrate Desuphtd Stm		
169	65	Flowrate Suphtd Stm*		
170	66	Flowrate Fuel Oil Burners		
171	67	Temp Fuel Oil Burners		
		-10 Regenerative Air Htr 1-		-10 Regen Air Htr 1-
173	69	Temp Air Inlet Regen Htr	40	Effectiveness
174	70	Temp Air Outlet Regen Htr		
175	71	Temp Gas Outlet Regen Htr		
		-11 Regenerative Air Htr 2-		-11 Regen Air Htr 2-
176	72	Temp Air Inlet Regen Htr	43	Effectiveness
177	73	Temp Air Outlet Regen Htr		
178	74	Temp Gas Outlet Regen Htr		
		-12 Feed Pump-		-12 Feed Pump-
187	83	Flowrate Fd Pump*	50	Turb Steamrate
188	84	Press Fd Pump Suct	51	Pump Eff
189	85	Temp Fd Pump Suct	52	Water Hp
190	86	Press Fd Pump Disch	53	RPM
191	87	Temp Fd Pump Disch		
192	88	Flowrate Stm Fd Pump*		
193	89	RPM Fd Pump		

THERMAL MICRO AND MACRO LIST (Cont)

SEN-SOR NO.	ADD-RESS NO.	MICROPARAMETERS	OP.	MACROPARAMETERS
		-13 Feed Pump-		-13 Feed Pump-
194	90	Flowrate Fd Pump*	54	Turb Steamrate
195	91	Press Fd Pump Suct	55	Pump Eff
196	92	Temp Fd Pump Suct	56	Water Hp
197	93	Press Fd Pump Disch	57	RPM
198	94	Temp Fd Pump Disch		
199	95	Flowrate Stm Fd Pump		
200	96	RPM Fd Pump		
		-14 Turbo-Generator-		-14 Turbo-Generator-
201	97	Flowrate Steam Turbo-Gen	58	Turb Steamrate
202	98	Kilowatt Output Turbo-Gen.	59	Kw Load
		-15 Distilling Plant-		-15 Distilling Plant-
203	99	Flowrate Stm Distiller	60	Lb Stm/Lb Water
204	100	Temp Dist S.W. Htr Outlet	61	Temp Rise S.W. Htr
205	101	Temp Dist S.W. Htr Inlet	62	S.W. Htr U
206	102	Temp S.W. Inlet Dist AE Condr		
207	103	Shell Press Dist S.W. Htr		
208	104	Flowrate Distillate		
		-16 Main Condensate Pump 1-		-16 Main Cond. Pump 1-
209	105	Kilowatt Input Cond Pump	63	Water Hp
210	106	Flowrate Mn Condensate*	64	Pump Eff
211	107	Disch Press Mn Cond Pump	65	Cond Flowrate
212	108	Suct Press Mn Cond Pump		
213	109	Barometric Press*		
		-17 Main Condensate Pump 2-		-17 Main Cond. Pump 2-
214	110	Kilowatt Input Cond Pump	66	Water Hp
215	111	Flowrate Mn Condensate*	67	Pump Eff
216	112	Disch Press Mn Cond Pump*	68	Cond Flowrate
217	113	Suct Press Mn Cond Pump*		
218	114	Barometric Press*		
		-18 Miscellaneous-		-18 Miscellaneous-
226	122	Xstem Gld Stm Supply	72	Shaft Horsepower
227	123	Xstm Mn Condr	73	Ov'l Sp Fuel Rate
228	124	Stm to Stack		

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                  DEMAND REQUEST MENU


          01   VIBRATION TRENDS
          02   THERMAL TRENDS
          03   ELAPSED TIME COUNTERS
          04   TAPE RELOAD
          05   PARAMETER UPDATE
          06   NRT DATA STORAGE
          07   BROADBAND POINT DISPLAY
          08   PREPROCESSOR DISPLAY
          09   RAW DATA
          10   TRIP PRINT AT DAY END
          11   ENTER OR EXIT INPORT MODE

          TYPE NUMBER OF DESIRED SELECTION
```

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                  PARAMETER UPDATE LIST


      01   NO. OF BASELINE RUNS
      02   NO. OF STANDARD DEVIATIONS
      03   THERMAL RANGES FOR SCALING
      04   NO. OF VIBR CHANNELS + SET ENDPTS
      05   NO. OF BASELINE LOAD POINTS
      06   NO. OF REGIONS
      07   NO. OF BANDS/REGION + ID VECTORS
      08   NO. OF GROUPS
      09   NO. OF BANDS/GROUP + ID VECTORS
      10   GROUP ALARM LEVELS
      11   REGION TREND LIMITS
      12   THERMAL LIMITS
      13   DURATION OF MULTIDAY DISPLAY
      14   MINIMUM TIME TO ALARM
      15   NRT ID VECTOR
      16   THERMAL CONSTANTS
      17   NEW TRIP INITIALIZATION
      18   MAXIMUM MACROPARAMETER DEVIATIONS
      19   EXIT PARAMETER UPDATE

      TYPE NUMBER OF DESIRED PARAMETER
```

ADJUSTABLE THERMAL CONSTANTS

1 AFLO	Total flow area (condenser)
2 DV	Design average velocity of circulating water in each tube (condenser)
3 DTO	Design circulating water temperature out of condenser
4 DTI	Design circulating water temperature into condenser
5 DDT	(DTO-DTI)
6 RHOSW	Used to calculate mass flowrate (condenser)
7 PSTD	Reference throttle pressure (H. P. Turbine)
8 VSTD	Reference throttle specific volume (H. P. Turbine)
9 SURFH	Total heat transfer surface (High Pressure Heater)
10 SURFI	Total heat transfer surface (Intermediate Pressure Heater)
11 ELNE	Non-extraction exhaust loss (L. P. Turbine)
12 SHPNE	Non-extraction shaft horsepower (L. P. Turbine)
13 SRNE	Non-extraction exhaust loss (L. P. Turbine)
14 ZEGNE	Non-extraction exhaust specific volume (L. P. Turbine)
15 HHV1	Higher heating value of F.O. (Boiler 1)
16 HHV2	Higher heating value of F.O. (Boiler 2)
17 CPFO1	Specific heat for I.O. (Boiler 1)
18 CPFO2	Specific heat for I.O. (Boiler 2)
19 C1	Constant for Feed Pumps
20 C2	Constant for Feed Pumps
21 PTEST	RPM threshold (Feed Pumps)
22 AKTEST	Kilowatt threshold (Condensate Pumps)
23 C	Constant based on tube size and material (condenser)
24 FB	Constant based on tube size and material (condenser)
25 SMC	Total tube heat transfer area in main condenser
26 CPSW	Specific heat of seawater (condenser)
27 DQ	Design heat rejection (condenser)
28 SBTU	BTU for dollar deviations

DISCUSSION

E. DuBack, General Dynamics, Electric Boat: Since you have very high propulsion noise, how are you going to make your vibration readings worthwhile?

W. L. McCarthy: This is one of the things that we are attempting to tackle. As we pointed out, right now we don't have a lot of data, so although, according to the program managers, we are supposed to be in an evaluation phase, we just don't have enough data for evaluation. To the operating people, it is a very obvious problem. With redundant machinery, an off-line pump could be monitored for background noise to establish a data base.

E. DuBack: Do you know how the threshholds were established?

W. L. McCarthy: The threshhold is three times the base line. This was established from our computer program. Perhaps we should have made use of data that are available from other industry applications, but we wanted to try to get some hard facts on a shipboard application.

M. B. Peterson, Wear Sciences, Inc.: You mentioned as one of your objectives reducing manpower in the engine room. Now that you have seen the system, do you think you can reduce the manpower?

W. L. McCarthy: Obviously, I think that if you can prove the concept, you can reduce manpower. Right now on the Johnson, during a normal watch period, there are two men - a licensed engineer and an unlicensed junior engineer. During maneuvering and other situations, more men help. I think that you could eliminate the junior engineer. There are systems now in Europe where there isn't any watch on board during steady state conditions. There is just the normal 8 to 5 workday. Again, this is strictly a monitoring system. If we can prove reliability in a computer in terms of data gathering, etc., we could apply similar techniques to control and automate the control portion.

SESSION IV

COMING REQUIREMENTS

Chairman: B. K. Genetti
General Electric Company

AN OVERVIEW OF CURRENT EFFORTS TO DETECT AND PREVENT STEEL WHEEL FAILURES

Gary L. Leadley
Association of American Railroads, Chicago, Illinois 60616

INTRODUCTION

According to annual statistics compiled by the Office of Safety in the Federal Railroad Administration(1) there were a total of 324 reportable derailments* attributed to wheel defects or failure during 1973. While this number represents only 4.4% of all such accidents during the year, it amounts to 18.4% of equipment related derailments and continues the trend of increasing frequency that has been established in recent years. The impetous behind this trend is primarily the parallel rise in both car loads and train speeds(2) which have placed many critical components, particularly wheels, in a severe stress environment. This situation will continue to be a driving force for railroads and their suppliers to improve wheel designs and material properties. However, until such efforts succeed in effectively eliminating wheel related accidents there must be an energetic parallel program to investigate the use of non-destructive diagnostic techniques to identify defective components prior to a damaging failure.

This paper will review the nature of railroad wheels, including their more detrimental defects and conditions, and then delve into several of the non-destructive detection and evaluation techniques currently being considered for use in their assessment.

RAILROAD WHEELS

While all railroad wheels have a similar basic design (Figure 1) and conform to certain dimensional requirements established by the Association of American Railroads, there is actually a wide variety of cross sections in use today. The exact contour of any given wheel is dictated by several factors; such as the manufacturing process, the intended application and the desired service life.

The first of these factors establishes a basic division in the character of the wheel population. Presently, there are two basic methods used in making

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*Those derailments which caused railroad property damage in excess of $750.00.

wheels - forging and casting. According to procurement figures compiled by the Association of American Railroads for the period 1970-1972 there were approximately twice as many cast wheels sold as forged (wrought) wheels. This sales ratio is about the same today and has resulted in a population that is nearly equally divided between the two types due to the more recent appearance of cast wheels.

The second influencing factor is the intended application, that is, the type and severity of service. As one would expect, higher car loads require the use of larger diameter wheels in order to maintain rail contact stresses at acceptable levels. Nominal diameters range from 28 in. to 42 in. (.71 m to 1.06 m) with corresponding recommended load limits of 21,600 lb. and 34,900 lb. (96,081 N and 155, 235 N). In addition to the load dictated design requirements there are those associated with special types of service. Examples of such special applications would be mass transit cars, industrial transfer cars and mine train locomotives.

A third factor that is considered in the design of a wheel is the desired wear life. The vast majority of wheels (≈ 85%) in service are designed for a single tread life. This design is appropriately called a one-wear wheel. Effective wheel life can be extended by making the rim sufficiently thick to allow remachining of the tread to restore the original contour. Wheels with this capability are designated as either two-wear or multiple-wear depending on the rim thickness. The Association of American Railroads' specifications for the one-wear, two-wear, and multiple-wear rims are minimums of 1.25, 2.0, and 2.5 in. (3.17, 5.08, and 6.35 cm), respectively.

Nondesign variables that can be adjusted to meet the various service requirements wheels encounter are material properties. Properties such as hardness, yield strength, fatigue resistance, and thermal cracking sensitivity are controlled principally by material chemistry and heat treatment. Since many properties are optimized by opposite adjustments of these factors it has been necessary to establish five classes of wheels tailored to meet different service requirements. The Association of American Railroads' chemical and hardness specifications(3) for these classes are listed in Table I along with their intended service.

There are two classes that receive no special heat treatment after fabrication - U and U1. The three heat treated classes increase in carbon content, hardness and severity of service with ascending alphabetical order, A, B, and C. Heat treatment generally consists of quenching and tempering the wheel rim only, leaving the plate and hub in a softer normalized condition. Entire wheel quenching is permitted for wrought wheels, however, undesirable tensile stresses are introduced into the rim by such processing. In comparison, rim quenching produces compressive residual stresses there that impede the formation and growth of cracks.

This basic review of railroad wheels illustrates the design and material variables that tend to complicate the development of NDE systems capable of inspecting all wheels with equal reliability and speed.

WHEEL DEFECTS

The types of wheel defects that are considered unacceptable for interchange service are described and illustrated in the Association of American Railroads' Wheel and Axle Manual (Sec. 3C) and the Association of American Railroads' Interchange Rules (Rule 41). Since the detection of the more common varieties of these defects should be the primary goal of any NDE system or combination of systems, it is appropriate to review typical examples.

One of the most common wheel defects is the fatigue breakdown of the tread surface known as shelling. Figure 2 shows deep-etched cross and tread sections of a rim from such a wheel. In this case the shelled band was 1.25 in. (3.17 cm) wide and extended to a depth of 0.094 in (.239 cm). There are many contributing factors to shell development including poor track conditions, excessive loads and speeds, insufficient wheel hardness and undersized wheels for the load. Such factors tend to increase the rail contract stresses above the endurance strength of the material.

A mode of wheel failure that commonly results in the loss of rim and flange sections is known as rim shattering. This type of defect usually initiates at internal inclusions located under the high contact stress areas of the tread. As shown in Figure 3, a fatigue plane, roughly parallel to the tread, extends out from these sites (arrows), under continued cyclic loading, until the front and/or the back rim face is penetrated to form a circumferential crack. At this point the wheel becomes condemnable by the Association of American Railroads' standards. Continued wheel operation usually causes cracking normal to the fatigue plane along its periphery and the eventual loss of entire rim sections.

Another cause of wheel failure, that is particularly important from a frequency standpoint, is thermal cracking. The occurrence of these defects is directly related to the fact that wheels function as brakedrums, as well as being supporting members for the vehicle. Thermal cracks can initiate by fatigue as the result of thermal cycling in repeated brakings or by a cleavage mechanism where the tensile stresses developed in a few severe brakings are sufficient to cause a brittle crack to form. Once initiation occurs by either mechanism the crack will extend under the continuing action of residual tensile stresses until the critical crack size for brittle fracture is achieved. At that point unrestrained crack growth will occur, which can result in explosive wheel fracture.

Examples of various thermally cracked wheels are shown in Figures 4-7. The first specimen is characterized by numerous transverse cracks that originated in the excessively heated outer tread and extended into the front rim. Apparently stresses in this wheel did not build to a sufficient level to cause brittle fracture. That condition was satisfied, however, in the wheel shown in Figure 5. This 33 in., wrought wheel developed a single thermal crack at the front rim edge (arrow). Subsequent stressing resulted in the rapid propagation of the crack through the rim and into the plate where it split to form two circumferential cracks that encircled the hub causing the total separation of the rim. Misalignment of the brake shoe over the rim edge was indicated by the thermal crack location and local discoloration. Another example of misaligned brakes causing excessive localized heat and resultant thermal cracks is seen in Figure 6. In this case, shoe contact was at the upper portion of the flange and the initial crack extended into the plate and almost 180° around the hub.

There is another railroad operation, not involving brake shoe application, which may generate the necessary wheel heat to cause thermal cracking. Wheel retarders, which physically rub against the back wheel rim, are used in classification yards to control car speed during switching. In cases where the car is allowed to reach excessive speed, the retarder action might produce detrimental heating on the back rim. Figure 7 shows a 33 in. cast wheel that developed a thermal crack (arrow) in that location from heavy retarder use.

The next form of wheel failure to be considered is plate cracking. Failures of this type commonly occur in either the back rim fillet (Figure 8) or the front hub fillet (Figure 9). Crack development is associated with the high radial tensile stresses that are generated in those fillet areas following prolonged braking and under the action of heavy cyclic vertical and lateral wheel loads. Initiation is usually by fatigue at surface defects such as imbedded mill scale, machining tears or decarburization. Crack growth can proceed around the wheel until arrest occurs, as in the two illustrations, or until the ends surface on the tread and result in the loss of a rim section.

An important category of condemnable wheels not discussed so far are those severely overheated in service from stuck or dragging brakes, but not exhibiting thermal or plate cracks. Such wheels are potentially dangerous because the high tensile stresses developed in the rim can lead to an instantaneous fracture in the presence of even small thermal cracks. At the present time detection of this hazardous wheel condition depends on the interpretation of visual evidence of overheating, such as charring of surface oil and the presence of heat discoloration. Such evidence is unreliable at best considering that not all wheels are oil covered and that discoloration is dependent on ambient conditions during heating, particularly humidity, and tends to disappear with further weathering.

In addition to those wheel conditions that are considered to be actual failures, there are many removal categories that deal with condemnable rim and flange geometry changes caused by normal and abnormal wear. Excessive flange wear causes particular concern because of its adverse effect on wheel gage and truck stability through track switches. This concern is justified considering that 135 derailments(1) in 1973 were caused by this type of wear problem.

The preceding review of wheel defects is by no means complete, however, those conditions that pose significant danger to the safe movement of freight and passengers are included.

CURRENT WHEEL INSPECTION

Wheel inspection begins in the manufacturer's shop with procedures defined in Association of American Railroads' specifications M107 and M208(4) for wrought and cast wheels, respectively. Both outline the same requirements for ultrasonic inspection of rims and wet magnetic particle inspection of plate surfaces for discontinuities, such as inclusions and voids. Adherence to these specifications effectively sets a minimum quality limit for all new wheels entering service.

The techniques and frequency of in-service inspection are not specified in the Association of American Railroads' rules, but are determined by the experience of each performing railroad. All railroads rely principally on visual inspection, with a modest use of magnetic particle or penetrant methods by some in certain questionable cases. The frequency of inspection appears to be flexible at best, depending heavily on the operating schedule of the vehicle and the repair needs of other components. This lack of explicit inspection intervals, which is almost inherent in the mobile nature of railroading, places an increased burden on the inspection that does take place to find defects in their earliest stages.

Experience has shown that the vast majority of defective wheels are detected visually before an accident can occur. Given this basic effectiveness, visual inspection is characterized by several factors that tend to limit its sensitivity and reliability. Primary among these is its inherent subjectivity. Any system that relies solely on people for critical decisions is subject to the inconsistencies generated by differences in individual motivation, skills, knowledge and health. Reliable wheel inspection depends heavily on such variables as inspector job satisfaction and visual acuity.

Another important factor to be considered is the variability of the inspection environment. Wheel inspection usually takes place in the yard where variables such as the ambient temperature, humidity and sun light will change throughout the year; influencing the comfort and, therefore, concentration of the inspector. These variables are more controllable in the repair shop setting, thus inspection decisions made there can be expected to be more consistent throughout the year.

The physical condition of the inspected wheel can also influence the ability of visual examination to detect small defects. The presence of oil and dirt on plate surfaces will hide all but the largest plate cracks. Similarly, hot and cold working of the tread can obscure thermal cracks with flowed metal.

Recognition of the preceding factors affecting the reliability of visual inspection lead to the development of an automatic system for objectively evaluating the condition of wheels. The system, first marketed twenty-two years ago by Wheel Checkers of Denver, Colorado, is designed for the detection of broken flanges and loose wheels on vehicles that are on track and in motion. The sensor system (4) (Figure 10) consists of a series of 124 spring loaded detector fingers oriented normal to a slightly offset section of rail. The opposite rail section is fitted with a guard rail to keep passing vehicles tight against it, establishing the necessary clearance between the inspected wheel and the offset rail. The operation of the detector fingers is illustrated schematically in Figure 11. The approach of a train triggers the application of a electric potential between the detector fingers and the rail. A normal wheel of proper gage will ride down the rail with the flange depressing the fingers sequentially by contacting the insulated wear plates. Since the flange prevents the finger points from touching the tread, the circuit remains open and no signal is generated. Should one of the fingers contact the wheel where the flange is missing its point would touch the tread and close the alarm circuit. When a wheel set that is out of gage, due to wheel looseness, improper mounting or excessive flange wear, passes over the detector finger contact is made with either the finger point or the 1A03 spring depending on the direction of gage error. In either case, the circuit is closed and an alarm signal is generated.

The basic effectiveness of the Wheel Checker system has been proven over many years, however, being primarily mechanical in nature, it is susceptible to failures allowed by insufficient maintenance. In addition, there have been occasions when dragging train equipment has torn out the entire line of detector fingers rendering the system useless.

DEVELOPMENT OF IMPROVED INSPECTION METHODS

In recent years there has been an accelerated effort, particularly by the federal government through the Transportation Systems Center of the Department of Transportation, to stimulate development of improved methods of nondestructively evaluating the condition of in-service railroad wheels. Investigators are applying a variety of techniques to various aspects of wheel inspection including ultrasonics, Barkhausen noise analysis, acoustic signature analysis and magnetic perturbation.

Before discussing the specifics of these techniques, it will be useful to consider the values obtained by Carter and Caton(5) for the critical crack sizes that can be associated with the various wheel classes under maximum probable stress conditions. At the stress level of 55 ksi (Table 2) the critical length of corner thermal cracks is only 0.10 in. (.254 cm) in high carbon class C and U wheels. Cracks into flat surfaces, such as the tread or back rim, can grow to 0.26 in. (.660 cm) in the same wheels before becoming critical. Plate cracks that develop in the rim fillet of class C and U wheels become critical if their length exceeds 0.16 in. (.406 cm). Finally, the presence of sharp bottom surface defects, such as machining tears, in the rim fillet of a high carbon wheel can initiate brittle fracture if its depth exceeds .028 in. (.071 cm). While these critical crack values were calculated assuming the severest probable stress condition, one that most wheels will never see, they do indicate the level of crack sensitivity that any NDE system should approach to achieve the highest reliability. The actual crack detection levels required by railroads will depend on the cost and physical requirements for maximum detection.

Ultrasonics - The science of ultrasonics is being applied to the problem of wheel evaluation in many forms. The first commercially viable system is the Wheelfax system developed by Scanning Systems, Inc. of Danbury, Connecticut.(6) The search unit of this system fits into a special section of rail that is designed to guide the outer tread of passing wheels over a fluid filled transducer boot, Figures 12 and 13. Inside the boot are two oppositely directed transducers set in a gimbaled support that allows them to maintain a constant entry angle to the wheel tread. On contact with a wheel, couplent is sprayed on the boot and an ultrasound pulse is directed circumferentially around the tread as a surface wave by one of the transducers. Initial and multiple order reflections are subsequently received by this transducer from any crack that has developed on the rim faces, tread or flange. It is claimed that reliable detection of cracks 0.5 in. (1.27 cm) long and 0.050 in. (.127 cm) deep can be achieved. After full attenuation of this initial signal has occurred, in about five milliseconds, a second pulse is directed around the wheel in the opposite direction by the second transducer. This dual pulse-echo technique enhances the chances of detecting cracks that are inclined to the surface since they are anisotropic in their ability to reflect sound. The use of dual transducers also allows the analysis of the through transmitted signal for additional information on the wheels' condition. Attenuation rate of this signal is indicative of the general wheel surface condition and is believed related to the near surface stress level. This relationship to stress level could be used to detect uncracked, overheated wheels. The time interval between multiple receptions of the through transmitted pulse is used to classify wheels by diameters and details of the pulse shape can reveal a high flange condition.

The Wheelfax system has several operational advantages in addition to its versatility. Primary among them is the ability of each search unit to inspect all the wheels on one side of a train moving at up to 30 mph (48.3 km/h). Reliable inspection at this speed results in minimum interference with train operation and maximum system utilization. Another operational advantage is the system's totally automatic nature. The initiation and termination of testing, the data processing and recording, and the defect alarm system are all controlled electronically from a trackside control center.

A recent investigation by Becker (7) at Battelle Northwest has confirmed the feasibility of detecting wheel plate cracks by introducing ultrasound radially into the tread. During the study two similar test procedures were considered; one based on the generation of Lamb waves in the plate and the other on a more conventional pulse-echo technique.

Results of several tests conducted under optimum conditions for each method indicate that the conventional pulse-echo technique is more suited to the task of detecting plate cracks than is the Lamb wave method. One of the main liabilities of the latter is its low signal to noise ratio. At the relatively low frequencies required for generation of optimum Lamb waves (640 KHz) the divergence angle of the sound beam is large compared to that found at higher frequencies in the more conventional pulse-echo method (1 MHz). As a consequence, a portion of the energy fails to enter the plate and is reflected by the adjacent rim surfaces. Such spurious reflections tend to reverberate in the rim, yielding a multitude of false indications.

Another undesirable feature of the Lamb wave method is its inherent sensitivity to plate thickness variation. Since the allowable modes of wave propagation are governed by the frequency - plate thickness product (F x d), it is evident that the operating modes will change with thickness variations within a plate and with plates of different designs. The associated variability in propagation velocity negates the use of fixed time acceptance gates on the return signal to isolate responses from the fillet areas for better resolution. This problem is not found in the higher frequency pulse-echo technique because of its constant propagation velocity across the wheel.

A third factor that limited the effectiveness of the Lamb wave method is its relatively long near surface dead time that seriously restricted the detection of rim fillet defects. The testing of one wheel at 640 KHz, with the transducer driven by a 20 μ sec. sine wave burst, resulted in a dead time of 30 μ sec., which is equivalent to about 4.5 in. (11.4 cm) of steel.

Becker estimated that the minimum detectable flaw sizes for an automated, pulse-echo inspection system would be approximately 0.0225 in.^{2}

(.145 cm^2) and 0.045 $in.^2$ (.290 cm^2) for rim and hub fillet flaws, respectively. Examples would be defects 0.09 in. (.23 cm) deep and .25 in. (.63 cm) long in the rim fillet and 0.125 in. (.32 cm) deep and 0.36 in. (.91 cm) long in the hub fillet.

One of the conceptual systems outlined by Becker for the automatic inspection of wheel plates under moving cars involves a series of transducers mounted in a special length of rail. Each transducer inspects a discrete radial plane as the wheel passes over. An illustration of the proposed transducer arrangement is shown in Figure 14. The transducers are held by a gimbaled support structure encased in a fluid filled boot. The approaching wheel triggers a couplent spray that keeps the outer boot surface wet. As the test wheel passes along the series of probes a guard rail arrangement on the mate wheel controls its lateral position while a spring loaded guide shoe positions the transducers opposite the plate. The probability of defect detection will be directly proportional to the number of probes used to inspect a given wheel.

This system appears to offer a simple, nonmechanical, low maintenance way of continuously inspecting wheels traveling at moderate speeds. These advantages are countered, somewhat, by the reduced defect detection probability that accompanies discrete radial inspection. In addition, the development of an adequate electronics system to operate the large number of transducers required will be one of the primary implementation problems.

