MONITORING AND ANALYSIS OF ROLLING ELEMENT BEARINGS

USING THE

FIBER OPTIC BEARING MONITOR

by

Gerald J. Philips
Philtec, Inc.

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Gerald J. Philips
Philtec, Inc.
P.O. Box 359
Arnold, Maryland 21012

ABSTRACT

Fiber optic displacement sensors are mounted inside a bearing housing to measure relative motion between a bearing and its housing. In this manner, extraneous noise and vibrations on the bearing housing are eliminated and the vibration of the bearing is clearly seen. The Fiber Optic Bearing Monitor has been developed to process bearing signals so obtained. This paper describes the FOBM and a fiber optic displacement transducer that has been recently developed, and highlights how this instrumentation can be used to give an absolute measure of bearing quality, detect and indicate the size of bearing flaws, detect lubricant contamination, and provide a measure of the load or stress on a bearing system.

INTRODUCTION

Traditional methods for monitoring machinery vibrations use accelerometers