Another aspect of wheel inspection, where an ultrasonic technique is being applied, is the detection of adverse stress conditions in the rim caused by overheating. The principle behind this technique is that the state of stress in a metal influences the propagation velocity of ultrasound. Therefore, the precise measurement of transit times through a known thickness of stressed material can give an indication of the average stress level. The key to obtaining reliable results is the accurate assessment of the effect material variables, such as chemistry, preferred orientation and microstructure, have on the sound velocity and the mitigation of these influences through adequate calibration.

Clotfelter and Risch(8) have applied this ultrasonic stress measurement technique to railroad wheels. The basic procedure was to measure the transit time differential of simultaneously generated 2 MHz pulses through an unstressed reference block and the stressed specimen. This was accomplished using a dual trace oscilloscope to display the two signals and by expanding the time base until individual pulse cycles could be seen. Since a difference in transit time appears as a phase shift in the two signals, the delay - time multiplier on the oscilloscope could be used to determine the differential by making the pulses coincident.

The actual determination of stress in steel is complicated by its anisotropic nature with respect to sound propagation. Under compression shear waves polarized parallel to the principal stress axis will travel faster than waves polarized perpendicular to it. The difference between the transit time differentials of the two wave orientations is, thus, a better measure of the average stress than either orientation alone. As applied to the evaluation of wheel rims, the parallel and perpendicular orientations correspond to the circumferential and radial directions, respectively.

The first step in utilizing this technique was the establishment of an acoustic stress constant for wheel material that relates ultrasonic velocity changes to applied stress. This was accomplished by incrementally loading a block of rim steel to simulate the circumferential compressive stresses found in wheels and measuring the transit time differential of pulses traveling in this block and an identical reference block. At each load level measurements were taken with wave polarization both parallel and perpendicular to the principal stress axis. The difference in transit time differentials of these two polarizations was used, in conjunction with the path length and the value of each load level change, to establish an acoustic stress constant of 0.405 nsec./in./ksi (2.31×10^{-6} nsec./m/N/m^2) for a typical wheel material.

Once the acoustic stress constant is determined the average stress across a wheel rim can be calculated by measuring the difference in the radial and circumferential transit time differentials and by knowing the sound path length. In a similar manner, stress changes can be detected by making measurements before and after the event of interest. The results of such an investigation by Clotfelter and Risch(8) involving wheel braking tests are shown in Table 3. These values reveal that a significant change has taken place in the sound propagation velocity as a result of wheel heating. This change is equivalent to an average compressive stress reduction of 13.9 ksi (9.6×10^7 N/m^2).

It has been demonstrated that accurate measurement of ultrasound propagation velocity in stressed wheels can be used to evaluate that stress condition. However, the material variability found in wheels of different classes and manufacture would require the use of some independent technique to establish material characteristics prior to any stress measurements. The technique also requires an accurate value for the sound path length, which may necessitate the actual measurement of the rim width of each wheel tested.

Lodding Engineering Corp. of Auburn, Massachusetts,(9) is presently marketing a device to measure ultrasound transit times to an accuracy of 0.1 nanosecond.

Barkhausen Noise Analysis - Another technique recently applied to the task of assessing the stress state of railroad wheels is that of Barkhausen noise analysis.

The phenomenon which is the basis of this technique is the abrupt, discontinuous movement of microscopic magnetic domain boundaries that often occurs in ferromagnetic materials under the influence of an external magnetic field. These nonuniform movements are reflected in the magnetization hysteresis loop of the material as small, discontinuous increments in the curve known as Barkhausen jumps or noise, after their discoverer. It has been established that the dynamics of domain boundary movement, and hence the level of Barkhausen noise, is strongly influenced by the state of material stress. In the specific case of steel, noise intensity increases under the application of tensile stress and decreases in a compressive stress environment.

An illustration of the basic elements needed for the excitation and detection of the Barkhausen effect is shown in Figure 15.(10) The excitation field is developed by a variable electromagnet in contact with the specimen. An induction coil between the magnet poles senses changes in specimen magnetization and translates this into a output voltage that is displayed on an oscilloscope. Cycling the external field polarity results in the output amplitude achieving a maxima that is indicative of the material stress state. To develop quantitative stress values from such information it is necessary to construct a calibration curve of stress versus Barkhausen noise intensity for the material of interest. Figure 16(10) shows a curve of this type for a wheel steel. It is evident that, in this case, maximum stress sensitivity occurs between -40 and +50 ksi (-215 and +344 MPa) and that more extreme values would not be definable.

A Southwest Research Institute study(10) recently established that the Barkhausen phenomenon generated in railroad wheels is sufficiently stress sensitive to be used as a stress indicator. However, there were significant variations and some inconsistencies in the data from wheel to wheel and at similar locations on the same wheel. This situation was attributed to, in part, the lack of a "magnetic feedback" system to detect variations in the effective magnetic flux near the specimen surface due to local differences in magnetic permeability. Such a system would sense the magnetic field and adjust the electromagnet strength to maintain the predetermined magnetization cycle independent of material condition.

Another factor contributing to data variability in the Barkhausen technique is the small volume of material from which the stress indication is obtained. The near surface nature of the Barkhausen effect, when combined with a coil pickup covering an area of only 0.01 in.^{2} (.064 cm^2), causes the technique to be more sensitive to short range stress gradients and shallow surface conditions than a conventional stress relaxation technique using strain gages.

Despite such characteristics, reasonable qualitative agreement was established between the two methods.(10)

As a step toward utilizing the Barkhausen noise technique to classify wheels according to the severity of overheating, the SwRI study tentatively identified the area on the back rim surface nearest the tread as that most likely to yield consistent linear results.

Acoustic Signature Analysis - One of the earliest methods of nondestructively evaluating railroad wheels was to have car inspectors strike them with a hammer and listen to the resulting sound. In this way it was possible to detect many defective wheels because they rang differently than good wheels. A more sophisticated version of this technique, known as acoustic signature analysis, is being investigated by Finch, et al,(11) at the University of Houston as a possible basis for an automatic, in motion, wheel inspection system.

In the acoustic signature method a wheel is excited, by either natural or artificial means, into vibrating and the radiant sound is analyzed for its characteristic spectral content or signature. The introduction of discontinuities, such as cracks, into the wheel will affect the modes of vibration and, consequently, the signature. Early results(11) have shown that artificial impact excitation is the most suitable means of generating sound of sufficient intensity and spectral content in the frequency range (1 - 5 KHz) found to be most sensitive to wheel integrity. In addition, this form of excitation allows the use of damping rate measurements as a supplemental indicator of wheel condition. It has been also established that the best detection system is one using a trackside microphone, near the impactor, to pick up airborne radiation. The alternative approach was to use a rail mounted accelerometer to monitor the impact induced vibrations, however, rail resonances were found that conflicted with those of the wheel, making this method undesirable.

An experimental impactor - microphone arrangement that was used in initial field trials(12) at the Union Pacific's Omaha East yard is shown in Figure 17. The impactor was designed to be wheel activated and adjustable in regards to the impact point on the rim. During the trials tape recordings were made of the sound emitted by a number of good and defective wheels under various conditions of train operation and hammer impact location. The signature of each wheel was processed by first converting it to a 1/3 octave band spectrum from 1 - 8 kHz. The spectrum was then normalized with regards to the overall intensity level to negate differences in sound amplitude. The normalized spectrum was compared to a good wheel standard spectrum and the difference found in each band was squared and summed. This summed value of deviation from the good standard was then compared to a predetermined limit to establish the presence of a defect. Additional defect confirmation could be obtained by comparing the sound decay time with a standard or by comparing both spectra and decay time of sound from two wheels on the same axle.

The initial field trials were successful in that the impactor survived repeated wheel contact at various train speeds and was able to produce sounds clearly distinguishable from the background noise. In addition, the spectrum analysis program was able to call out all the defective wheels used, including one with a plate crack and three with only thermal cracks. Areas needing hardware improvements were also defined. The impactor design needs refinement to insure that uniform excitation is imparted reliably to each passing wheel. It was also determined that the spectrum analyzer with a scanning time constant of 0.2 m sec was too slow to allow more than one spectrum reading on each wheel at the train speeds used. A faster unit would average several spectra in the allotted time, increasing the reproducibility of a given wheel evaluation.

Magnetic Perturbation - A unique method of detecting thermal cracks in moving wheels was recently patented by Gieskieng of Wheel Checkers, Denver, Colorado.(13) The technique consists of moving a magnetic tape, carrying an alternating magnetic signal, across the magnetized tread of a wheel. In those areas where the wheel material is continuous little or no change will occur in the tape signal, however, where a flaw or crack contacts the tape the external magnetic flux at those discontinuities will effectively erase the signal. The detection of such perturbations in the tape signal will, thus, indicate the presence of defects. A illustration of this phenomenon is shown in Figure 18.

A field installation of the Gieskieng system would involve a special length of rail with the wheel magnetizing equipment at one end and the magnetic tape arrangement at the other. The magnetization is accomplished using a long narrow plate, wound as an electromagnet, attached parallel to one side of the rail. As a wheel passes the plate the rim alone is transversely magnetized. The detector portion of the system includes a continuous loop of magnetic steel tape attached parallel to the rail so that the outer portion of the wheel tread will contact it on passage. A schematic of the detector elements is shown in Figure 19. The tape, which rotates in a direction opposite to that of the wheel, is erased of prior information by head 80 and an alternating magnetic carrier signal of approximately 200 Hz is applied by head 81. After contact with the wheel, the tape passes the pickup head (85) where any anomalies in the applied signal will trigger a defect alarm. A contact switch located at point 86 is used as an axle counter to correlate recorded defect indications with wheel position in the train.

Modification of the basic tape loop location enables the Gieskieng system to detect defects near the flange - tread fillet and on the top of the flange.

A prototype system has been constructed and tested with success in the laboratory, however, there have been no field trials to establish its crack sensitivity and mechanical durability in a railroad environment.

CONCLUSION

This paper has taken an overview of several detection and evaluation techniques that have shown promise in the area of improved railroad wheel inspection. The intent of these discussions was to stimulate interest in the application of other techniques to the problem and the development of practical methods of utilizing techniques already investigated.

When commercially viable NDE systems are developed for the railroad wheel application, the nation as a whole will benefit from the improved transit safety and the reduced railroad accident costs.

EXCLUSION

The Association of American Railroads does not necessarily endorse nor approve the equipment described herein. Statements made in this paper are not to be used in any advertising or promotion implying Association of American Railroads' approval.

REFERENCES

1. Accident Bulletin, No. 142, 1973 Edition, Office of Safety, Federal Railroad Administration.

2. Yearbook of Railroad Facts, 1974 Edition, Association of American Railroads.

3. Manual of Standard and Recommended Practices, Section A, M-107 and M-208, Association of American Railroads.

4. Literature supplied by Wheel Checkers, Denver, Colorado plus private communications.

5. C. S. Cater and R. G. Caton, "Fracture Resistance of Railroad Wheels", September, 1974, Report No. FRA-ORD & D-75-12.

6. Literature supplied by Scanning Systems, Inc., Danbury, Connecticut, plus private communications.

7. F. L. Becker, "Ultrasonic Detection of Plate Cracks in Railway Wheels", DOT-FRA-726, via private communications with R. Steele, Transportation Systems Center, Department of Transportation, Cambridge, Massachusetts.

8. W. N. Clotfelter and E. R. Risch, "Ultrasonic Measurement of Stress in Long Lengths of Welded Rail", NASA TMX-64863, July, 1974.

9. Literature supplied by Lodding Engineering Corp., Auburn, Massachusetts.

10. R. King, J. Barton, and W. Perry, "Stress Measurement in Railroad Wheels via the Barkhausen Effect", DOT-TSC-713, December, 1974.

11. K. Nagy and R. D. Finch, "Feasibility of Flaw Detection in Railroad Wheels Using Acoustic Signatures", DOT-FR-30002, September, 1974.

12. K. Nagy, "Report on a Preliminary Yard Test of the Acoustic Signature Method for Railroad Wheel Inspection", University of Houston, unpublished report, 1974.

13. M. W. Gieskieng, "Method and Apparatus for the Detection of Cracks and Flaws in Rail Wheels, Rails and the Like by Sliding a Prerecorded Magnetic Medium Over the Test Piece", U. S. Patent 3,820,016, June, 1974.

TABLE I

SPECIFIED PROPERTIES AND INTENDED SERVICES OF WHEEL CLASSES (Ref 3)

Class	Intended Service	Rim Hardness (BHN) Min	Rim Hardness (BHN) Max	Carbon (a) Content %
U	General service where an untreated wheel is satisfactory	-	-	0.65 - 0.80
A	High speed service with severe braking conditions but moderate wheel loads	255	321	0.57 Max
B	High speed service with severe braking and heavier wheel loads	277	341	0.57 - 0.67
C	(1) Service with light braking conditions and high wheel loads (2) Service with heavier braking conditions where off-tread brakes are employed	321	363	0.67 - 0.77
U1(b)	Not defined	-	-	0.95 - 1.20

a All wheel classes require the following: 0.60 - 0.85 Mn, 0.05 Max P, 0.05 Max S, 0.15 Min Si.

b Cast only

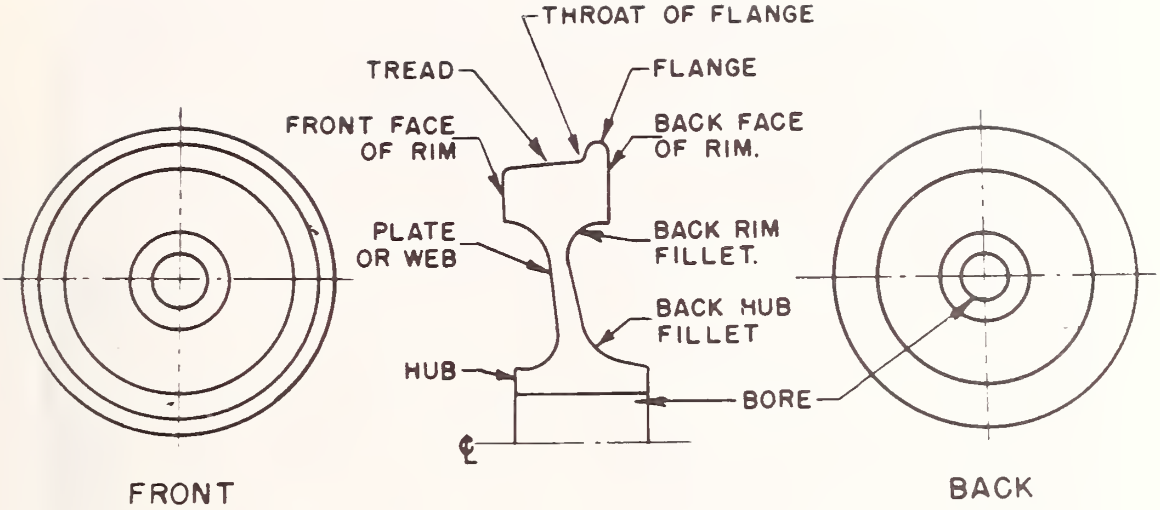

FIGURE 1
TYPICAL RAILROAD FREIGHT CAR WHEEL

FIGURE 2
PORTION OF A SHELLED WHEEL AFTER DEEP ACID ETCH

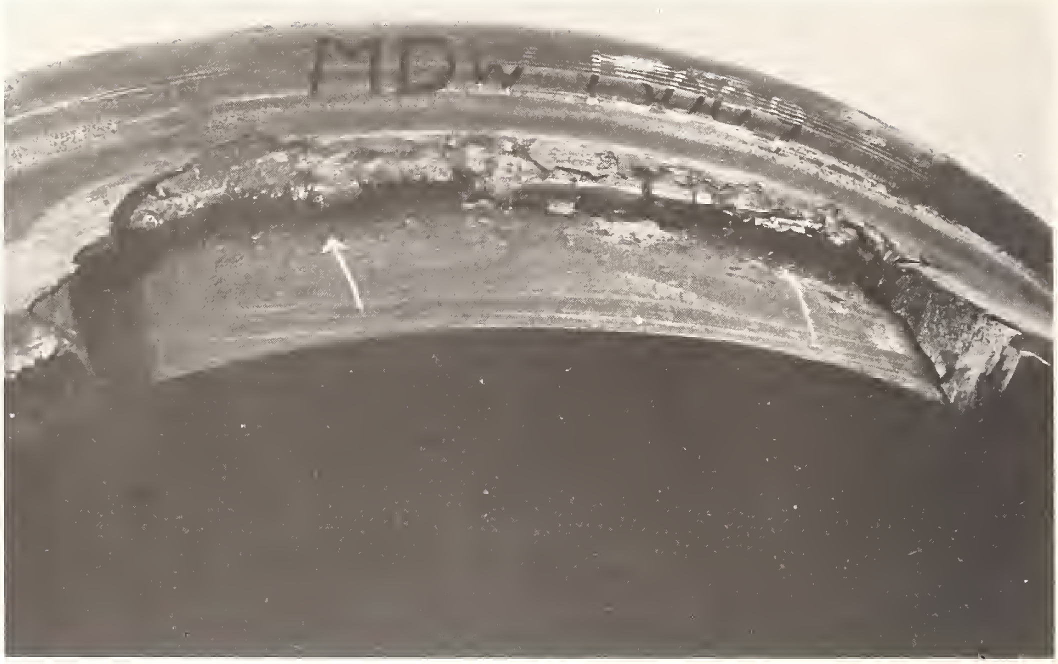

FIGURE 3
A WHEEL WITH A SHATTERED RIM

FIGURE 4
WHEEL EXHIBITING THERMAL CRACKS ALONG FRONT RIM EDGE

FIGURE 5
WHEEL SHOWING EXTENSIVE BRITTLE FRACTURE
INITIATED AT THERMAL CRACK

FIGURE 6
THERMAL CRACK DEVELOPED ON THE FLANGE FROM
BRAKE SHOE CONTACT

FIGURE 7
WHEEL WITH THERMAL CRACK ON BACK RIM FACE
INDUCED BY RETARDER ACTION

FIGURE 8
PLATE CRACKING FOUND IN THE BACK RIM-PLATE FILLET

FIGURE 9
PLATE CRACK THAT DEVELOPED IN THE FRONT HUB-PLATE FILLET

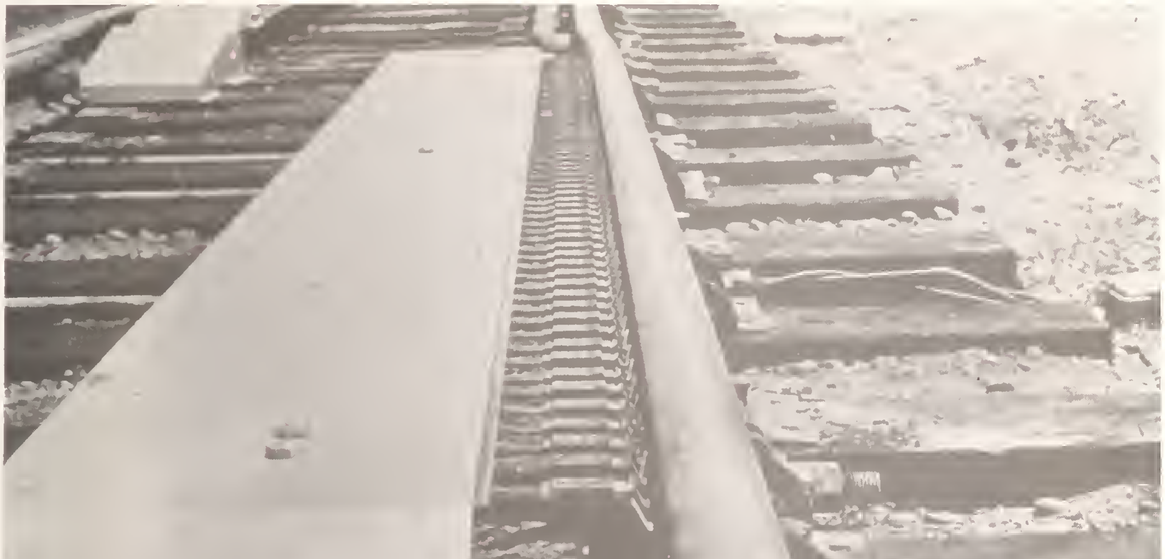

FIGURE 10
FIELD INSTALLATION OF THE WHEEL CHECKERS BROKEN FLANGE AND LOOSE WHEEL DETECTOR (REF. 4)

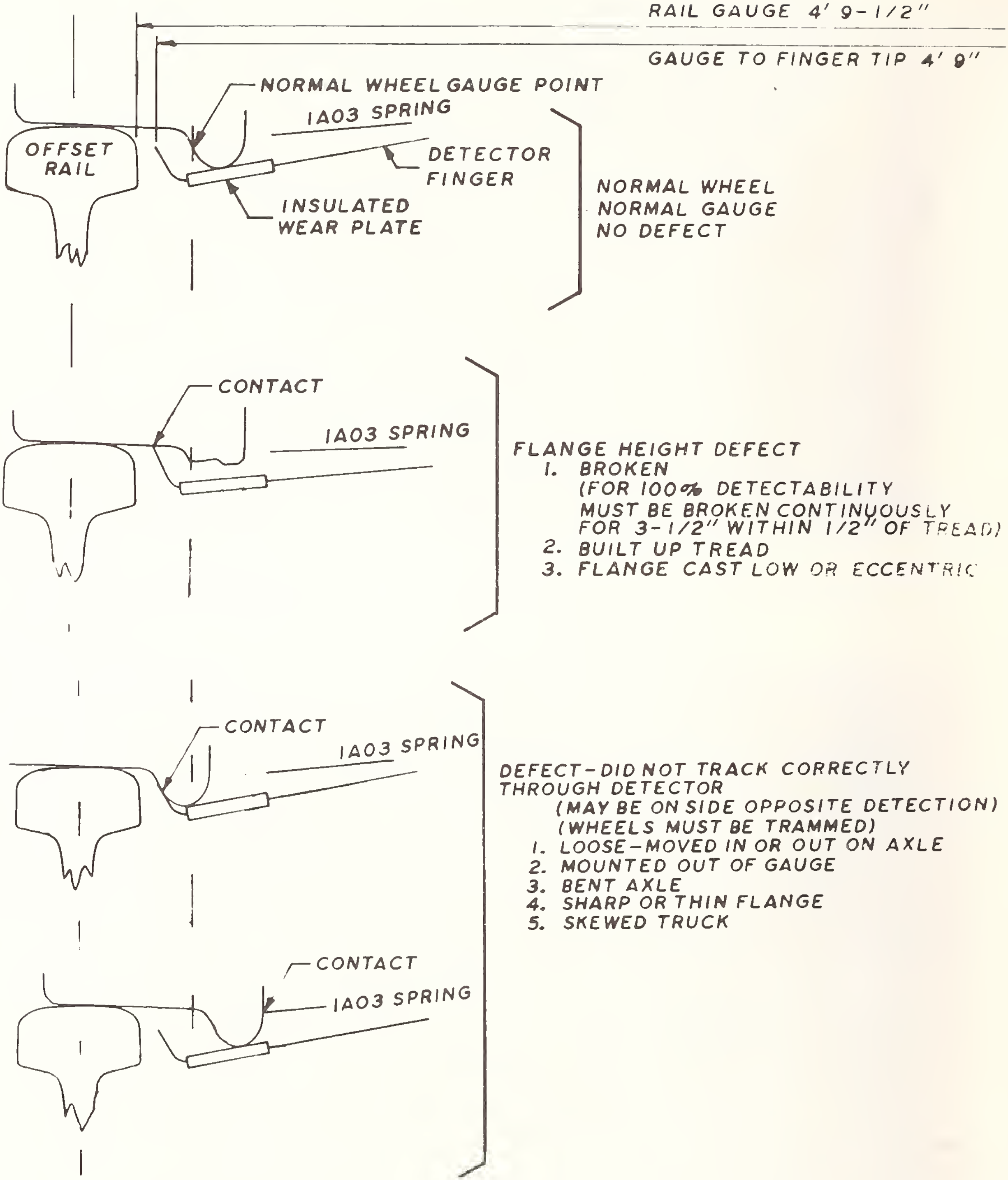

FIGURE 11
OPERATION OF THE WHEEL CHECKER WHEEL
INSPECTION SYSTEM (REF. 4)

TABLE II

CRITICAL CRACK SIZES AT AN APPLIED STRESS OF 55 Ksi (After Carter and Caton, Ref 5)

	THERMAL CRACKS		PLATE CRACKS	
Class	Corner Crack[a]	Surface Crack[a]	Surface Crack[a]	Surface Defect[b]
A	0.25	0.65	0.50	0.084
B	0.14	0.36	0.25	0.043
C	0.10	0.26	0.16	0.028
U	0.10	0.26	0.16	0.028

[a] Crack length in inches
[b] Defect depth in inches

FIGURE 12
FIELD INSTALLATION OF THE WHEELFAX ULTRASONIC WHEEL INSPECTION SYSTEM (REF. 6)

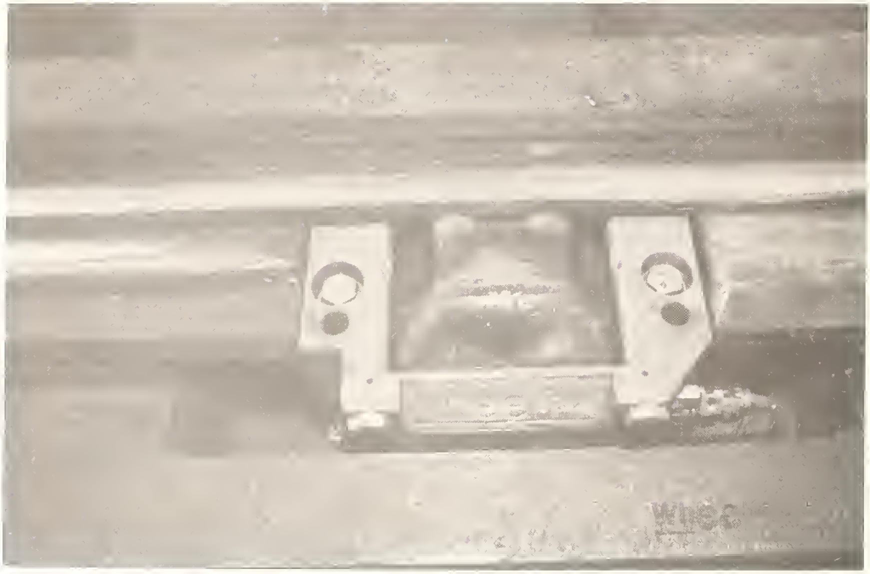

FIGURE 13
CLOSEUP OF WHEELFAX TRANSDUCER BOOT (REF. 6)

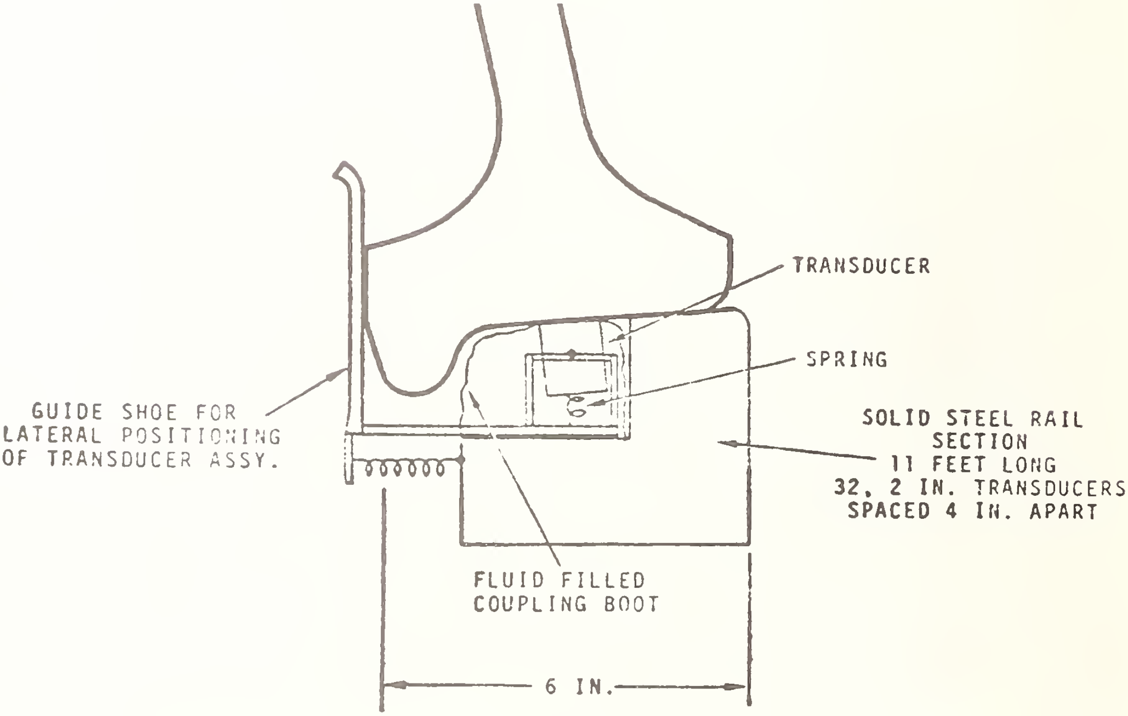

FIGURE 14
A CONCEPTUAL IN-RAIL TRANSDUCER ARRANGEMENT
FOR THE INSPECTION OF WHEEL PLATES (REF. 7)

Wheel Position	Time Before, nsec/m (nsec/in.)	Time After, nsec/m (nsec/in.)
1	708 (18.00)	468 (11.90)
2	536 (13.60)	279 (7.10)
3	507 (12.90)	276 (7.00)
4	492 (12.50)	205 (5.20)
5	575 (14.60)	330 (8.40)
6	575 (14.60)	386 (9.80)
7	516 (13.20)	457 (11.60)
8	614 (15.60)	350 (8.90)
Average	565 (14.37)	344 (8.73)

TABLE III
ULTRASOUND TRANSIT TIME CHANGES ASSOCIATED
WITH A BRAKING TEST (REF. 8)

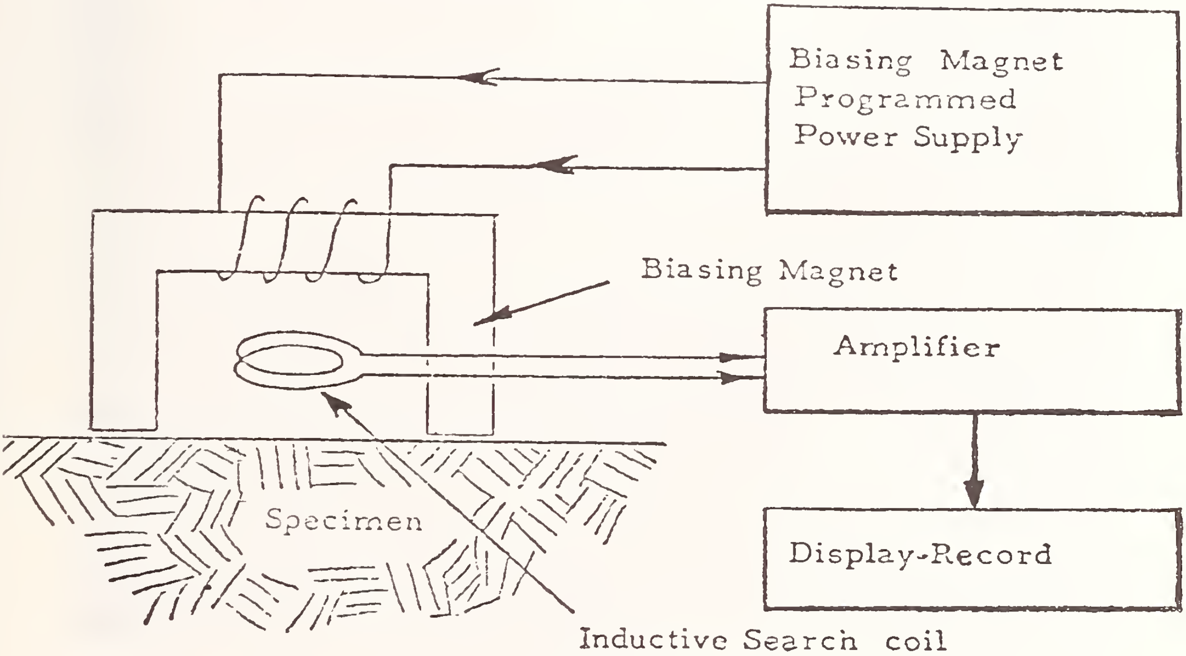

FIGURE 15
THE ESSENTIAL ELEMENTS OF A BARKHAUSEN NOISE
ANALYSIS SYSTEM FOR MEASURING STRESS (REF. 10)

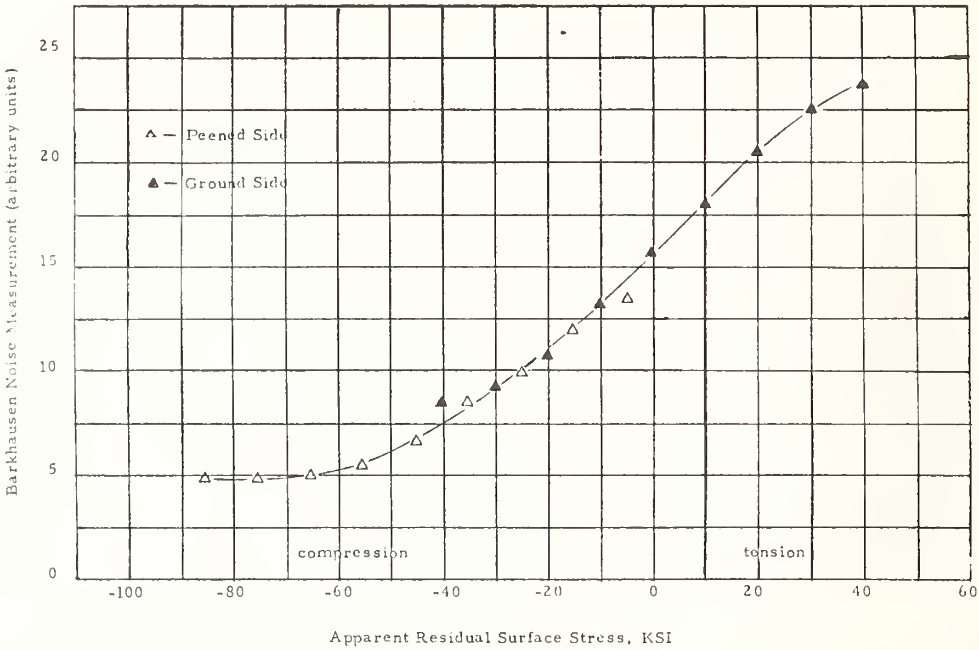

FIGURE 16
BARKHAUSEN NOISE CALIBRATION CURVE FOR A WHEEL MATERIAL (REF.10)

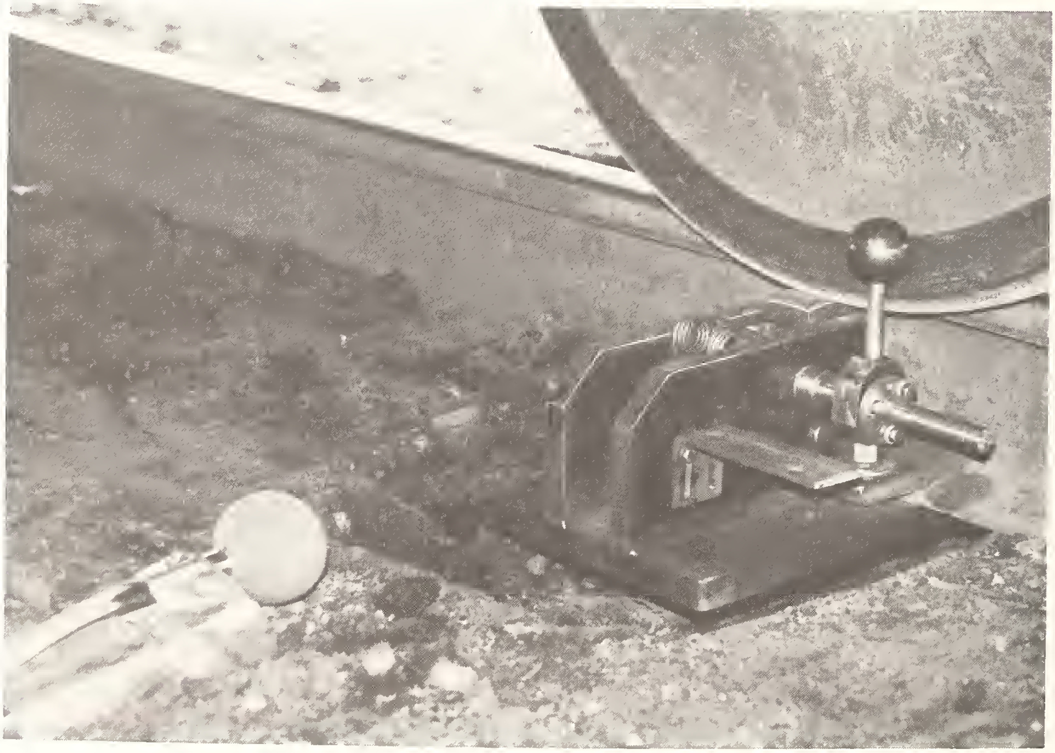

FIGURE 17
AN EXPERIMENTAL IMPACTOR-MICROPHONE ARRANGEMENT
USED IN ACOUSTIC SIGNATURE ANALYSIS WHEEL INSPECTION (REF. 12)

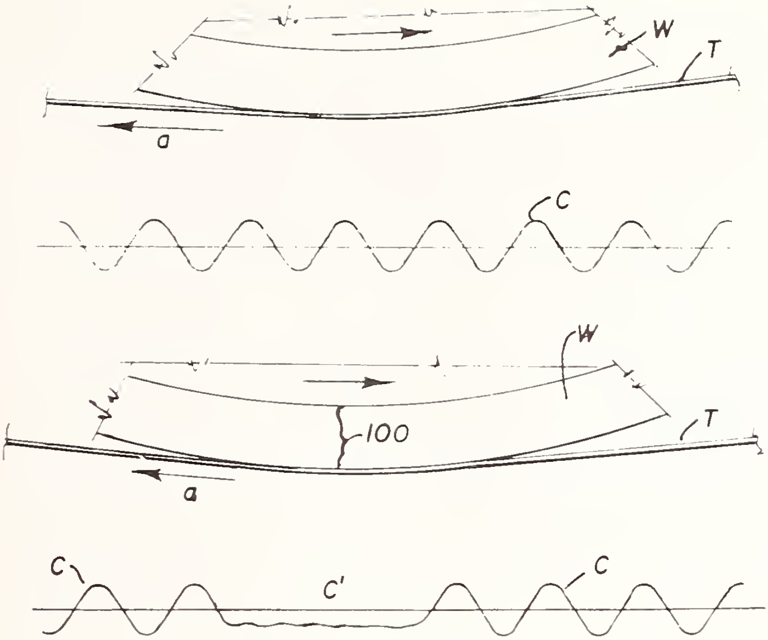

FIGURE 18
THE MAGNETIC PERTURBATION PHENOMENON USED IN THE GIESKIENG SYSTEM FOR THERMAL CRACK DETECTION (REF. 13)

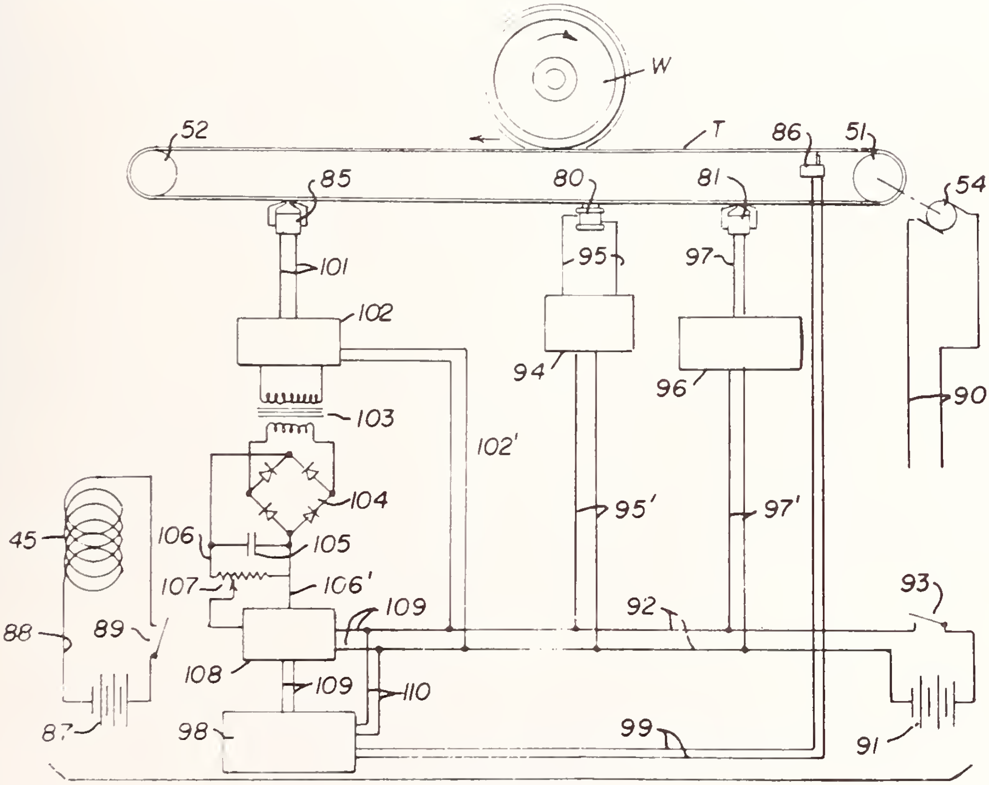

FIGURE 19
SCHEMATIC OF THE DETECTOR ELEMENTS IN THE GIESKIENG SYSTEM (REF. 13)

DISCUSSION

H. E. Dunegan, Dunegan-Endevco Corporation: Has there been any consideration about using acoustic emission for this problem?

G. L. Leadley: There are proposals for using acoustic emission.

DIAGNOSTICS FOR REFRIGERATOR CAR DIESEL GENERATING SETS

Robert F. McKee,
Pacific Fruit Express Company
San Francisco, California 94105

BACKGROUND: For over 100 years the ice bunker railroad refrigerator car was the standard transportation vehicle for perishable foodstuffs between the fruit and vegetable growing areas in the south and west to the major population centers in the east and middle west. The growth of the frozen food industry in the late 1930's and during World War II, however, led to the necessary development of refrigeration systems capable of providing the 0°F holding temperature required by that industry, and which could not be obtained by ice refrigeration.

The result was adaptation of commercial compressor - condensing refrigeration equipment to the railroad environment, and the early to middle 1950's saw a fleet of frozen food mechanically refrigerated cars grow into several thousand cars to serve the frozen food industry. Fresh perishable shippers also became interested in the advantages of controlled temperatures as their shipping practices became more sophisticated, so that by 1957 the last ice bunker refrigerator car was built in the United States and from then through the 1960's the fleets of railroad refrigerator cars were replaced by mechanical cars. In 1973, railroad icing operations were terminated and all perishable movements are now protected by mechanical refrigeration.

THE MECHANICAL CAR: There are now about 28,000 mechanical refrigerator cars in the United States, of a general standard configuration as shown in Figure 1. The cars are generally configured with a 50 foot inside length and a machinery compartment at one end, which contains a diesel engine driven generator set and the high temperature components of the refrigeration system. The air circulation blower and cooling coil are located within the insulated compartment at the wall adjacent to the engine compartment.

The refrigeration system operates on 3 phase 60 Hertz 220 volt AC power supplied by the generator set, using standard commercial electrical controls and motors. Provisions are made for connection to an outside source of power for operation of the system within enclosed areas during loading and unloading operations. On board fuel capacity is provided for from 20 to 25 days continuous operation, and all systems are designed with sufficient capacities of oil and coolant to operate for this period without further servicing.

The systems are fully automatic. When the engine starter button is pushed and the engine starts, the control system actuates the various components to supply cooling or heating as required to maintain thermostat settings from 0°F to 70°F. Heating is provided by electrical heating elements in the cooling coil, which are also employed to defrost the coil when the control system detects the need for defrost, which is also fully automatic.

A multi-stage thermostat senses the car interior air temperature returning to the cooling coil as shown in Figure 2. The thermostat provides stages of cooling by varying the compressor capacity and/or diesel-generator speed to alternate the output to the actual refrigeration demand as the thermostat setting is approached. At the thermostat setting the refrigeration compressor stops and starts as required, while the diesel engine runs constantly to provide power to drive the air circulation system and the temperature and electrical controls.

Should the temperature continue to fall the system automatically switches to the heating mode, and continues to maintain interior temperatures at any outside temperature encountered. All controls are in the engine compartment, visible and accessible through the side access door.

THE PROBLEM: The environment in which the railroad mechanical refrigerator car operates is inherently hostile to operating machinery. In addition to ambient conditions which can vary from -30°F to +150°F in the engine compartment, and elevations of below sea level to over 8,000 feet, there are the conditions imposed by movement over land and sea (by railroad barges). These include coupling shocks to 20 g, vibrations, dirt, dust, salt atmosphere and long periods of unattended operation.

In the early stages of development of mechanical systems the objective was to survive any given trip which might vary from 5 to 15 days depending upon intermediate stops for loading and unloading. A process of survival of the fittest over the early years developed tight specifications not only for equipment operating characteristics to survive the environment, but eventually to individual designs of certain manufacturers which proved to be inherently superior.

This process applied to major components such as engines and compressors, as well as to motors, valves, electrical contractors, relays, wiring, and controls, gauges and indicators. As a result the industry has standardized the major components and accessories, so the operating problems have also become somewhat standardized. This is an industry-wide problem, as mechanical refrigerator cars are interchanged between owning railroads and others throughout the United States, Canada and Mexico.

Experience has established that mean time between failures ranks as follows in ascending order:

Diesel Engine-Generator
Electrical System
Refrigeration System
Thermostatic Controls

Therefore, when the refrigerator car owners determined to form a combined task force to determine means of improving dependability and reducing intransit failures the diesel engine-generator was selected as the most applicable common ground for a joint effort to develop diagnostic analysis systems. It was also the area of greatest standardization since practically all diesel engines in current use are Detroit Diesel Allison 2 cycle blower scavenged type in Model 2-71 and Model 3-53.

Figure 3 shows a typical DDAD Model 2-71 generator set of the most prevalent type in service. It operates at 1200 RPM to produce 17-20 KW of 220 volt 3 phase 60 Hertz power, with a dual range governor to operate at 800 RPM to provide 11-13 KW at 150 volts and 40 Hertz. (It is possible to operate standard 60 Hertz equipment at 40 Hertz as long as the voltage/frequency relationship remains constant, since the impedance of inductive devices varies directly with the frequency.)

A SOLUTION: Upon the decision to concentrate on the diesel-generator set, a contract for a feasibility study was let to a firm who had previous experience not only with diagnostic systems and their hardware, but who had also done studies of the DDAD 2 cycle engine for military automotive applications.

The engine generator was divided into sub-systems for individual analysis consisting of:

Coolant
Lubrication
Fuel

Combustion
Mechanical
Electrical
Starting

Each sub-system was analyzed with a view toward selection of parameters for study, followed by sensing means for collecting the necessary data for each system considering the physical configuration.

Early in the study it was decided that sensing devices must be applied at each engine test since the environment was too severe for any practical service life of the necessary transducers. Therefore non-intrusive applications were preferred, and rapidity of set-up prior to test was of high priority. Sensing points selected were as shown in Figure 4.

Truth tables were developed based upon test of the actual engine under all conceivable failure modes as previously experienced from analysis of available intransit performance data from the various equipment owners. From these were constructed the logical diagnostic sequences for each sub-system, and for all sub-systems taken together.

The feasibility study indicated strong potential for a diagnostic system which could provide advantages as follows:

1. In-car analysis of any or all sub-systems to ascertain presence of incipient failure conditions prior to each trip.

2. Status of sub-system at each subsequent inspection to include trend analysis.

3. Provide data for improvement of components, servicing practices and preventive maintenance procedures currently in effect.

4. Pre-overhaul analysis to enable more effective overhaul procedures based on true needs of each sub-system.

5. Reduction of unneeded repairs.

6. Quality control improvement on engines tested after overhaul.

7. Receiving inspection of new engines to reduce infant mortality during first few trips.

8. Develop information useful to the manufacturer for product improvement.

9. Provide data base for overall fleet analysis and actuarial projections.

10. Improve intransit performance by restriction of necessary maintenance and repairs to the repair shop.

STATUS: Upon completion of the feasibility study actual hardware was acquired through request for proposals from qualified suppliers having systems capability, with respect to both the diesel engine generator and the diagnostic hardware and software. Again we were able to obtain service of a firm already working with the manufacturer of the engine in other applications.

By applying our railroad experience and the approaches suggested by the feasibility study, a diagnostic analyzer design was developed to meet our needs as an exploratory tool. This included the capability of revising programs and procedures as actual usage and experience dictated for optimum results.

The design for the analyzer chosen is shown in the block diagram in Figure 5. It enables storage of parametric data for the particular engine under test, and is programmable for the different kinds of tests to be conducted. The present equipment is being used with narrow band inputs, but provisions are incorporated for wide band inputs which are under consideration for the future with respect to signature analysis for the mechanical and combustion systems.

The field test phase of the analyzer development is just getting under way, and it has become obvious that the most immediate problem is selection and application of transducers which lend themselves to use as part of a field tool where they must be applied and removed, suffering the rigors of the field mechanics' practices yet maintaining their ability to supply useful data with a high degree of dependability and respectability. We are also finding that wiring harnesses and connectors will require much development work before they will be wholly acceptable.

Another side benefit from the field study of the analyzer has been its use as a tool to acquire and print out transient information in further study of the operating characteristics of each of the sub-systems. For example, the behavior of the fuel system during changes in speed and load is found to be somewhat different from what we were led to expect from steady state data taken as individual readings under differing levels of operation. This is enabling us to revise procedures having to do with test of primary and secondary fuel filters for preventive maintenance in a most troublesome area which is the greatest single cause of intransit engine shutdown.

THE FUTURE: As the diagnostic analyzer is developed for the diesel engine-generator set it will also be considered for application to the other components of the refrigerator car. Next for consideration are certain troublesome areas in the refrigeration system, to be followed by the electrical control system.

Another area for independent investigation is that of the many bearings of all types on board the mechanical refrigerator car. There are at least a minimum of 50 bearings in each car, of which many are in relatively inaccessible locations for service, but which may be subject to successful signature analysis.

One peculiarity of the mechanical car environment is the period of operation of the car when the various cooling and heating systems are turned off. Experience indicates much bearing degradation takes place during non-operating time due to the shock and vibration from the car structure, and from the temperature changes which occur within the system causing entrance of moisture vapor.

Much work remains to be done in the diagnosis, analysis and prognosis of the various systems, and the state of the art appears to offer much opportunity for application to the railroad mechanical refrigerator car.

Another area for consideration is intransit monitoring of the performance of the car during its unattended operation. As part of the attention being given to the diesel engine, a correlative program is under way to develop an intransit monitor which will stay aboard the car and which will indicate cause of engine shutdown. Such a device now under development is shown in Figure 7.

It will indicate to an inspector investigating a dead car the diesel sub-system which apparently led to shutdown, since the time lapse between the cause of shutdown and the first inspection capability upon arrival at a terminal may be several hours and the symptoms long since gone. Many engines will start and run normally during the short terminal time within which to observe them, so a means must be provided to signal the cause, such signal to remain available from battery supplied power for as much as 24 hours to be useful.

Such a device becomes an on-board diagnostic tool for intransit repairs, and data gathered from it will also be available to the diagnostic system to point out areas requiring further attention on that particular engine.

A subsequent development now being considered is to provide a communication link between the car and wayside interrogators to enable all cars passing such points to report their condition and cause of malfunctions which may be present. This will permit repair forces to be waiting when those cars requiring attention arrive, avoiding time lost inspecting long trains to discover any such cars, when that time could be used to effect repairs without delaying the train.

With the emphasis on use of rail transportation to handle the large volumes of perishable foodstuffs for an increasing population at the lowest cost in terms of precious fuel, means of further improving the effectiveness of the rail mode of transportation will be increasingly cost effective, enabling the state of the art in the industry to be applied at an increased level of activity.

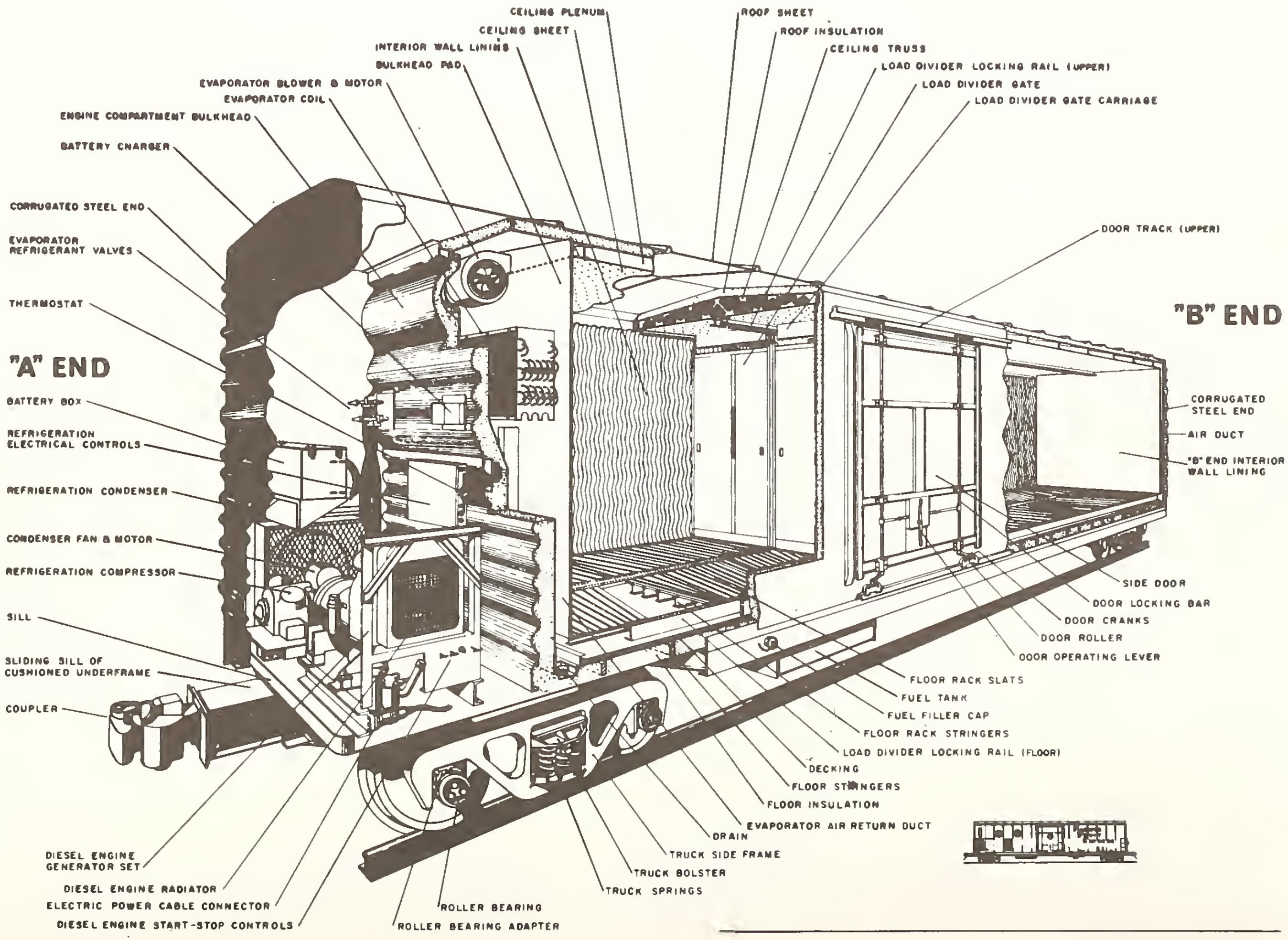

Figure 1. Mechanical refrigerator car cutaway illustration.

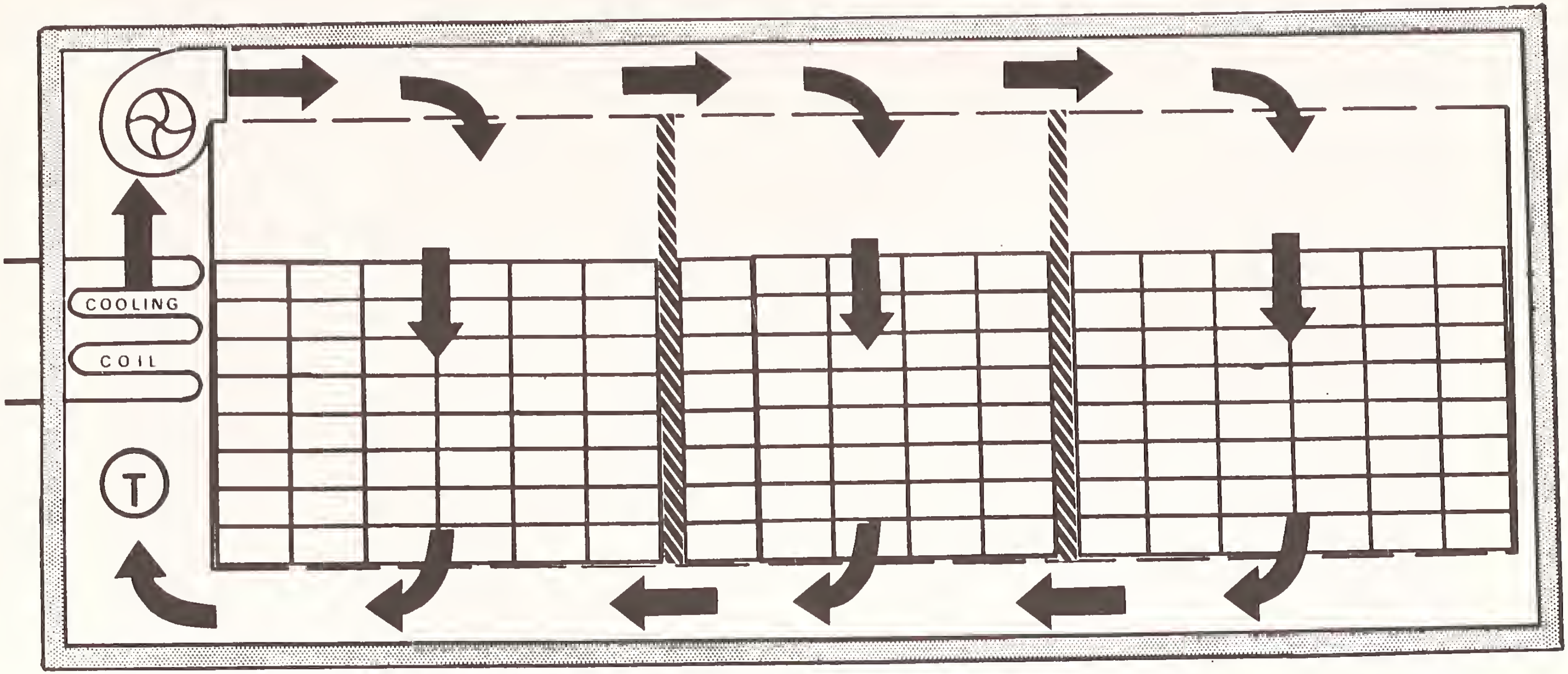

Figure 2. Typical air circulation system.

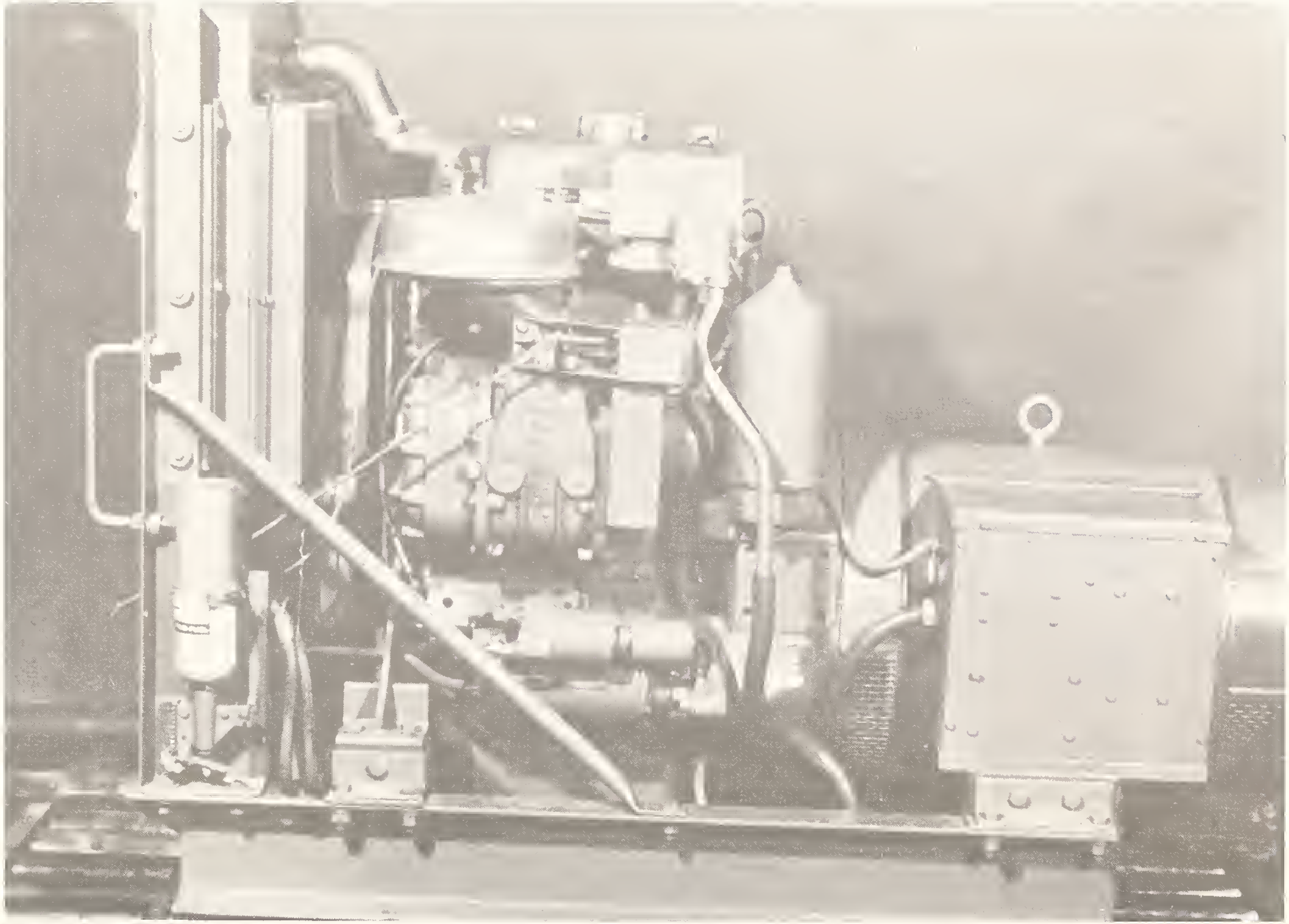

Figure 3. Typical DDAD Model 2-71 generator set.

LIST OF SENSORS

SENSOR NUMBER	FUNCTION
A1A	Exhaust Manifold Surface Temperature (Cylinder 1)
A1B	Exhaust Manifold Surface Temperature (Cylinder 2)
A1C	Exhaust Manifold Surface Temperature (Cylinder 3)
A2	Exhaust Manifold Riser Temperature
A3	Exhaust Manifold Pressure
B1	Engine Side Temperature (Air)
B2	Lower Radiator Temperature
B3	Upper Radiator Temperature
B4	Engine Block Coolant Temperature
B5	Radiator Pressure
B6	Block Coolant Pressure
C1	Sump Oil Temperature
C2	Oil Cooler Return Temperature
C3	Air Out Temperature
C4	Lube Pump Pressure
C5	Gallery Oil Pressure
D1	Fuel Pump Suction Pressure
D2	Fuel Pump Pressure
D3	Common Rail Pressure
D4	Fuel Line Suction
D5	Intake Manifold Pressure
D6	Air Box Pressure
G1	Crankcase Pressure
H1	Cranking Current
110H, 110L	Alternator Frequency
230H, 230L	Two-Speed Solenoid
SSV	Starter Solenoid Voltage
BATTV	Battery Voltage
STARTV	Starter Voltage

Figure 4. Model 749 diesel diagnostic analyzer.

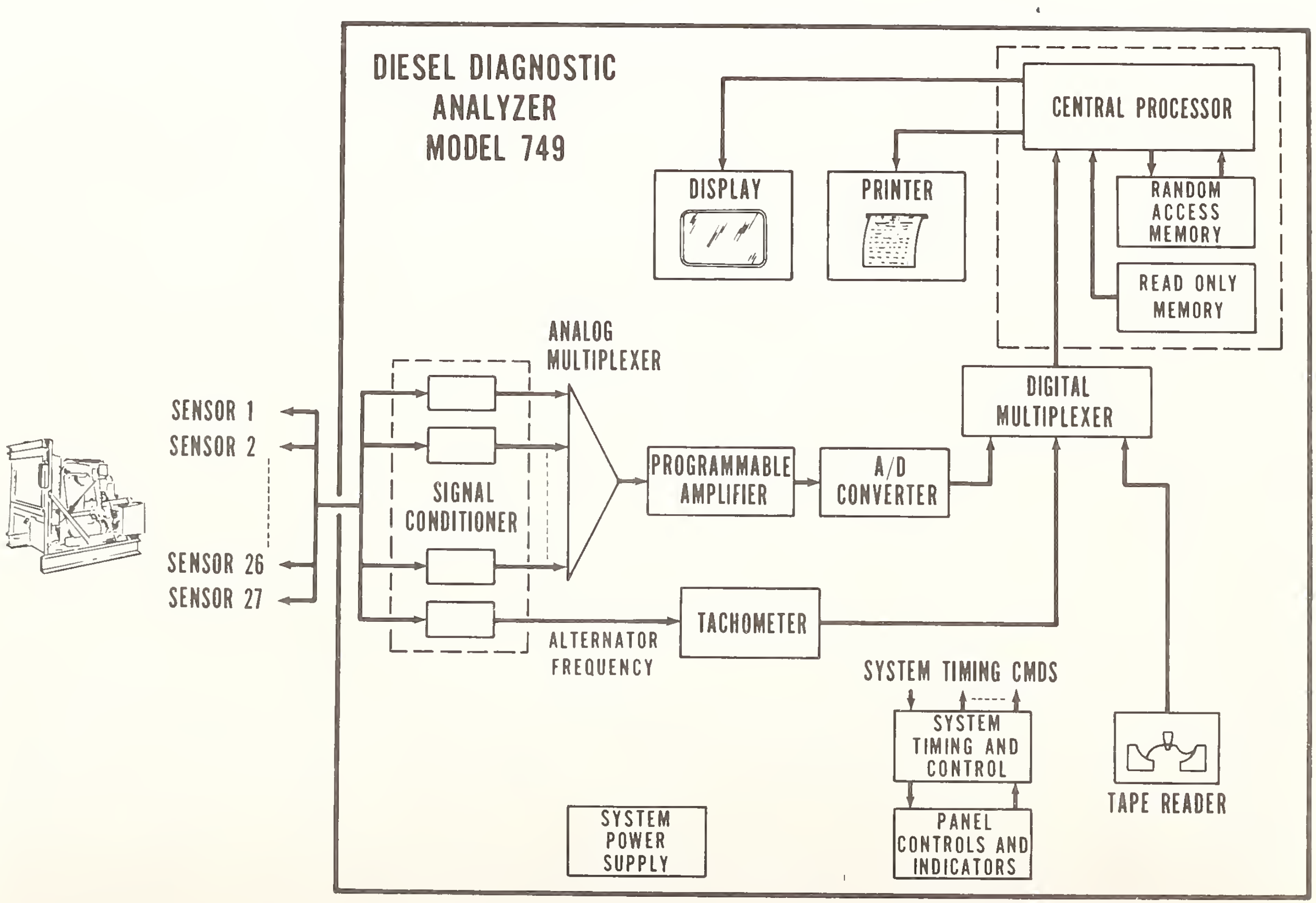

Figure 5. Functional block digram.

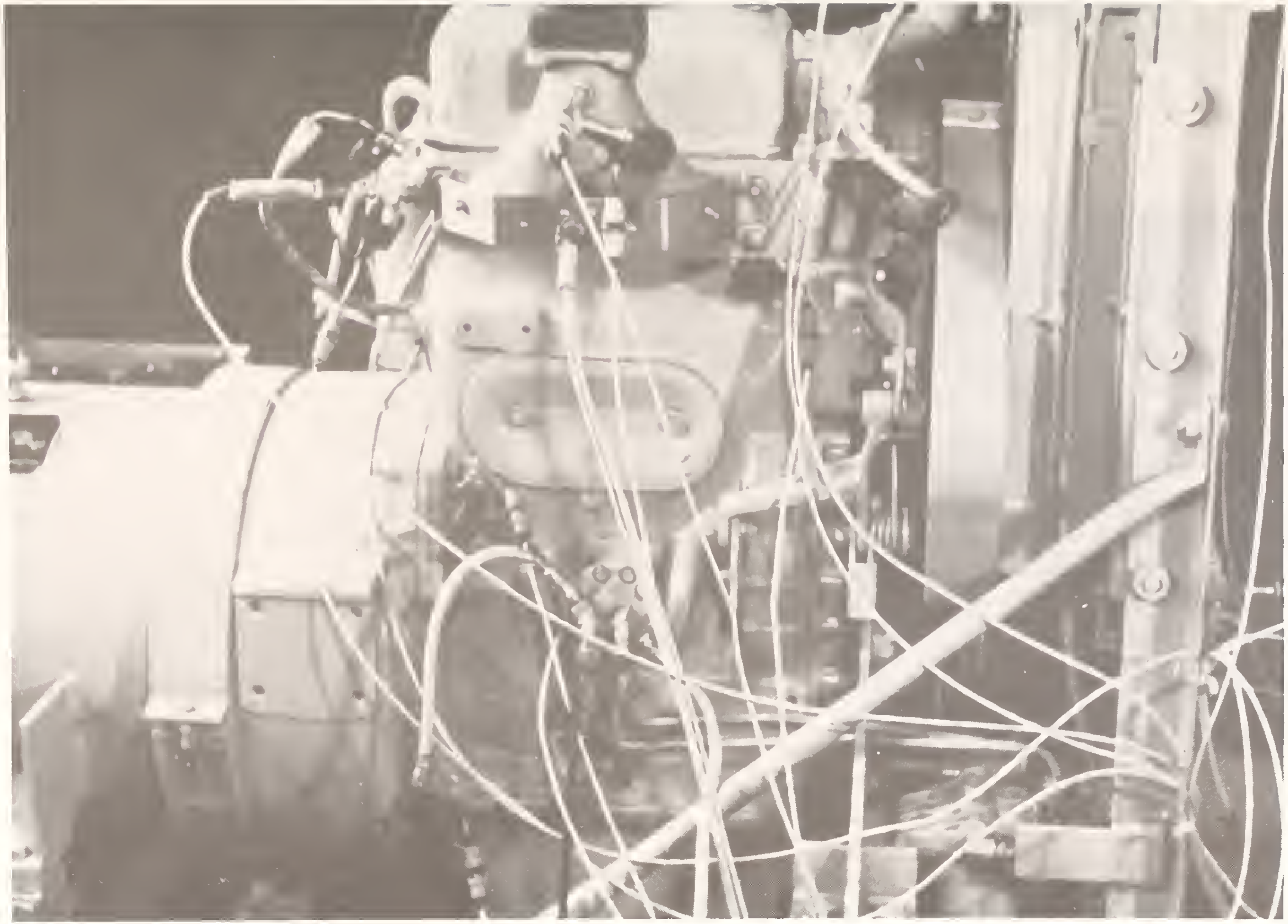

Figure 6.

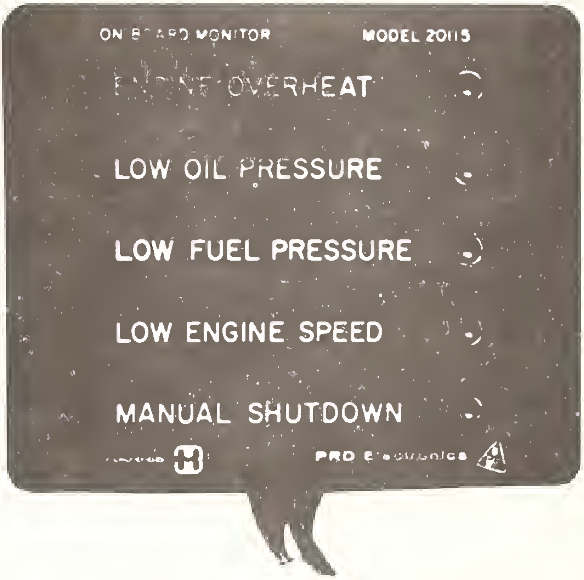
ON BOARD MONITOR
MODEL 20115
ENGINE OVERHEAT
LOW OIL PRESSURE
LOW FUEL PRESSURE
LOW ENGINE SPEED
MANUAL SHUTDOWN
PRO Electronics

Figure 7.

DISCUSSION

J. W. Forest, Ontario Hydro: What provisions, if any, are there for isolating the systems from the shock and vibration of the railroad environment?

R. F. McKee: For many years we didn't know what the environment really consisted of. We knew that it was bad but we really didn't have any good measurements. Our specifications call for a capability of 20 G's longitudinal to the rail, 10 G's lateral to the rail, 5 G's vertically as far as original manufacture is concerned. Through shake table and impact experiments on equipment, we developed ways to either isolate shock loads from the system or have a system capable of riding through the spikes, by mounting equipment more solidly. In the beginning we did a lot of isolating work. Now we are bolting things down pretty solidly because we have found that we were getting secondary relationships that were unmeasurable. Some things still have to be isolated. The thermostat, for instance, has microswitches in it which are very sensitive and we still isolate that. We are getting insiduous results on long-term service life of various components through the vibration spectrum, and we are going to study this as our next phase.

K. R. Thomas, Deere and Company: Are you going to have a problem getting mechanics to install all those transducers?

R. F. McKee: In our company we have a separate lab where the mechanics come by and see what we are doing. They are always suspicious of us anyway so we think the best approach is to treat this as just one more sophisticated step in giving mechanics tools so that they are working on the thing that needs to be worked on and not searching for the problem.

USING ACOUSTIC EMISSION TECHNOLOGY TO PREDICT STRUCTURAL FAILURE*

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The problems associated with assuring structural integrity of large complicated structures, such as bridges and power plant pressure vessels, have been the cause of much concern to the prime contractors manufacturing these structures, and to the licensing agencies and code writers whose responsibility it is to assure public safety. This concern is rightly justified since we are continually striving for greater efficiencies in the use of materials which call for higher strength-to-weight ratios, higher operating temperatures and pressures, and economics in manufacturing. Each of these factors requires that better inspection techniques and more quantitative information be available for making a judgment of operating efficiency as well as safety.

One approach that has been taken to help solve some of the problems is sponsored research in linear fracture mechanics and nondestructive testing technology. Much progress has been made in both areas over the last decade such that the combination of design based on linear fracture mechanics coupled with a thorough NDT inspection is sufficient precaution in most cases to prevent structural failures. Problems that can arise in applying this technique come about by the inability, in some instances, to accurately determine the stresses under operating environments and the size and shape of the flaw. Both pieces of information are needed to determine the stress intensity factor at a flaw site, and therefore predict structural failure.

The purpose of this report is to show how acoustic emission techniques can be used to estimate the stress intensity factor of a growing crack, and therefore provide predictive ability for determining failure.

In acoustic emission, the energy input is in the form of strain energy due to mechanical, thermal, or intrinsic stresses. Interaction and redistribution of stresses within the vicinity of a defect on a local level gives rise to the acoustic emission signal. This comes about due to sudden irreversible phenomena (such as plastic deformation, cleavage, or phase transformation) which releases minute quantities of strain energy,

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*This paper is an excerpt from an article that appeared in METALS ENGINEERING QUARTERLY February 1975 part of which is emitted as an elastic wave - sometimes called a stress wave.

The step of displacement which generates this stress pulse can occur on the order of 10^{-8} s. Thus, the stress pulse has very broad band frequency components. Most engineering structures are two-dimensional in nature. Therefore, the stress pulse will normally be dispersive in nature, taking on the characteristics of a guided wave. Since the acoustic emission transducer is normally attached to the surface of a structure, the primary modes of interest for detection are the shear and surface wave components of the stress pulse.

Both Lamb waves and Rayleigh waves can be detected at the surface. With thin plates and detection frequencies between 0.1 and 1 MHz, Lamb waves are the most important consideration, for thick-plates Rayleigh waves become the more dominant. Both of these wave propagation modes have the advantage that geometrical losses go as R^{-1}, as opposed to R^{-2} for infinite medium waves where R is the distance of the wave packet from the source. Thus, a piezoelectric transducer placed on the surface of a part subjected to stress will detect the stress pulses emanating from a localized deformation, even though it is physically removed from the source by some distance (tens of ft. in some cases). By measuring the time of arrival of the stress pulse at several transducers located on a structure, one can accurately locate the source of the signal. (This is analogous to locating the epicenter of an earthquake, which emits an acoustic signal on an immense scale.)

FRACTURE CONSIDERATIONS

Most structural failures occur by the initiation and growth of a crack. The crack may already be present, or cracks may initiate due to nonmetallic inclusions, hydrogen embrittlement, stress relief heat treatment, stress corrosion cracking, or fatigue at a stress concentration. In other instances, a structure may simply fail due to accidental overload, or become overloaded at working stresses due to thinning of material from the working environment. Acoustic emission techniques appear to be more suited to the first case where failures occur due to the growth of cracks at gross stresses well within the design limits of the structure. A failure of this type is usually caused by the slow growth of a crack to a critical size, such that catastrophic crack propagation occurs and the structure fails.

A whole new methodology, called Linear Elastic Fracture Mechanics, has developed over the past decade specifically directed toward determining the stresses in the vicinity of cracks. These stresses are controlled by a single parameter, K, known as the stress intensity factor.[1-4] This parameter depends on the body geometry, the shape, size and location of the flaw, and the type of loading that is present. Since the acoustic emission in a specimen containing a crack stressed below general yield is dependent on the plastic strains in the vicinity of the crack tip, and these strains in turn depend on the stress intensity factor, it was expected, and found to be true,[5] that the acoustic emission characteristics should be closely related to the stress intensity factor for the cracks present.

The importance of the relationship between acoustic emission and the stress intensity should not be overlooked. Since the stress intensity factor, K, is the controlling parameter for the stresses in the vicinity of a crack, and the critical value of K (called K_c, or the fracture toughness) is where failure will occur, failure of a structure can easily be predicted if one can estimate, from acoustic emission monitoring of a structure, the value of K for the defects in the structure and the fracture toughness K_c for the material is known. Therefore, one need not know the flaw size, stress or any other parameter in order to make failure prediction - it is the local stresses in the vicinity of the defect and not the defect size or gross stresses alone that are important. From this, one would expect a small defect in a highly stressed region or one containing tensile residual stresses to be a more important consideration than a larger defect in a relatively lower stressed region, because the stress intensity could be higher for the smaller defect (since it depends on both the flaw size and gross stresses).

Estimating Stress Intensity Factors

The fact that a defect is or is not present in a structure should not be the most important consideration. It is the defect that will grow in service that will lead to problems, and it is the detection of the growing defect and the estimate of the stress intensity in the vicinity of the defect that will allow a technical judgment to be made for keeping a structure in service. The remainder of this report will show how acoustic emission techniques can be used for estimating the stress intensity factor, K, near a growing crack for three types of service conditions: 1) subcritical growth due to hydrogen embrittlement or stress corrosion; 2) subcritical growth due to fatigue; and, 3) subcritical growth due to rising load tests that would be encountered for instance during proof testing of pressure vessels.

FATIGUE CRACKING

Basically, two acoustic emission methods can be used to detect fatigue crack growth. In one, the acoustic emission is recorded on a periodic basis from a structure that is loaded in a single cycle to a stress higher than the working stress (periodic overload). Second, the structure can be continuously monitored during service.

Periodic Overload

This technique will work as well on subcritical growth due to hydrogen embrittlement or stress corrosion cracking, but has usually been used in fatigue crack growth studies.[6-8] The technique utilizes the "Kaiser" effect, an irreversible nature of acoustic emission, in the following way. Assume a structure containing a defect is initially proof loaded to a value such that the stress intensity factor present at the proof load is

$$K_p = \alpha\sigma\sqrt{a} \qquad [1]$$

where

K_p = stress intensity at proof load
α = geometry function
σ = stress at proof load
a = initial crack size

The structure is subjected to its working environment for some period, and is again loaded to the same maximum proof stress while monitoring acoustic emission. It has been determined[5] that the acoustic emission, N, as a function of the stress intensity, K, could be expressed as

$$N = AK^m \qquad [2]$$

If no crack growth has occurred during the working environment, K_p at the proof stress will be identical to what it was during the initial proof load. Because of irreversibility (that is, no new plastic deformation), there will be no acoustic emission present during the second loading to the proof load. On the other hand, if crack growth has occurred such that a in Eq. [1] is larger and the structure is loaded to the same maximum stress, the stress intensity factor, K_p, will be greater due to the increase in the crack length. Therefore, new deformation will occur, and acoustic emission will be present between the working stress and proof stress. Thus, the presence of acoustic emission between the working stress and proof stress during a periodic overload of a structure is a qualitative measure that defect growth has occurred at the working stress since the last proof test.

Recovery effects of materials especially under high temperature environments may affect the irreversible nature of the acoustic emission results. Palmer[9] has conducted extensive experiments on pressure vessel steels in the U.K., and reported that for temperatures encountered in most power plant pressure vessels, recovery effects are minimal.

To get more quantitative results on a periodic overload test, one needs to obtain fatigue crack growth data on the materials used in a structure to be tested. Paris found that the fatigue crack growth rate depended solely on the range of the stress intensity factor, K, encountered in a cyclic test.

$$da/dn = B\Delta K^n \qquad [3]$$

where

da/dn = crack growth per cycle
K = stress intensity factor
n = exponent ranging between 2 and 4

By conducting rising load tests on fracture toughness specimens while recording acoustic emission, measuring fatigue crack growth rates as a function of K, and knowing an expression for the stress intensity factor, one can evaluate the constants in Eqs. [1], [2], and [3]. By simultaneous solutions of these equations, one can obtain an expression for the acoustic emission counts observed during a periodic overload as a function of the number of fatigue cycles at the working load. (See Refs. 6 and 7 for more detailed analysis.)

Fig. 1 shows what one experimentally observes while recording acoustic emission during periodic overloads on a fracture specimen, and what one can theoretically predict by combinations of Eqs. [1], [2], and [3]. The sharply increasing slope indicates impending failure, and a conservative estimate of the number of cycles to failure could have been made on strictly theoretical considerations. Application of this technique to welded pressure vessels can be found in Ref. 8.

Continuous Monitoring of Fatigue Crack Growth

Very little work was done until recently on the application of acoustic emission to monitor fatigue crack growth. One of the primary reasons for this was the problem with background noise from grips, rubbing surfaces, etc. Nakamura,[10] one of the early researchers in this field, was able to overcome much of the interference with the background noise by using spatial filtering techniques. Within the last two years, further improvements in transducers and instrumentation techniques have allowed crack growth measurements to be made in the presence of high background noise. This has led to major breakthroughs in continuous monitoring of fatigue crack growth, and a considerable amount of work is presently going on in this area.[11-18]

Harris and Dunegan[14] reported detecting fatigue crack growth rates of 10^{-6}in./c and below on high strength aluminum alloy. It was also found in this work that, if the acoustic emission counts per cycle were plotted as a function of energy released by crack extension per cycle, data from steel and aluminum were normalized for a given bandwidth and sensitivity. It was also observed (Fig. 2) that a peak occurred in the data when plotted in this manner. The peak was found to occur within the transition region from plane strain to plane stress along the crack front. This phenomenon has important implications for possible quantitative use of acoustic emission data for predicting fatigue lifetime.

RISING LOAD TESTS

Large pressure vessels and many other types of structures are normally tested to a proof stress higher than the working stresses prior to being put into service. It was stated previously that the stress intensity factor, K, controls the magnitude of the stresses at the crack tip. Therefore, if one can measure the stress intensity factor during a proof stress cycle using acoustic emission techniques, a judgment can be made concerning the integrity of the structure. For example, Fig. 3 is a plot of the acoustic emission from several specimens[19] containing different crack lengths. We see that all the data is normalized when plotted as a function of the stress intensity factor.

Corle[20] has extended this concept to improve the reliability of rocket motor cases. He demonstrated the flaw detection improvement achieved by the use of acoustic emission during proof testing of motor cases over the reliability achieved by the proof test alone. From the acoustic emission standpoint, the improvement was greater in air melted and welded structures than in unwelded, vacuum melted structures.

Thus we see for small structures without a great deal of complexity one can use acoustic emission to accurately evaluate integrity once the material characteristics are established. For complex structures containing riveted joints and other types of mechanical fasteners, one must locate the source of the acoustic emission signal to more accurately take into account signals from several sources.

FLAW LOCATION

For some types of geometries (linear welds and tubes, for example), a one-dimensional location scheme is adequate. Bailey, et al[21], used this concept to good effect for locating fatigue cracks growing from rivet fastener holes during fatigue testing of an aircraft structural section. Fig. 4 shows the type of specimen and the acoustic emission display used to locate the cracks. All cracks when first detected were under nuts, bolt heads, or in faying surfaces - locations which are difficult to reliably inspect by conventional nondestructive techniques. Bailey, et al, also stated that the fatigue tests were only monitored 10 pct of the total test time, and that 15 of the 18 potential cracks identified were confirmed by visual means at 50 times magnification.

Thus we see that, under certain situations, economical and fairly simple hardware can be used to identify that a crack is present, and the extent of cracking, once located, can be checked by other methods. As the size and complexity of a structure increases, many more channels of instrumentation interfaced with a computer are normally required to properly locate and keep track of the acoustic emission signals.

Multi-Channel Computer Instrumentation

Previous sections of this report have shown how acoustic emission from a defect can be used to estimate the stress intensity factor at the defect site. In some instances on larger structures, more than one defect may give rise to acoustic emission signals, and extraneous noise sources may be present. Then one must be able to locate the source of the acoustic emission as well as evaluate the signals from each source to judge the degree of damage occurring.

A considerable amount of work[22-33] has been done over the past few years in the development and use of computer interfaced systems for flaw location. Many different approaches have been used for handling and display of the data. The one common feature of all approaches is the measurement of time of arrival of an acoustic emission signal to a multiple array of transducers located on a structure. From the time difference observed between individual sensors, computations can be made of the location of the defect.

Most of the work to date has been concentrated on accurate location of the defect so that other methods (such as ultrasonic and X-ray techniques) can be utilized to evaluate the defect. More recent instrumentation designs have incorporated location, as well as a measure of the severity of the defect, by determining the number of counts received from individual locations.

Fig. 5 illustrates a portable 16-channel system, expandable to 32 channels, which incorporates a realtime CRT display of the location and the number of counts received from each location. Fig. 6 shows four transducers mounted on a plate with two symbols marked by black tape. Ultrasonic pulses were coupled into the plate to simulate acoustic emission signals at the locations marked by the tape. Fig. 7 shows the CRT presentation of the transducer locations and corresponding locations detected from the injected pulses. The distance between transducers in this example was 16 in.

The accuracy with which one can locate a source of emission can vary from 1 to 10 pct of the transducer spacing or greater, depending on the source of the signal, attenuation, and geometry effects and surface condition of the structure. The histogram shown by the eight small dots in the lower left-hand corner of Fig. 7 represents eight different arrays of four transducers each. In this example, Array No. 2 which is displayed in the right portion of the CRT was used to accumulate data from the plate. Approximately 400 signals were injected into the plate to provide the readout as shown. A similar type of histogram can be displayed on the CRT, which shows the number of ring-down counts from each array.

This gives a measure of the amount of deformation or crack growth occurring at specific locations covered by each array.

The type of printout one can obtain from this system provides the time difference information between transducers, the X-Y coordinates of the source, the number of ring-down counts from the signal (which is a measure of the severity or the amount of crack growth), and a parametric input such as pressure, force, etc.

Thus we see that the ability to locate a source of acoustic emission, coupled with the ability to evaluate individual signals from each location, allows us to treat the large complex structure as a composite of many localized small scale components. We can apply the ability to estimate stress intensity factors at these local levels to determine structural integrity.

CONCLUSIONS

The combination of acoustic emission and linear fracture mechanics can provide quantitative information regarding structural failure. This report has shown that, for certain situations, acoustic emission techniques can be used to accurately estimate the stress intensity factor, K, at a growing crack, and therefore provide predictive information regarding structural failure. The importance of locating defects in large structures was also stressed, and a multiple-channel computer system was described for accomplishing this function. The ability to locate a growing defect, coupled with the ability to quantify the growth rates with fixed sensors (no scanning required) places acoustic emission in the forefront of new techniques for the prevention of structural failure.

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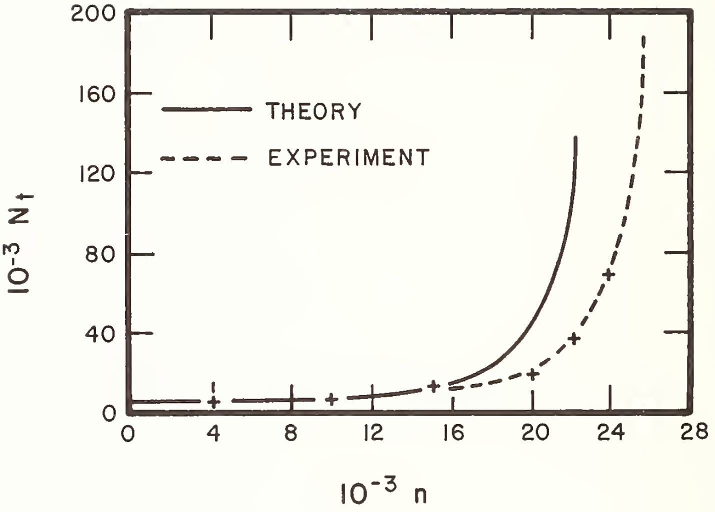

Fig. 1 - Experimental and theoretical results of total counts observed during the proof cycle versus the number of fatigue cycles at the working stress

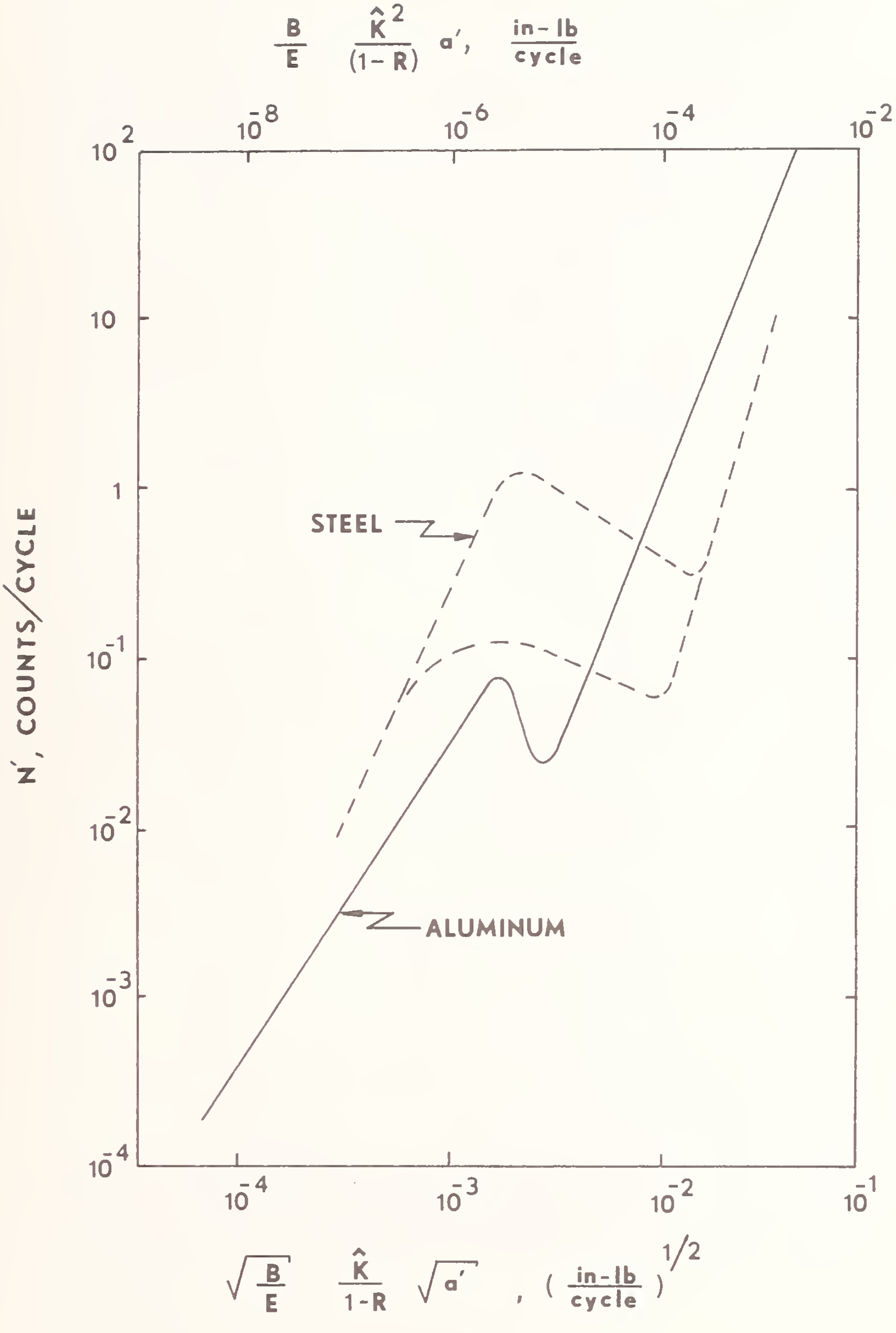

Fig. 2 - Counts per cycle as a function of energy per cycle for aluminum and steel specimens undergoing fatigue crack growth

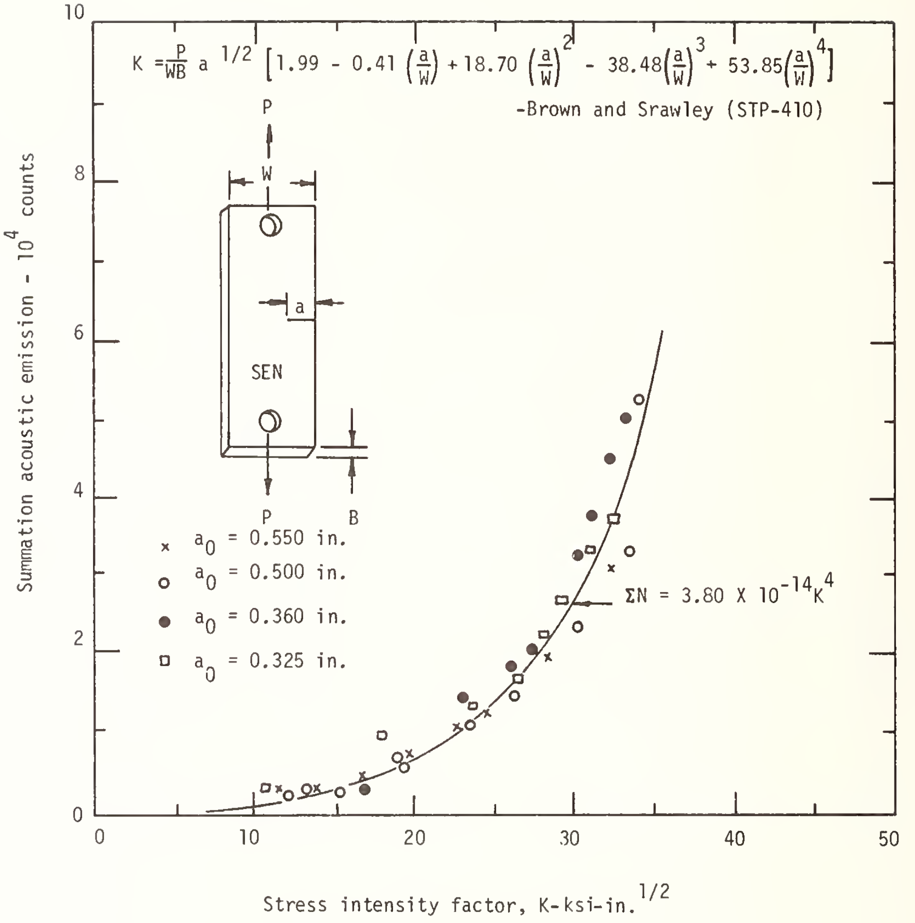

Fig. 3 - Summation of acoustic emission as a function of stress intensity factor for SEN fracture specimens of 7075-T6 Al with different initial crack sizes

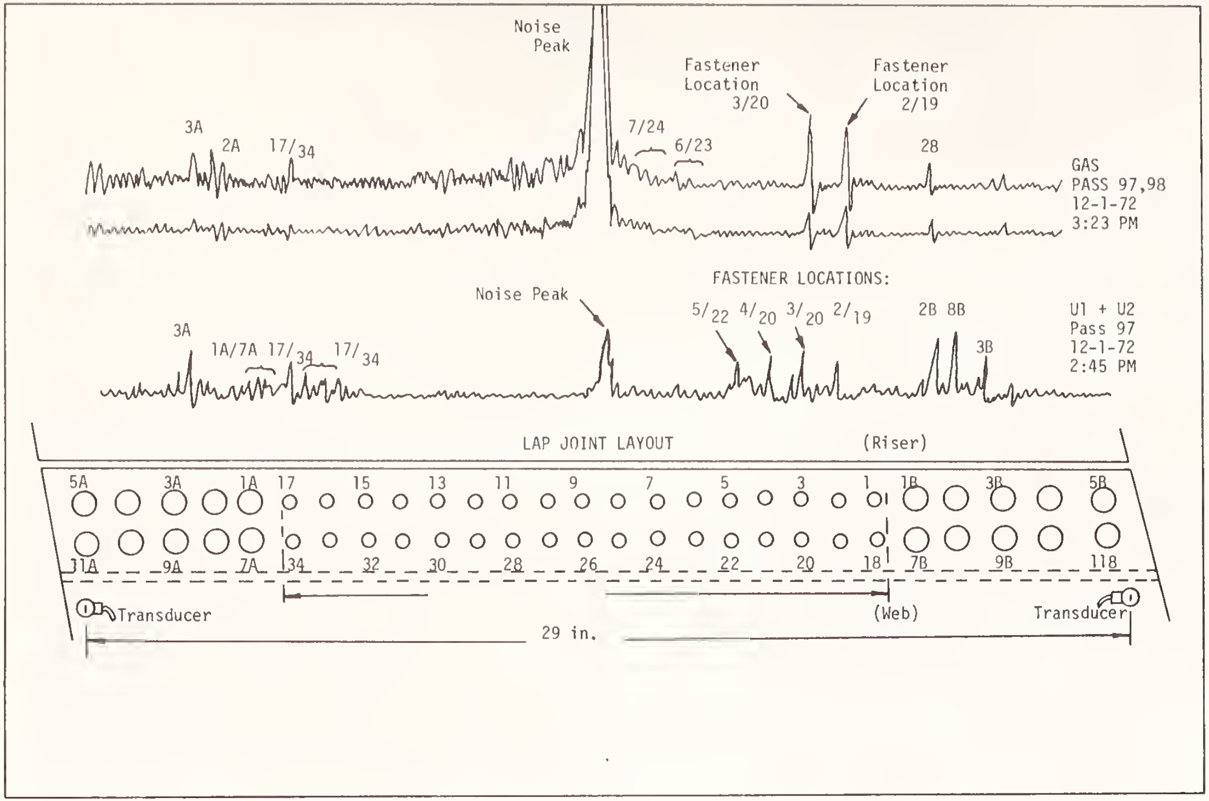

Fig. 4 - XY plots of one-dimensional acoustic emission location of cracks originating at rivet holes on a complex aircraft structure component[21]

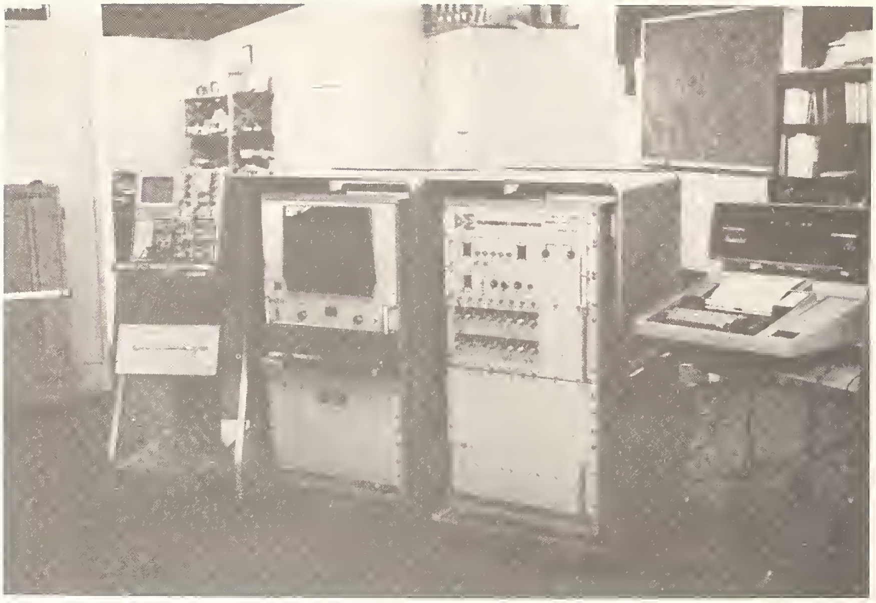

Fig. 5 - Multiple channel acoustic emission system

Fig. 6 - Transducer placement on a metal plate and symbols used for illustrating flaw location by acoustic emission multiple channel system

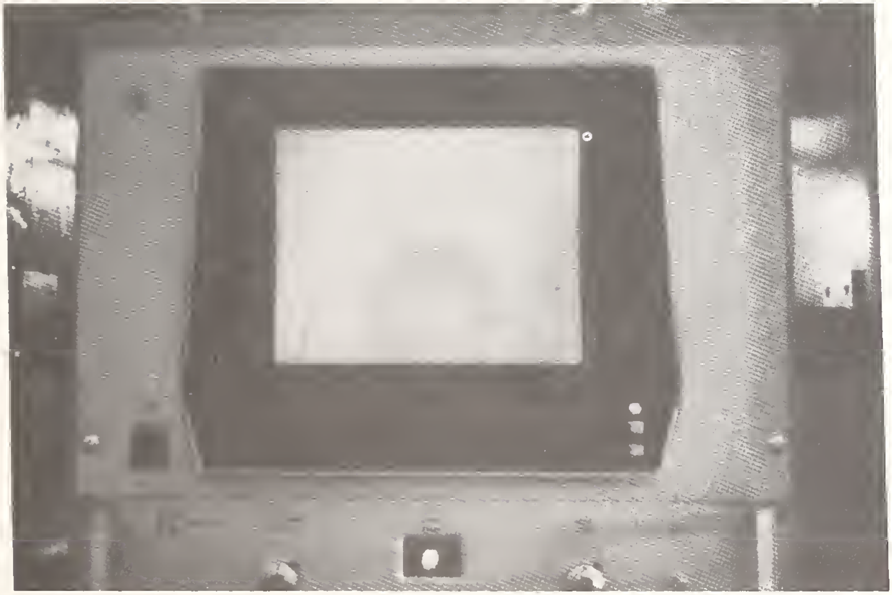

Fig. 7 - CRT presentation obtained by injecting simulated acoustic emission signals at location shown by symbols in Fig. 6

DISCUSSION

J. W. Forest, Ontario Hydro: How do you go about establishing the threshholds and how does that level affect the results?

H. E. Dunegan: You have to determine the signal level expected from a given increment and the background noise in a particular frequency range. So it may involve using either changing sensitivities or changing frequencies depending on the conditions.

J. L. Frarey, Shaker Research Corporation: When a reactor is under steady state loading, wouldn't the signal-to-noise ratio be a real problem?

H. E. Dunegan: We were pleasantly surprised. We have sensors on four boiling water reactors now. We find that when the reactor comes up under cold start-up, there is a lot of noise. Once temperature and full operating load are reached, things quiet down drastically. So we were pleasantly surprised that under operating conditions the reactor is actually quieter than it is when it is being started up.

J. L. Frarey: But also the crack isn't progressing as fast.

H. E. Dunegan: You may want to look at the ratio of activity from an area over the last 24 hours compared to the activity over the last 30 days. Then you can construct a curve of the ratio of activity as a function of time. If there is a change in slope, that would be an indicator that there is something very active there. It's somewhat difficult at this point to make quantitative measurements.

APPLICATIONS OF THE SHOCK PULSE TECHNIQUE TO HELICOPTER DIAGNOSTICS

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INTRODUCTION

An investigation has been carried out on the feasibility of shock pulse techniques in the detection of failures in helicopter power trains. A standard off-the-shelf SKF Industries model MEPA-10A was employed to construct shock emission envelopes of shock rate versus shock level. Data was collected from the hanger bearings of the tail rotor drive shaft assembly, the 42° and 90° gear box assemblies, and the transmission and mast assemblies as installed on operational UH-1 series helicopters of an Army Aviation Reserve unit. Further data was obtained from helicopters at Fort Rucker, Alabama with implanted bearings of known condition. The correlation between the shock emission envelopes and the degree of degradation as revealed by teardown analysis will be described. This paper will summarize the evaluation carried out to date.

THE MEPA-10A SYSTEM

Details of the SKF shock pulse meter (Figure 1) and its operation has been described in an earlier MFPG proceedings[1]. Briefly, the technique employed is to construct a shock emission envelope containing the rate of shock emission as well as the measurement of the amplitude of shock developed by a particular bearing. When a bearing race, or rolling element, contains a discrete fault, such as a pit or spall, the contact between this fault and the rolling elements will result in repetitive impacts of short duration. As a result of these impacts, a shock wave propagates through the structure. The shock pulse travels through the bearing and causes a pulse displacement input to an accelerometer. The equipment used in the MEPA-10A system includes a 38 kHz resonance response accelerometer. The output of the accelerometer is passed through a high gain amplifier tuned at the resonant frequency of the

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accelerometer. This amplifier acts as a very sharp band pass filter. After the signal is suitably processed, the output is displayed on a counter which provides the frequency of peaks above any desired peak amplitude. No other processing is required for analysis.

A graph is made of the shock emissions (Figure 2) and from this data a determination of condition is made. With the accelerometer attached, an initial rate and value evaluation is made. The rate found becomes the first point plotted on the ordinate at a shock level of one. A threshold varying dial, on the instrument housing, ranges from a level of one to ten thousand on a logarithmic scale. As the threshold is increased, successive rates are plotted until a curve crosses the abscissa. This value at the intercept becomes the highest potentiometer level at which at least one shock pulse per second can be measured. Rate values are in pulses per second and the shock level obtained is a function of the accelerometer used. The curves are evaluated by their general curve form as well as the magnitude of rates and/or levels obtained. Approximately three minutes is required to obtain shock emission curve.

SKF Industries indicates in the operators manual of the MEPA-10A that all curve forms are a variation of three general forms (Figure 2): 1) one with high rates and relatively low levels--an apparent indication of foreign matter in the lubricant of the bearing; 2) a curve shape of low rates and relatively high shock levels--indicative of a bearing with insufficient lubricant or possible element damage; 3) a curve with both significantly high rates and levels, with the amount of "filling out" of the curve proportional to the extent of damage. However, in the helicopter applications to date, the relationship between curve shape and degradation was found to be more complex.

LABORATORY FINDINGS

A laboratory study was undertaken to provide experience and to develop the methodology to be utilized on the actual UH-1 aircraft. A bearing test rig was set up utilizing the same type, make, and size as those employed as hanger bearings on the UH-1 series aircraft. The hanger bearing fixture was identical to that of an operational helicopter. The major results:

1. The SKF-provided vice-grip to which the accelerometer is attached proved unsatisfactory. Significant differences were found in readings dependent on placement and

security of the vice-grip attachment. A pressure clamp has been fabricated which can be fitted to the lands of the bolts which hold the bearing fixture in place. The accelerometer, in turn, is attached to the pressure clamp. Shock rates and levels are easily reproducible for a given bearing assembly. Figure 3 shows the attachment on some assemblies investigated.

2. Differences between samples of new bearings and those determined as unserviceable and rejected for aircraft use could be seen (Figure 4).

3. The general shape of the shock emission curve varies with type and extent of damage. Figure 5 shows artificially degraded bearings in comparison to data obtained from samples of new bearings. Although the curves do not follow the SKF representation of Figure 2, the increase in level over the new bearing data is evident.

4. The rates and levels are speed dependent (Figure 6).

5. Although a damaged bearing could be discerned, it was not possible to localize the damage as to inner or outer race, rolling element, etc.

6. Laboratory readings of rate versus level differed from those of the same bearing assembly installed on a UH-1H helicopter. Thus, generalized damage assessment curves must be generated with the bearing in the actual operating environment (Figure 7).

In addition to the hanger bearing tests, SKF Industries, under subcontract to the College, investigated the ability of the MEPA-10A to detect gear-sourced shocks. The College provided technical assistance and monitored the performance of the task. Three UH-1 42° gearboxes with several different types of gear damage were subjected to shock pulse monitoring during runs at different loads and speeds. It was determined that the MEPA 10A can supply warnings as to the onset of damage in a gearbox. If the damage originates in the bearings, an indication directly correlated with damage is received. If the damage originates in the gears, the indication is obtained indirectly through the sensing of particulate contaminant passing through the bearings (Figure 8).

UH-1 DATA

Hanger Bearings

Seventy-two hanger bearings as installed on UH-1 helicopters were tested. The helicopters were made available on a non-interference basis by an Army Aviation unit stationed near the College. All tests were at N_2 = 6600 rpm. Selected hanger bearings were removed for teardown analysis. These include bearings with potentiometer levels from moderate to high. The teardown analysis was performed either by Bell Helicopter Company or by the College. Defects, if they existed, consisted primarily of pitting and corrosion varying from slight to severe. Figure 9 shows the shock emission curve of a bearing with marginal level of damage. Figure 10 illustrates the level of pitting and corrosion. Wherever a hanger bearing was removed for teardown analysis, readings were taken on the new, or replacement, bearing. In each case, a marked reduction in rates and levels was noted.

The extensive hanger bearing data has been summarized in a single damage-assessment shock emission curve (Figure 11).

Additional data was collected on hanger bearings installed on helicopters in the AIDAPS program at Fort Rucker. These hanger bearings were inspected and found acceptable prior to their use in that program. In particular, the effect of engine rpm variation and anti-torque pedal (tail rotor) inputs were investigated. Although shock emission curves varied with rpm as previously noted, pedal deflection gave an insignificant increase in potentiometer level.

42° Gear Box

Readings were taken on forty-two 42° gearbox drive quills. Nine gearboxes were removed for teardown analysis, either due to high rates (rather than high levels) or due to excessive needle swing. Typical of the latter is given in Figure 12 wherein the rate would not stabilize at a fixed value but would vary between the limits shown. This swing could be due to the multiple bearing and gear assemblies present in the input and output quills. Teardown analysis did indicate corrosion and pitting throughout the output inner and outer ball, radial scratches in the output roller bearing (Figure 13), as well as an output gear pattern too high and too far toward the toe, and pits on the input ball and roller bearings.

Further data was collected on the AIDAPS helicopters at Fort Rucker, Alabama, from gearboxes of known condition.

Each gearbox was completely disassembled, inspected, and any necessary component replacement accomplished prior to reassembly and use in the program. This data included that from an implanted input quill duplex bearing with known defects.

In one case, the outboard half of the duplex bearing had a single spall in the outer race, 0.14" x 0.14", with a definite depth; the inboard half had some corrosion-caused pitting with one pit in the ball's path. The increase in rate and level when compared to a damage-free gearbox is evident from Figure 14.

A second case, a duplex ball bearing with a single shallow spall approximately 0.08" x 0.08" in the outer race, gave evidence of progressive damage while the test was in progress. The shape of the shock emission curve changed continually over a period of minutes in both rate and shock level. Figure 15 shows two curves developed on a single run. A change in slope takes place (A), a sharp increase in rate (B-C), a continual change in slope (C-D). Without shutting down the engine, the second curve (E-F-G) was developed. After engine shutdown, an oil sample analysis revealed traces of metal, although not beyond that considered acceptable. The dotted line is an extrapolation of the initial slope and gives an indication of the shock level stabilizing at a factor of ten higher. Two more runs were made which essentially repeated curve E-F-G. Teardown analysis showed that the original degradation had not noticeably changed but the new spalls were found on the outer race and on one ball bearing.

90° Gearbox

Twelve 90° gearboxes were tested. Figure 16 is a scatter diagram of shock emissions. Two assemblies indicate either a higher rate or higher level than the average of those tested. These are continuing to be monitored until replacement gearboxes are available. The curve labeled "damage-free" is taken from a gearbox of known condition installed on an AIDAPS helicopter. Figure 17 shows the shock emission envelope of a gearbox removed for teardown analysis. The reason this particular one was chosen was because of the continually changing curve shape during the test run. This slope change could be indicative of progressive damage or metal contaminants in the oil. Figure 18 shows the sharp burred edge spall in the outer race and spalling in the inner race of the small duplex bearing, as well as pitting and corrosion in the outer race of the duplex bearing.

Mast Bearing and Transmission

Figure 19 is a scatter diagram of nine different mast assemblies. The solid line, again, is from an AIDAPS helicopter. The assembly chosen for teardown was the one exhibiting the high rate and level. The outer race had scratches one centimeter in length, scuffs, false brinnelling, heat discoloration and corrosion. Several balls had scratches and nicks and the inner race ring also had scratches (Figure 20).

After the new mast bearing was installed, the shock and rate levels of the replacement bearing were markedly reduced.

No transmission assemblies indicated any abnormal rates or levels on readings taken from the input drive quill and therefore, none were removed for teardown analysis.

Flight Tests

All the previous data was collected on ground runs. A series of tests were conducted to compare ground runs, hover-in-ground effect, low and high speed flight and autorotation conditions. All data collected was from the input drive quill of the transmission. This component was selected because of ease of accelerometer mounting and lack of necessity of any aircraft modifications. The various flight conditions, and hence loadings, had negligible effect on the shape of the shock emission envelope.

SUMMARY

The SKF MEPA-10A has shown its effectiveness and reliability as a bearing health analyzer in helicopter applications. The shock pulse technique has proven its value as a quick and accurate means to determine the general health of selected components on operational helicopters through the means of the shock emission profile. When components were tested and reviewed in comparison with others of the same type, it becomes apparent that the shock pulse technique can separate assemblies by degrees of degradation and damage. However, it was not possible to localize the damage as to the rolling elements, inner or outer race, gear teeth, etc. All of the damage as revealed by teardown analysis was correlatable to the data of the shock emission curves, that is, moderate rates and/or levels indicated moderate degradation and high rates and/or levels indicated severe degradation.

Although an off-the-shelf piece of commercial equipment, the MEPA-10A did not have any malfunctions operating in field conditions. Ambient temperatures ranged from -30°C to 40°C. Accelerometers were exposed to exhaust gas temperatures in excess of 200°C. However, the present system of plotting the shock emission data by hand and the necessary judgment required to determine bearing health does not lend itself for use by Army Aviation maintenance personnel. When a fully automated system is available, the shock pulse technique will prove itself to be an effective tool in reducing aircraft maintenance costs.

ACKNOWLEDGEMENTS

The study was performed under contract to the United States Army Aviation Systems Command (USAAVSCOM[2]). Parks College gratefully acknowledges the support and assistance of the USAAVSCOM Flight Operations Division, Saint Louis, Missouri; Hawthorn Aviation, Fort Rucker, Alabama; Bell Helicopter Company, Fort Worth, Texas; United States Army Flight Test Board, Fort Rucker, Alabama; and the 102d USARFFAC, Cahokia, Illinois.

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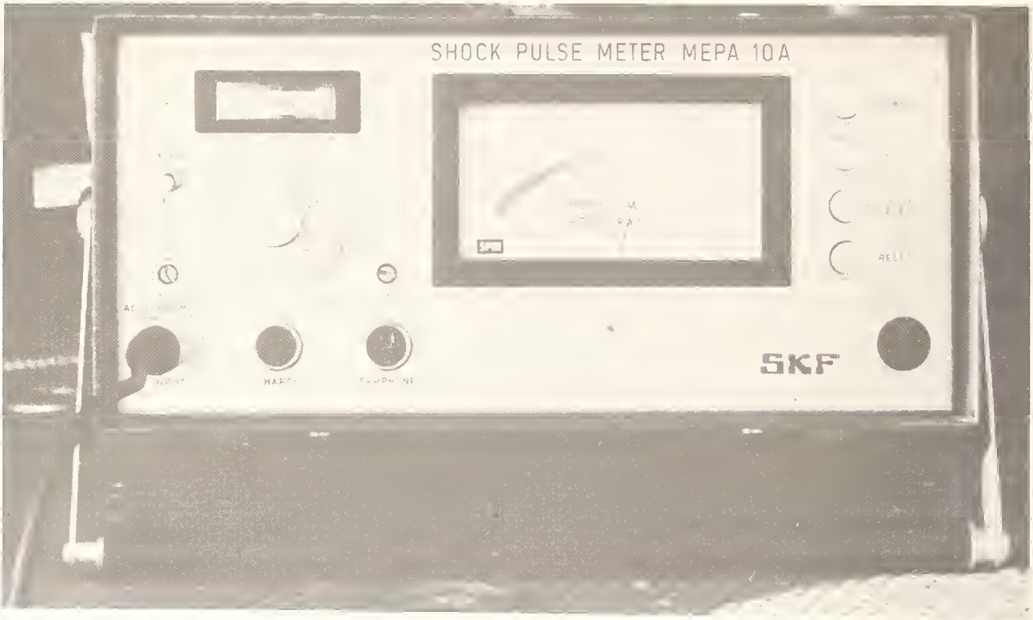
[1] P.L. Howard, "Shock Pulse Instrumentation", Proceedings of the 14th Mechanical Failures Prevention Group Meeting, Los Angeles, California, Jan. 1971; MFPG Technical Report 2, Feb. 1971.

[2] T.C. Mayer, E.F. Covill, J.A. George, J.T. Harrington "Applications of the Shock Pulse Technique to Helicopter Diagnostics", USAAVSCOM Technical Report 75-18A,B, 1975.



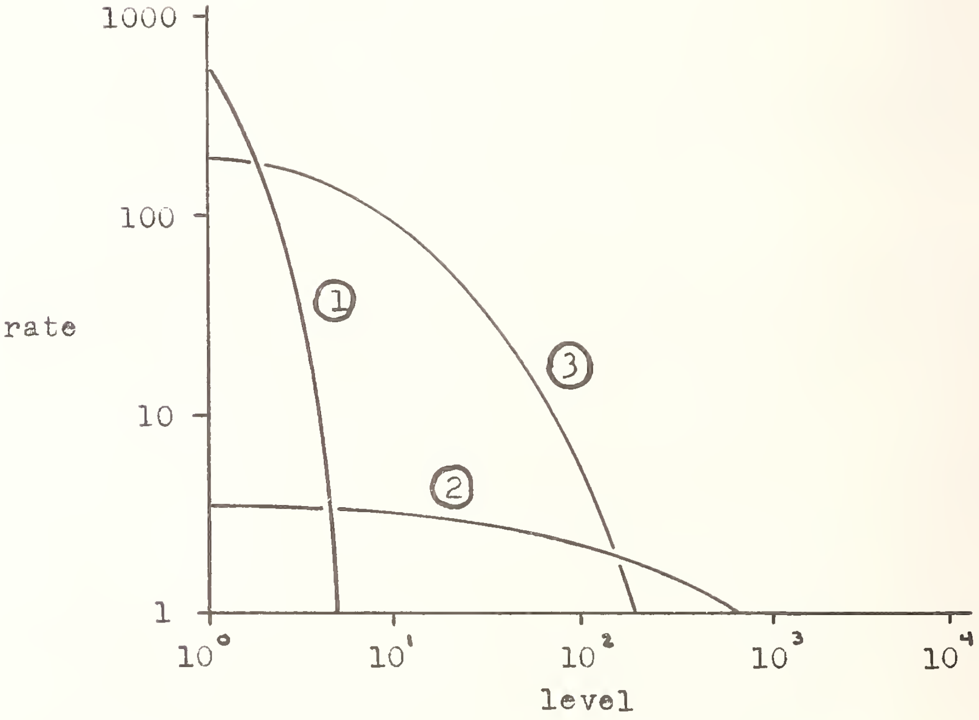
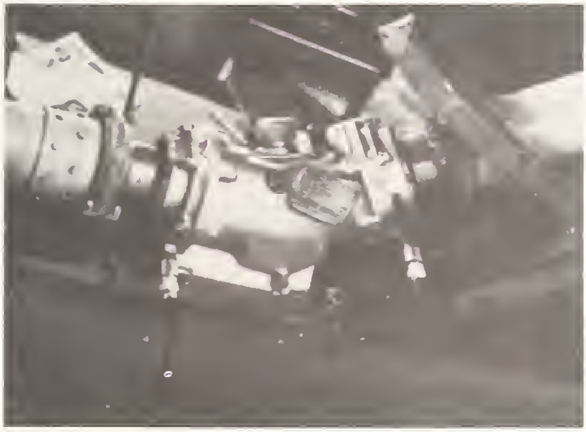


Figure 2. Basic types of shock emission curves

Hanger Bearing

90° Gear Box



42° Gear Box

Drive Quill

Mast Bearing

Figure 3. Accelerometer attachments

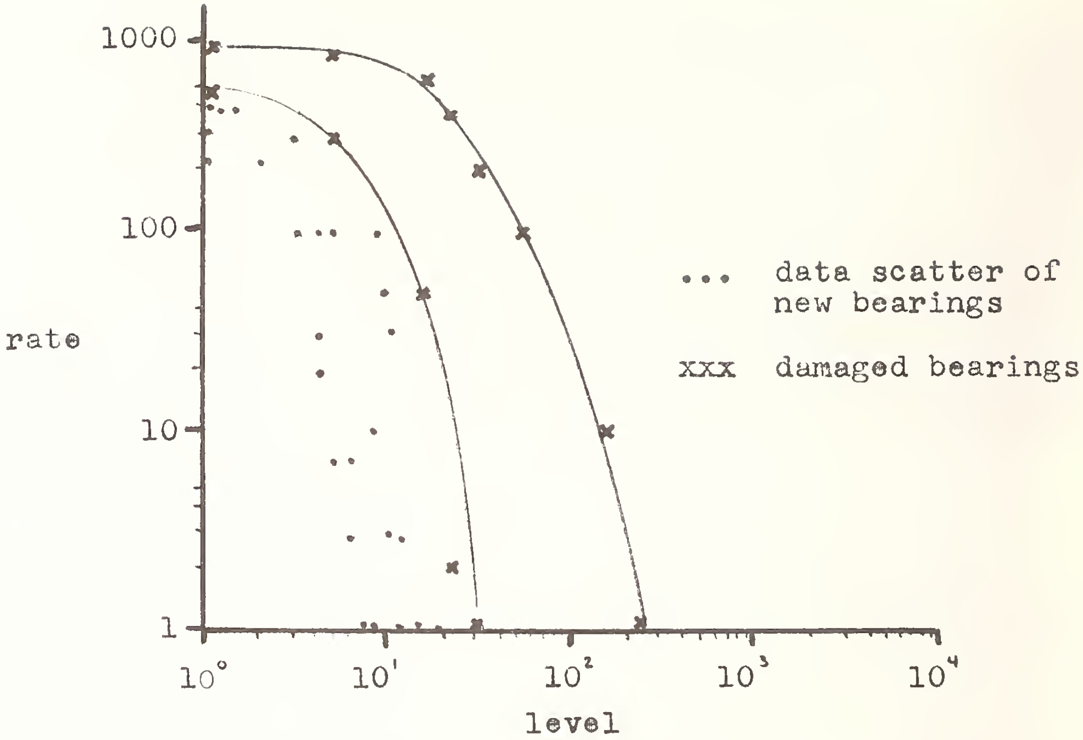


Figure 4. Comparison of new and damaged bearings in a laboratory environment.

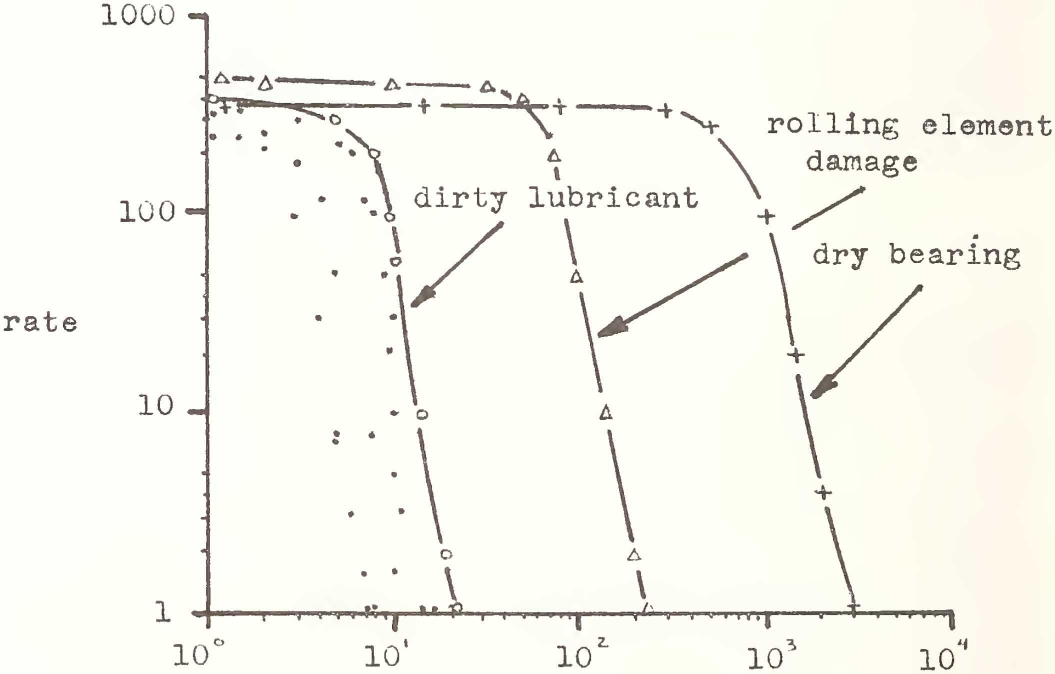


Figure 5. Scatter diagram of new bearings versus artificially degraded bearings.

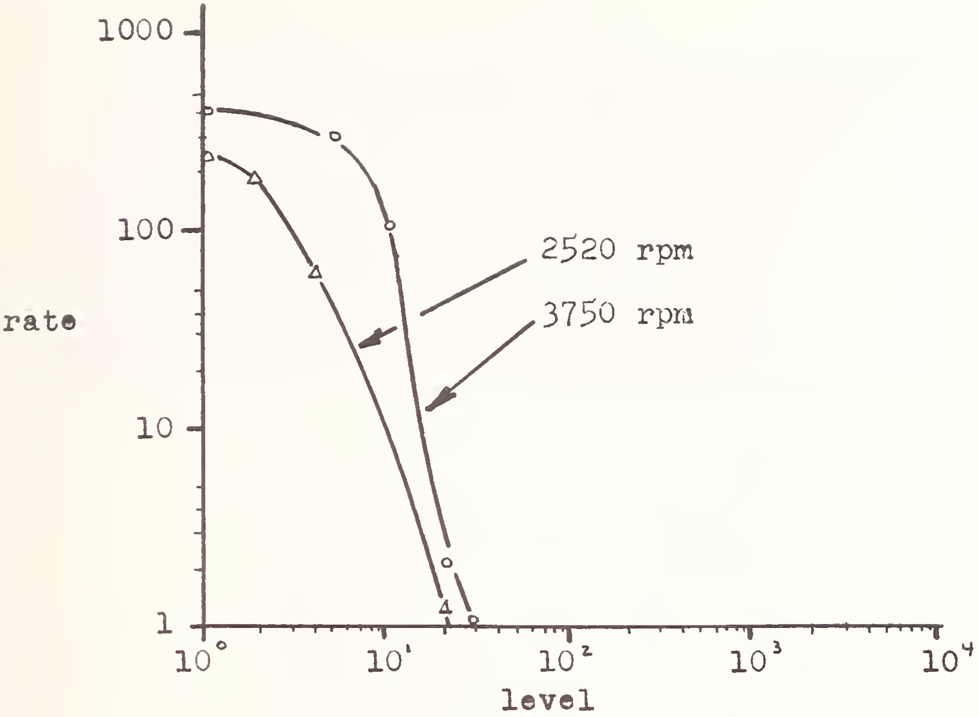


Figure 6. Speed dependence of shock emission envelope.

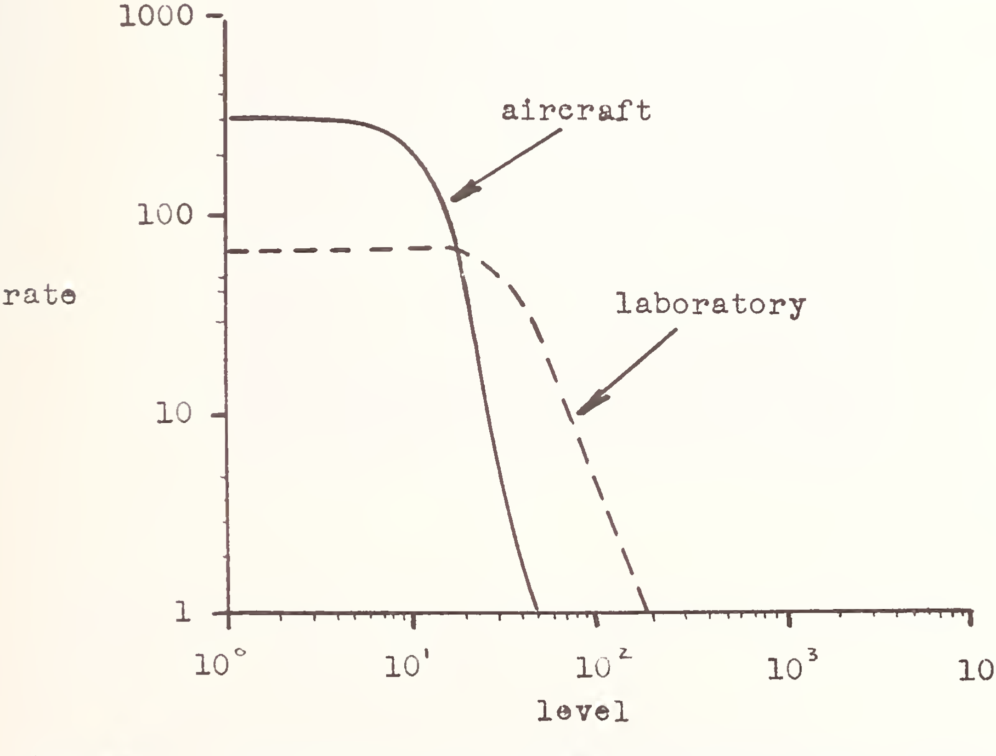


Figure 7. Comparison of hanger bearing shock emission envelope from aircraft and laboratory.

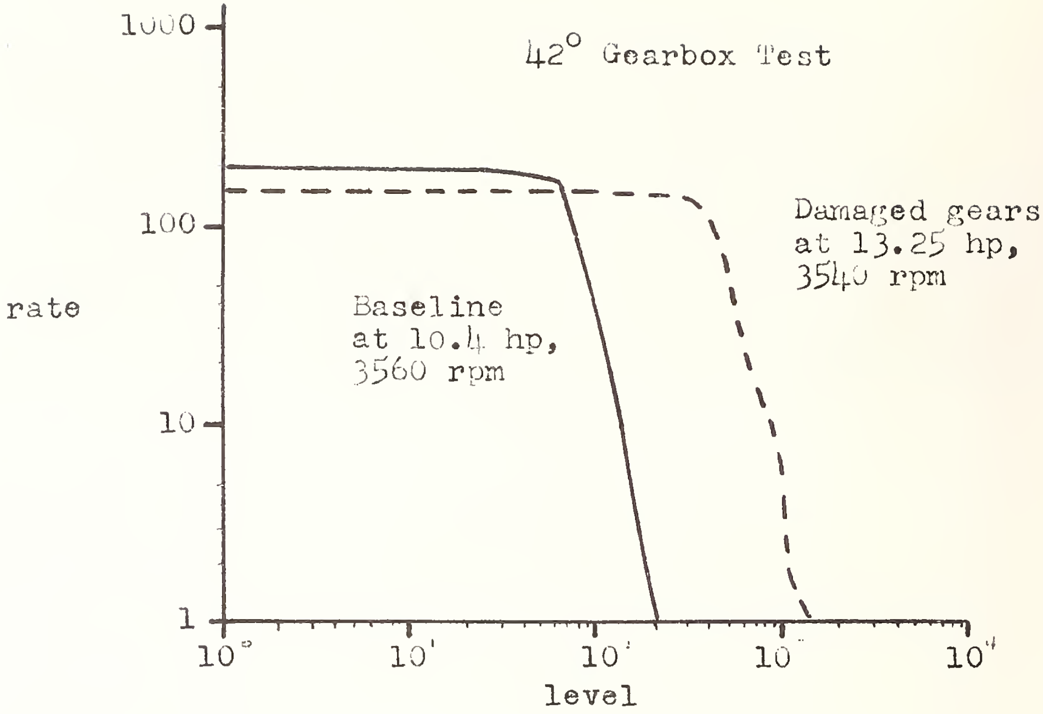


Figure 8. Baseline versus damaged gears with particulate contaminant in the oil.

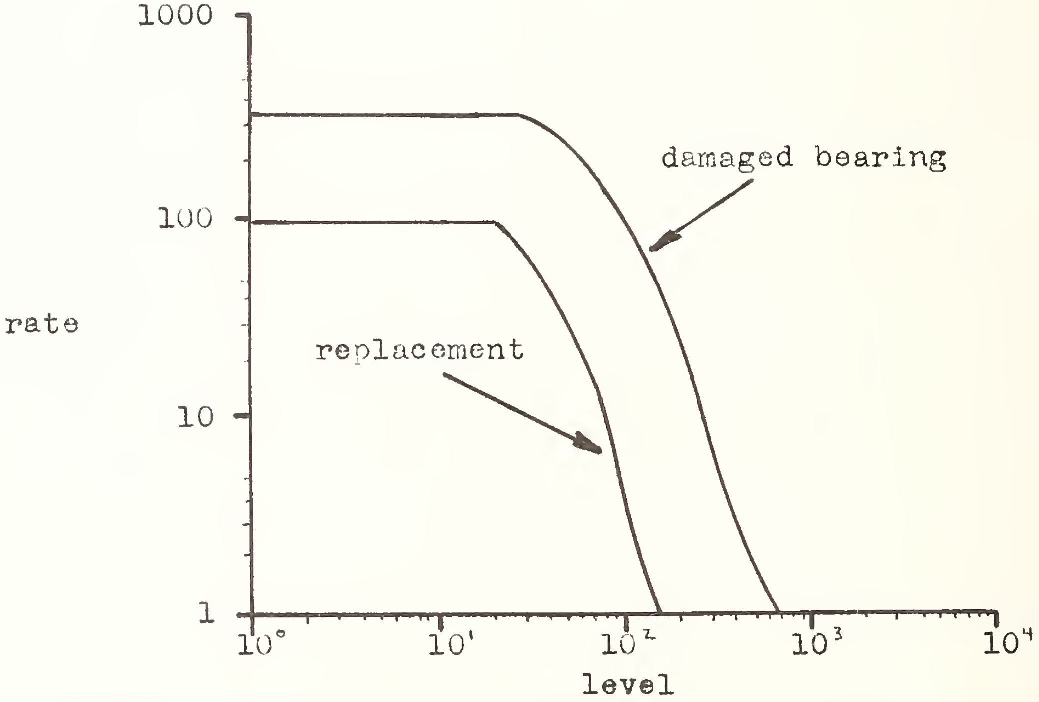


Figure 9. Comparison of damaged and replacement hanger bearing.

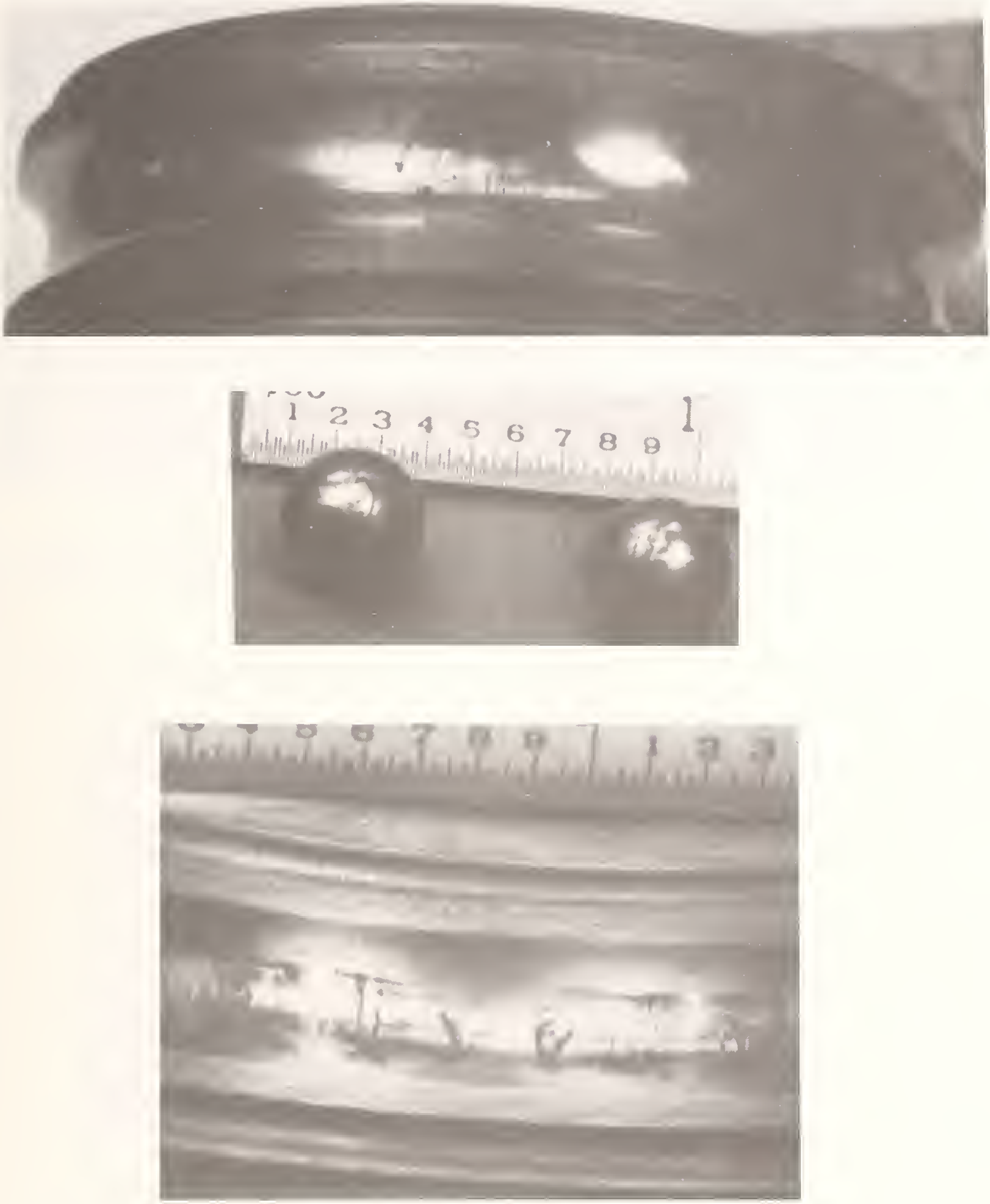


Figure 10. Damaged hanger bearing removed from UH -1H helicopter.

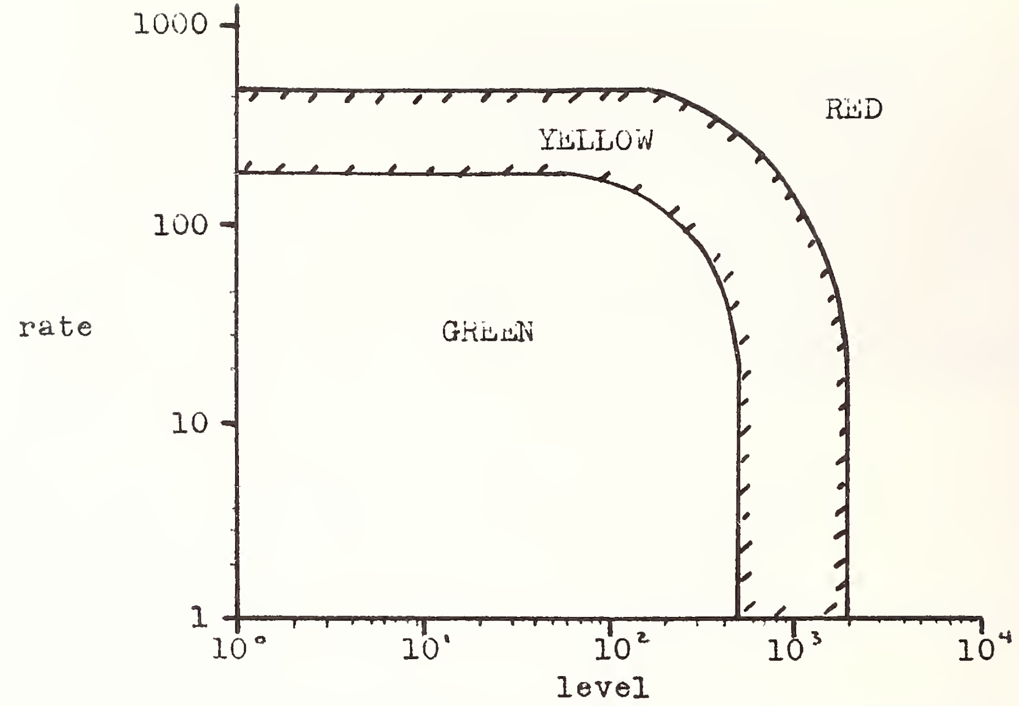


Figure 11. UH -1 hanger bearing damage assessment shock emission curve.

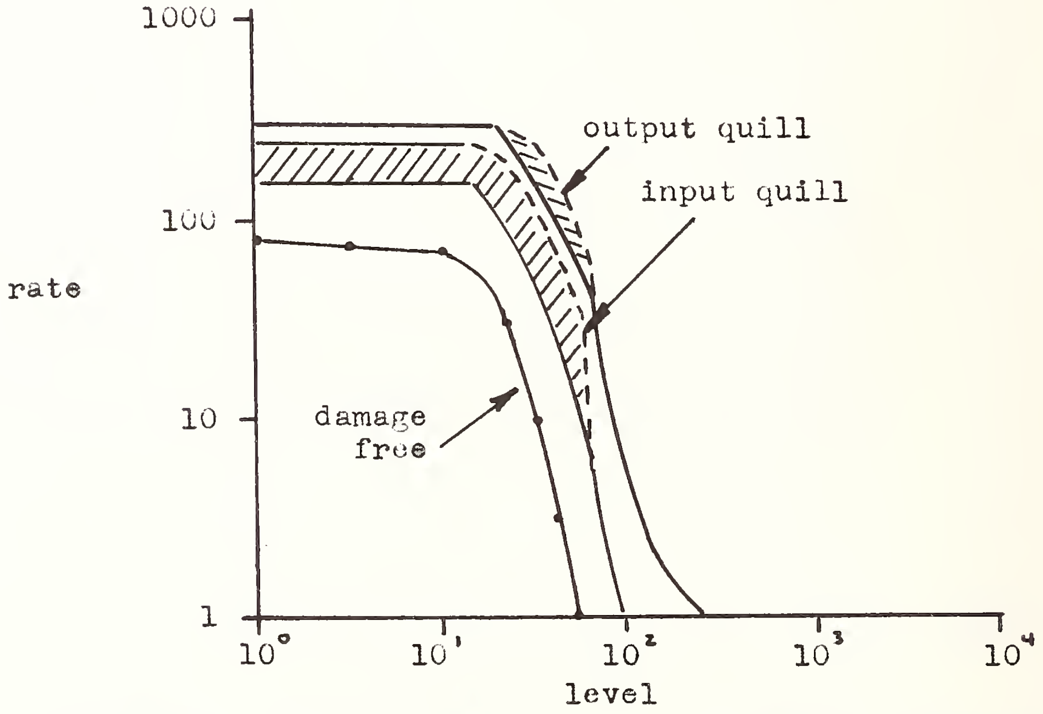


Figure 12. Shock pulse curve of 42° gearbox removed for teardown analysis. Lined areas indicate variation in ouput readings.

42° gearbox, output, inner ball bearing with corrosion damage on outer race.

42° gearbox, output, outer ball bearing with corrosion and pitting damage on outer race.

Figure 13. Damage seen in 42° gearbox removed from operational helicopter.

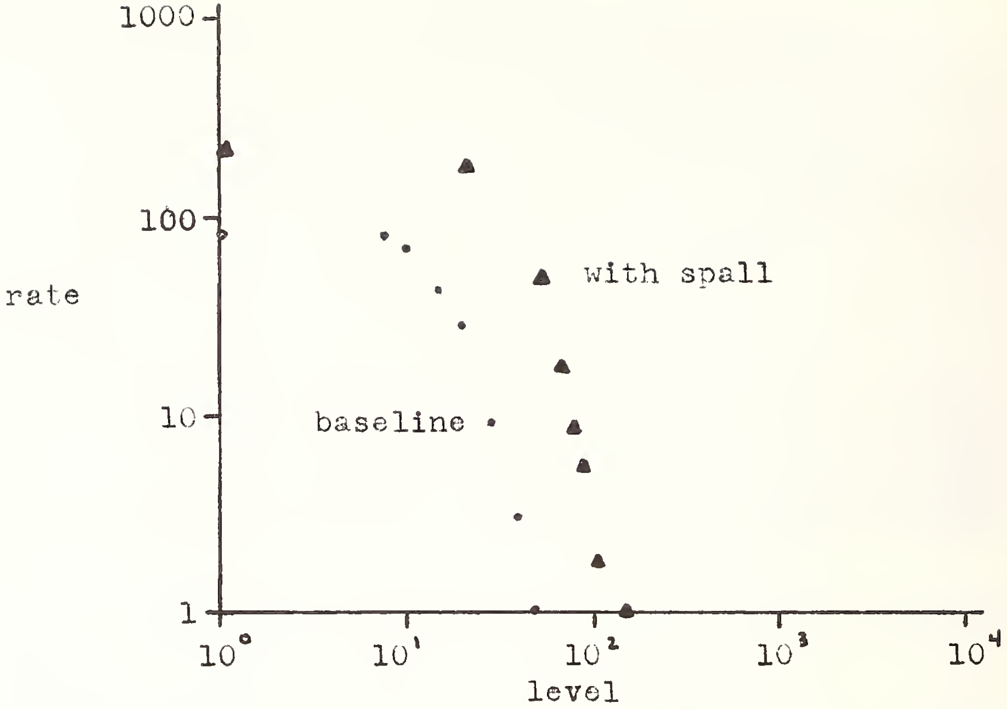


Figure 14. Comparison of baseline and degraded gearbox implanted with spalled duplex bearing.

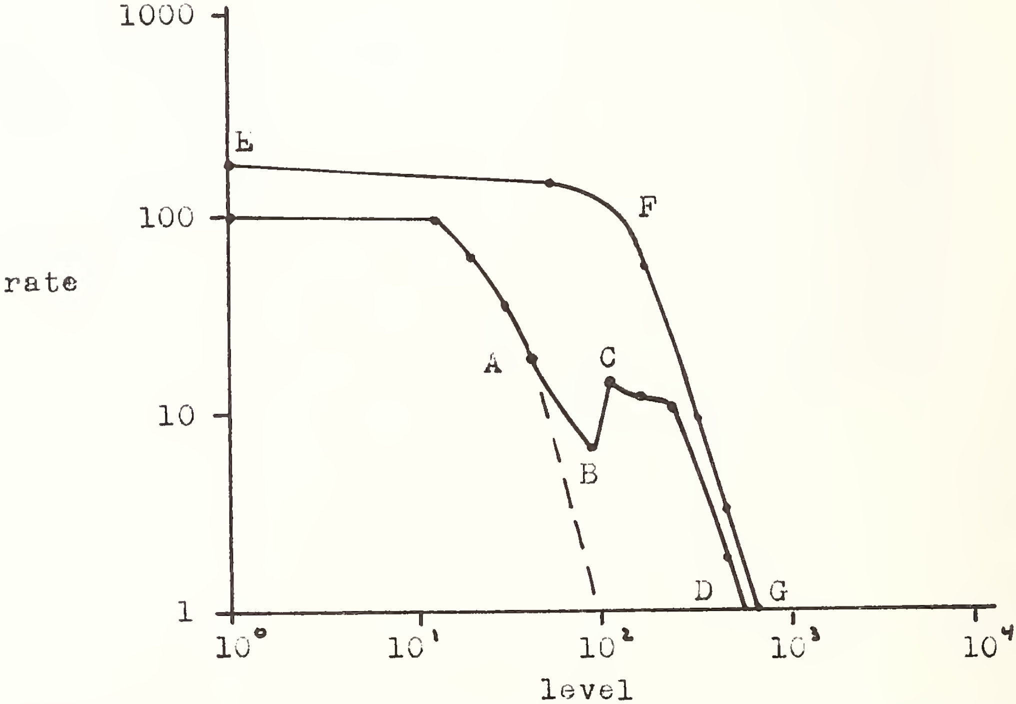


Figure 15. 42° gearbox implanted with a spalled duplex bearing. Evidence of damage progressing.

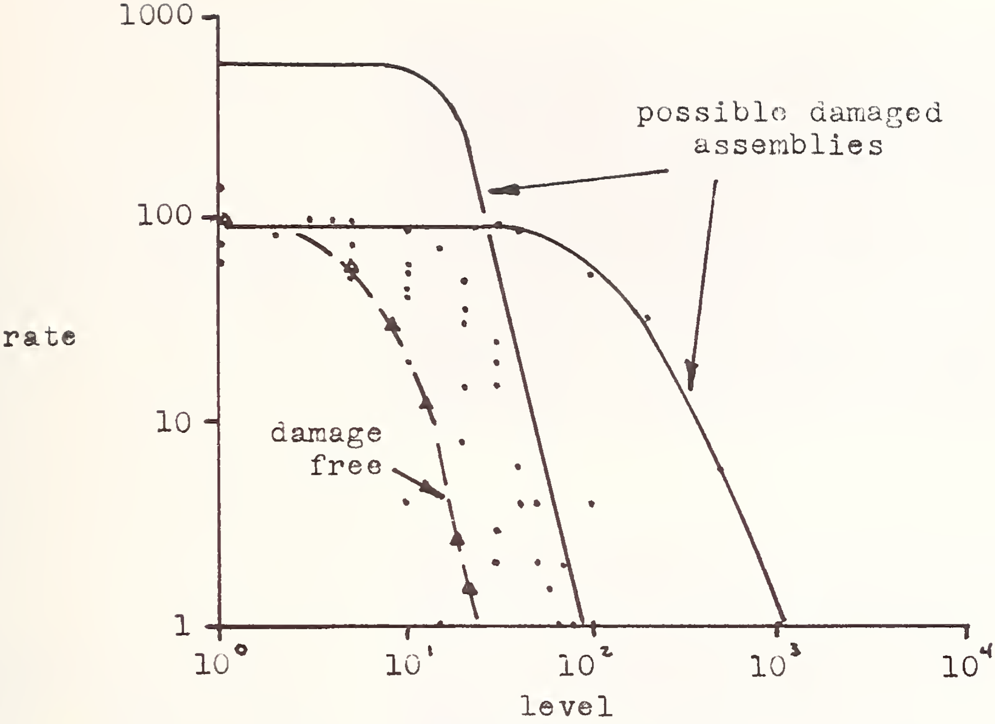


Figure 16. Scatter diagram of 90° gearbox assemblies.

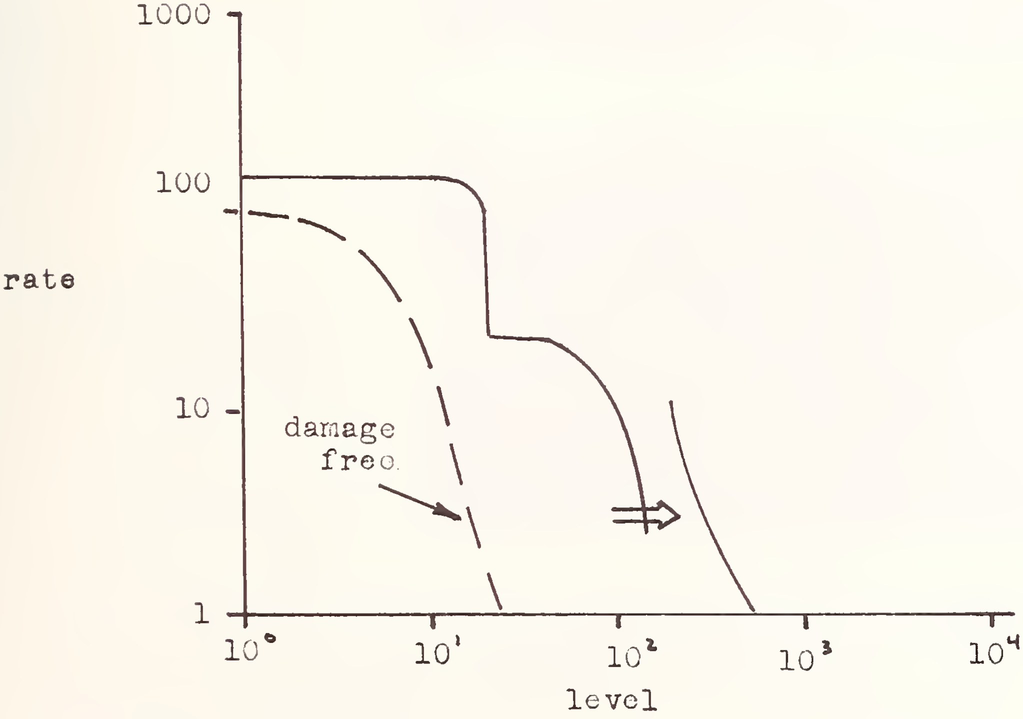
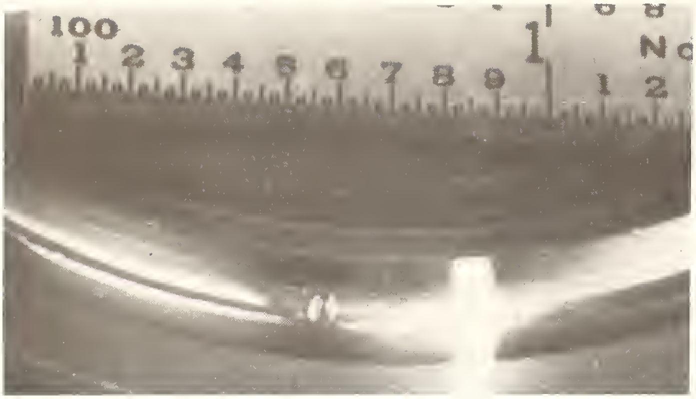
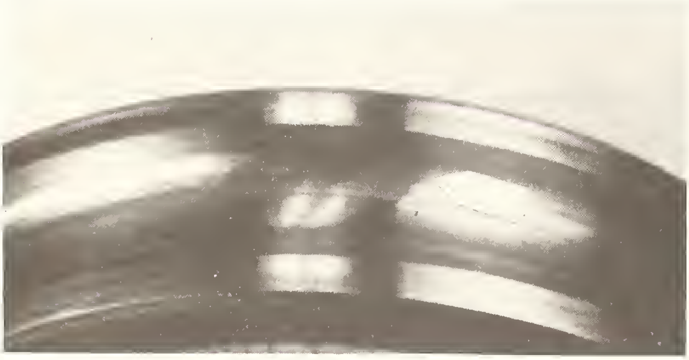


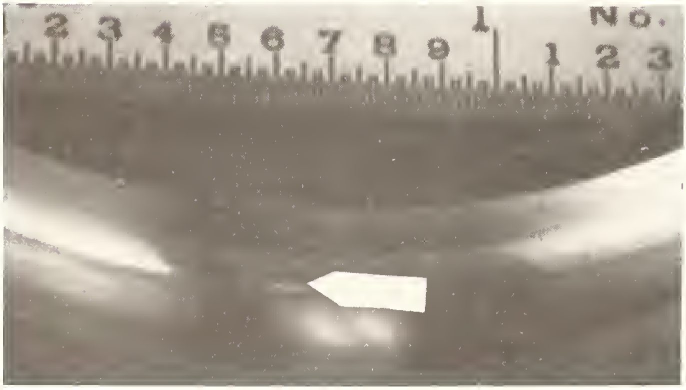
Figure 17. Shock emission curve of 90° gearbox removed for teardown analysis.



small duplex bearing, outer race with burred edge spall



small duplex bearing, inner race with spalls



duplex bearing, outer race with pitting and corrosion

Figure 18. Damage seen in 90° gearbox removed from operational helicopter.

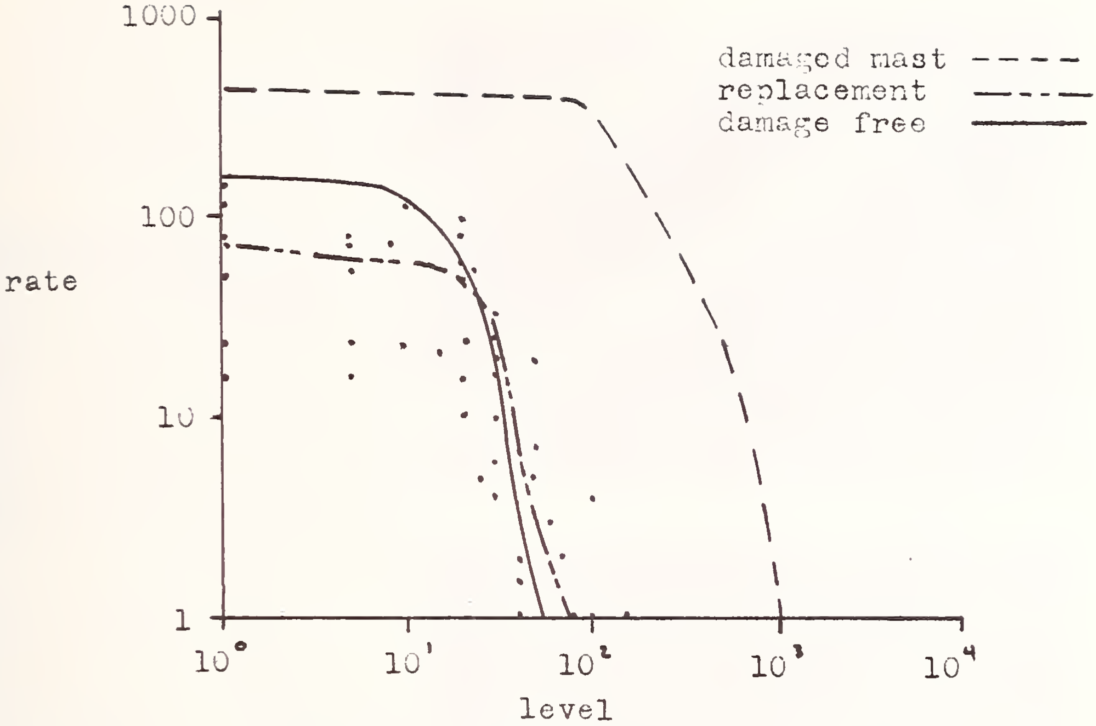


Figure 19. Scatter diagram of mast assemblies.

false brinelling on outer race of mast bearing

pitting on outer race of mast bearing

scoring on balls of mast bearing

Figure 20. Damage as seen on mast bearing removed from operational helicopter.

DISCUSSION

R. Lenich, Caterpillar Tractor Company: Would the mechanic have replaced all of the bearings that the shock pulse method indicated were bad if the shock pulse method had not been used?

J. A. George: All of these were good operational bearings as far as the present inspection procedures indicate. But if these bearings were sent to overhaul, there would be components replaced. In other words, those that we said were good were indeed good, those that we said were moderate would be replaced because the bearing was out, and those that were severely damaged very definitely would be replaced.

J. L. Frarey, Shaker Research Corporation: Did you do enough work with the speed dependence to determine if it is a linear or a square relationship. In other words, do you think you could build this in as a correction factor for a variable speed machine?

J. A. George: We did not look at it directly. Offhand, I would say they are not directly linear.

J. L. Frarey: How far away from the bearing could you get. In other words, could you do the 42 and the 90 in one central position if you didn't care whether it was the input or the output?

J. A. George: If you are riding on the input side you could probably detect eventual degradation on the output, but we have been riding as close to the bearing as we can. On the 90 there is only one place we can go - we are detecting both input and output.

LST 1179 DIESEL DIAGNOSTIC SYSTEM FEASIBILITY STUDY

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J. Frarey
D. Dominy
H. Hegner
H.C. Burnett
*Wear Sciences, Inc., Scotia, New York 12302

Introduction

The Mechanical Failures Prevention Group has been requested by Mr. Ray Coulombe of the Engineering Branch of NAVSEC to undertake a study to determine the advantages to be gained by the Navy in the development and use of a propulsion condition monitoring system. In response to this request a task force was formed by MFPG which is currently conducting such a study. This paper is a progress report on the results to date.

Task Force

The task force shown in Table I was selected by the Executive Committee of MFPG to conduct the study. The selection was based upon the individual's background to perform the functions as shown in Table II. In addition, a committee of approximately 20 members of MFPG has been selected to review the work of the task force so that the conclusions can be said to represent the collected view of the MFPG.

Method of Operation

The advantages of a diagnostic system are quite well known to most engineers who work in this field. However, one cannot assume that these advantages will necessarily result in a real cost saving when installed. In fact, one could imagine that with a reliable, trouble free, well maintained engine there might be a cost penalty when one requires a better "read out" on its condition. For this reason the task force proposed to compare the relative costs involved of ships' maintenance with and without a diagnostic system. The 1179 class LST was chosen by the Navy to use as an example.

To conduct this study, two areas of investigation were necessary. First, one must propose a diagnostic system and then determine the accumulated costs of development, manufacture, installation and checkout. This requires a knowledge of the engine parameters and malfunctioning components to be measured. These, of course, must lend themselves to practical realities of shipboard conditions and competence. Secondly, one must accumulate as accurately as possible the total maintenance costs on the ship and the variety of malfunctions which make up these costs. The question of course to be answered is which of these malfunctions and maintenance costs would have been avoided if the proposed diagnostic system would have been installed.

The work scope to accumulate the desired information is given in Table 2. The task force is now in its fourth month of operation. The purpose of this paper is to present the results on each of the task items listed in Table 2 along with the conclusions to date.

Program

As a first step in the program, Mr. Dominy, who has had considerable experience with this particular engine, made a list of all the engine components and what in his experience generally go wrong with them. He then proposed a list of measurements which would have to be taken to diagnose malfunctions with these components. At this time the practicality of the measurements was not given detailed consideration. The purpose of a diagnostic system is not only to diagnose component malfunctions but also to determine if the engine parameters are within the prescribed limits. This was also included in the list of measurements which are shown in Table 3.

The information provided by Mr. Dominy was supplemented by data from the ship. First of all, a list of the measurements now taken on the ship was made. These are the underlined quantities of Table 3. It is immediately apparent that most of the measurements proposed are already taken on the ship in one way or another. Thus, we are not really proposing anything new, only a better way of collecting and presenting the information.

In reality, only three new types of measures are needed:

Contamination
Position
Vibration

As it turns out, these measurements are extremely important and will diagnose the most troublesome malfunctions actually found on the LST 1179s. Of course, one could look at this from another point of view. Maybe these are the most troublesome components because such measurements are not now commonly taken.

This list of proposed measures was supplied to Mr. Hegner who is determining their feasibility and practicality for shipboard use. His main concern is with means of measuring the new parameters and the cylinder pressures. Many of the diesel inspectors rely quite heavily on this quantity.

A considerable amount of time was also devoted to accumulating shipboard maintenance experience that is used in determining what propulsion system problems have been encountered in service and what these problems have cost the Navy. Information on the most common problems were accumulated from the following sources:

(1) Interviews with shipboard personnel
(2) Diesel inspectors' reports
(3) Gibbs and Cocks Causality Report Review
(4) Class maintenance problems
(5) 3M LST maintenance history

The 3M maintenance history was particularly valuable since it not only allowed an independent problem review to be made but also provided a means to determine the cost of each problem encountered. For example, an injector change-out costs $7,250 plus 7 labor hours.

Based upon the 3M system the total repair costs per ship for the past four years are shown in Table 4. This works out to an average of 1000 hours and $14,000 materials costs per year. These numbers, although not excessive, seem rather high considering that these are brand new engines only 2 to 4 years old which are not used very often. Furthermore, these are minimum costs since many of the material charges may not appear, being charged to another account.

In the 3M system, charges are allocated by system categories. Examples are diesel engine, reduction gear, clutches and brakes, exhaust, fuel oil, water, etc. Each system is then broken down by equipment. Thus a complete review of the 3M system will yield the high cost systems and the high cost malfunctions. These are listed in Table 5. If the repair costs are to be reduced, the diagnostic system must be able to detect these faults.

The repair costs are only one item of the total maintenance costs. Others include the planned or scheduled maintenance costs, shipyard costs, overhaul costs, engineering costs associated with shipboard maintenance and personnel costs as represented by the type commander, NAVSEC personnel, and NAVSEA. A review of these costs was also made. Unfortunately, this information is only available for the last two years; however, it does give a rough estimate of the level. These data are given in Table 6.

Also shown in Table 6 is the hours devoted to engine watch apportioned to sea and shore. This is representative of the fact that there are four men per engine room, three engine rooms, and three shifts of eight hours each for a total of thirty-six men along with several others. This is based upon the actual "underway" watch bill of a given ship.

The scheduled maintenance costs were acquired by collecting all the maintenance cards for the propulsion system and adding up the total number of hours in the 3-year cycle. This number is also low since many of the maintenance cards say "as required". These hours were not included.

The planning costs have not been estimated; however, these will probably be small since only a few people are directly involved. Although a diagnostic system will greatly assist such people in planning shipyard maintenance it will probably not reduce their costs.

The overhaul costs are somewhat uncertain since only two ships have been overhauled to date. However, we may use the figure of $70,000 per engine once every five years as a representative figure. This amounts to approximately $100,000 per year.

Evaluation

It is now necessary to ascertain what reduction in these costs would result if a diagnostic system was available. Sufficient information is now on hand to make a reasonable estimate; however, this will depend upon the diagnostic system. Thus, final conclusions are not as yet available. Some conclusions, however, can be made.

First, it is obvious that if substantial savings are to be made, they will have to come from "watch", scheduled maintenance, shipyard or overhaul costs. So the following questions may be asked:

(1) Can the use of the proposed diagnostic system substantially reduce the "watch" man hours?

(2) Can the use of the proposed diagnostic system eliminate a substantial number of scheduled maintenance items?

(3) Can early diagnosis of failures reduce the need for dry docking or reduce repair costs?

(4) Might it be possible to postpone overhaul with the proposed diagnostic system?

Of these questions the first appears to be the greatest source of saving. The diagnostic system is intended to do exactly the same time as "watch". During "watch" the enginemen perform the following type tasks:

Watch engine
Take readings
Run subsystems (purifier)
Oil analysis samples
Change filters
Set controls

It can be seen that no repair or scheduled maintenance is performed. If it is only possible to reduce those hours by 1/2 and using the direct labor rate of $3/hour, a saving of $87,000/ship or $1,740,000 for the LSTs will result. A diagnostic system almost seems justified on this basis alone.

It should also be noted that the total man hours add up to 13 man hours/hour. The only way this can be accomplished is to have 39 men on board. These, of course, are not available and the scheduled maintenance must be neglected. Thus, the diagnostic system would release men for more productive activities.

The advantages of a diagnostic system are not limited only to the above cost savings. Other more intangible benefits relate to the advantages of greater awareness of the ship's condition.

These are as follows:

(1) Type Commanders (LST maintenance) have been involved with the "day to day" ship repairs. With the reorganization recently completed the type Commanders will only be involved in shipyard work. This will require the ship's force to assume greater responsibility for the planning and execution of repair work.

(2) In the past, repairs (RAV's/TAV's) were accomplished when needed. A new system is now being instituted in which ship repairs will be accumulated and accomplished during a prescribed period of time (once per year). With this system, greater planning will be necessary.

(3) Lead times on parts required for repair are becoming excessively long (for example, gears require 18 to 24 months for LST).

(4) The maintenance cycle has been increased from three years to five years.

(5) Engineers required to understand engine problems and to prepare ship alterations rarely have sufficient information as to the background of the problem. In addition, it often is difficult to determine if a solution has been obtained.

The task force has tried to remain objective in its study and has also considered the disadvantages of introducing a diagnostic system. These are listed as follows:

(1) Cost
(2) Over reliance

As far as the costs are concerned it is not only the diagnostic system which must be considered but the costs to make it fully operational.

The second disadvantage is that the ships force may become too reliant on the system. That is, no maintenance will be performed and little attention paid to the propulsion system unless the lights flash. The ship must be capable of operating as an independent unit and close identification with the engine and its performance is encouraged. To answer this criticism, experience with other diagnostic systems is being ascertained.

Diagnostic Systems Initial Consideration

Figure 1 is the initial simplified block diagram of a possible diagnostic system for the propulsion system of a LST 1179 class vessel. The system employs one minicomputer along with peripheral input/output devices. This portion of the system would be located in a central or convenient location on the ship. Each engine room is considered an independent entity and each is instrumented with the required transducers, signal conditioning equipment, multiplexing and data transmitting equipment. It is presently proposed that this portion of the system contain an A/D converter so that all data transmission is accomplished digitally.

Several modes of system operation are to be considered. Certain modes--for example, alarm indication--take priority over others. A time-sharing software package is envisioned that will allow different operation modes to proceed seemingly simultaneously.

The requirements on the system are as follows:

(1) Continuously cycle through propulsion system measurements and compare each measurement against engine limits. In the event an out-of-limit condition exists, an alarm will be sounded and backup details typed out on the typewriter.

(2) All parameters measured in 1 above associated with the alarm will be continuously stored on the magnetic disc or tape for analysis after shutdown.

(3) Once a day at preselected propulsion system power settings, data will be converted to engineering units and compared with the last previous stored data at this power setting. The data will be stored if different. If not different, the data will be discarded. Since the ship will not go through all preselected power settings each day, different amounts of data will be recorded, depending on operations.

(4) Data trends will be analyzed and degrading components identified. Once the degraded component has been identified, appropriate maintenance action will be typed out on the typewriter.

(5) Periodically, the system will provide the engineering officer a status report including data tabulations and plots.

(6) Periodically while in port, system provisions will allow the copying of data for transmittal to the class maintenance officer.

(7) Periodically, data will be inputted to the system such as SOAP readings. These data will be stored and trended along with measured data.

(8) The system will allow the engineering officer to use the system as a preprogrammed or easily programmed microcomputer or programmable calculator.

The above system description is being used as a basis of review with system manufacturers to obtain initial hardware/software costs. These costs will be evaluated against the benefits derived from system installation.

Table I

Task Force

H. C. Burnett	National Bureau of Standards
D. Dominy	Mechanical Technology, Inc.
J. Frarey	Shaker Research Corp.
H. Hegner	General American Corp.
M. Peterson	Wear Sciences, Inc.

Table II

Work Scope

Diagnostic Feasibility Program

Drive System Parameters
Common Malfunctions
Maintenance Experience
Sensor Measurements
Diagnostic System Design
System Effectiveness
Report and Review

Table III

Propulsion System Measures

Ambient Pressure
Ambient Temp
RPM
Exhaust Temp
Firing Pressure
Cylinder Pressure
Torsional Vibration
FO Pump Pressure
FO Header P
FO Rack Position
Fuel Analysis
Shaft Run Out
Coupling Displacement
Pedestal Temp
Clutch Temp
GOV Load Position
Propeller Pitch
GOV HO Pressure

Manifold Temp
Manifold Pressure
Turbo Exhaust T
Turbo Vibration
Turbo LO Pressure
Exhaust Smoke Meter
Water in T
Water Out T
LO Pump P
LO Header P
LO Level
LO Oil Analysis
GB Bearing Temp
GB LO Pressure
GB LO Temp
GB Bearing Position
Gland Temp
Contamination

Table IV

LST 1179 Ship Repair Costs

3M System

Ship	Commissioned	Man Hours Repair	Material Costs $
1179	9/69	4821	52,913
1180	4/70	4109	39,414
1181	8/70	2533	63,682
1182	12/69	3936	51,721
1183	3/70	6919	79,139
1184	4/70	3450	154,236
1185	6/70	7140	106,267
1186	8/70	4167	56,417
1187	10/70	1841	51,815
1188	2/71	2994	56,772
1189	4/71	5217	108,642
1190	6/71	4601	48,402
1191	7/71	3252	45,364
1192	9/71	1625	35,687
1193	11/71	1668	34,047
1194	1/72	2847	24,766
1195	3/72	2189	44,788
1196	5/72	1715	10,252
1197	5/72	1791	12,596
1198	9/72	5467	18,042

Table V

LST 1179

Common Malfunctions

Operational Limits
Head, Valves
Injectors, Pumps, etc.
Salt Water Pumps
Turbocharger
Air Start Motor
Governor
Pistons
Fluid Contamination
Clutch and Brake
CPP Pumps
Gland Seals
Accessory Drive Gears
Fuel Oil Pump
CPP Gears
Linear Corrosion
Exhaust Leaks
Gear LO Pumps

Table VI

Costs Per Year Per Ship

	Man Hours	Materials
Watch Sea	42,000	---
Shore	16,430	---
Repair	1,000	$ 14,000
Scheduled Maintenance	50,448	---
Shipyard		32,380
Overhaul	---	100,000
Engineering	5	4,000
Planning Ty Com	---	---
NAVSEA	---	---

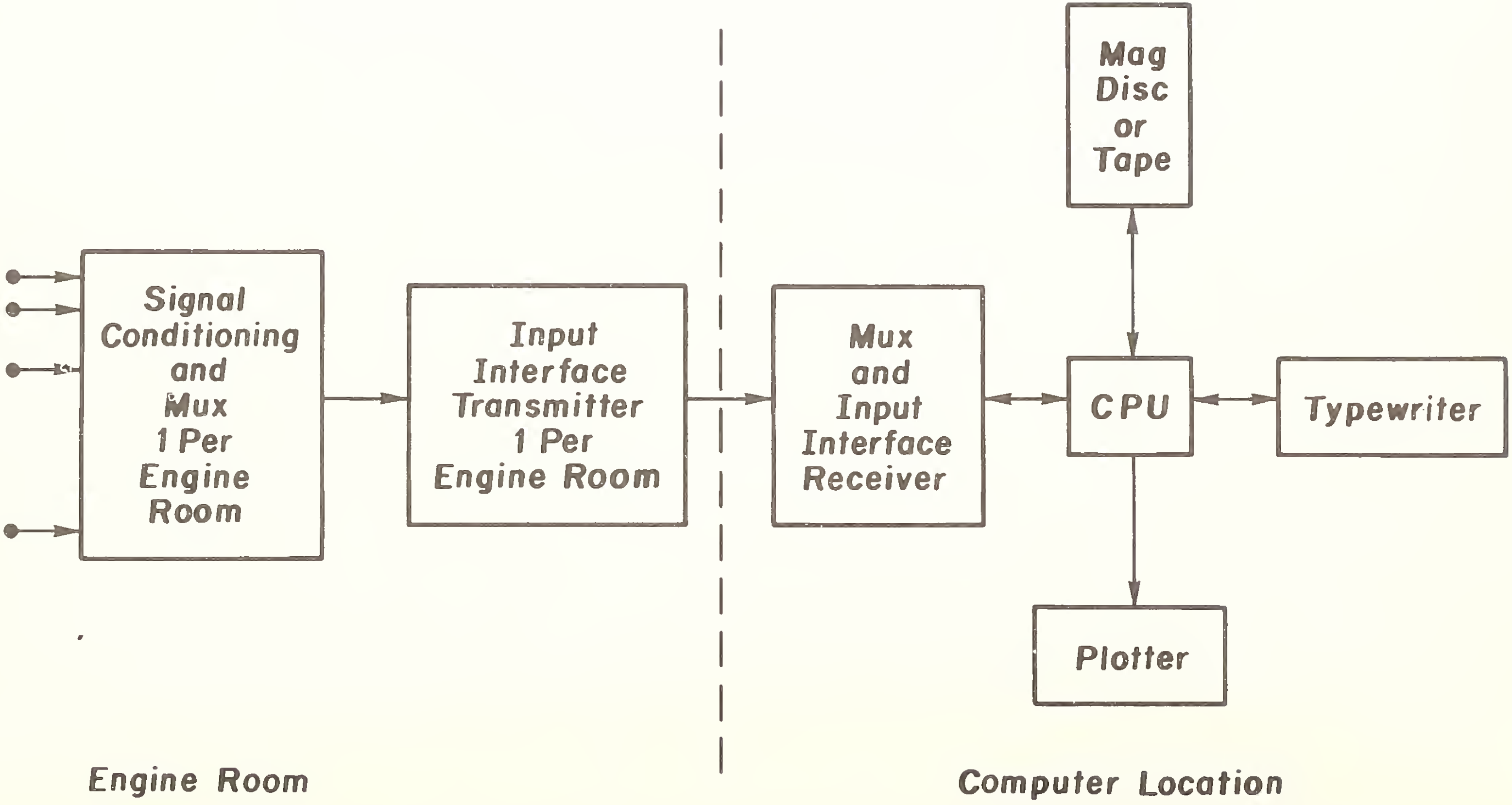

Figure 1. Block Diagram of One Engine Room Connection to Computer.

DISCUSSION

R. A. Coulombe, U.S. Naval Ship Engineering Center: The second phase of this work will be a pilot program on a selected ship and the progress report indicates to me that this is going to be justified.

MECHANICAL FAILURES PREVENTION GROUP

22nd MEETING

Detection, Diagnosis and Prognosis

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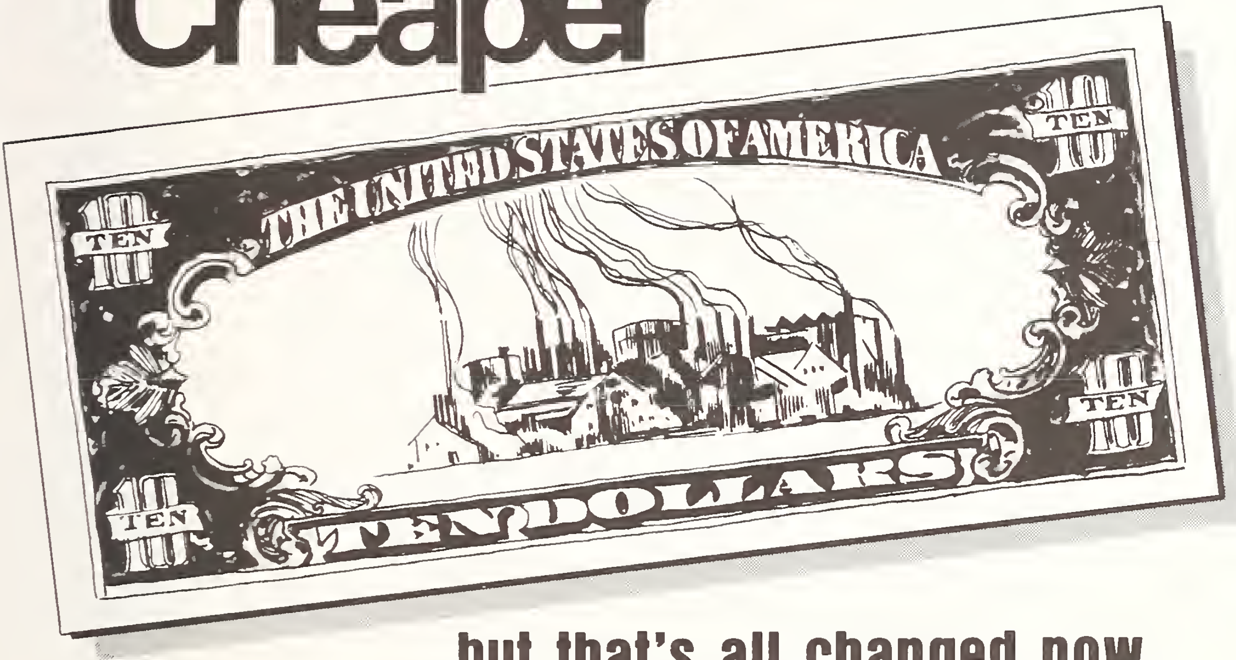

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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards
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U.S. DEPT. OF COMM.
BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NO.
NBS SP-436

2. Gov't Accession No.

3. Recipient's Accession No.

4. TITLE AND SUBTITLE
Detection, Diagnosis and Prognosis--Proceedings of the 22nd Meeting of the Mechanical Failures Prevention Group

5. Publication Date
December 1975

6. Performing Organization Code

7. EDITORS
T. Robert Shives and William A. Willard

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*
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NASA, Goddard Space Flight Center, Greenbelt, MD 20771
Frankford Arsenal, U.S. Army, Philadelphia, PA 19137
FAA, Dept. of Transportation, Washington, D.C. 20591

13. Type of Report & Period Covered

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number: 75-619365

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

These Proceedings consist of a group of nineteen submitted papers and discussions from the 22nd meeting of the Mechanical Failures Prevention Group which was held at the Grand Hotel in Anaheim, California on April 23-25, 1975. Failure detection, diagnosis, and prognosis represent the central theme of the Proceedings. Technology and techniques, ongoing diagnostic programs, and coming requirements in the field of DD&P are discussed. In addition, several case histories are presented.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*
Diagnostic case histories; diagnostic systems; failure detection; failure diagnosis; failure prevention; failure prognosis

18. AVAILABILITY ☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☒ Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13.10:436

☐ Order From National Technical Information Service (NTIS) Springfield, Virginia 22151

19. SECURITY CLASS (THIS REPORT)
UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE)
UNCLASSIFIED

21. NO. OF PAGES
366

22. Price
$4.25

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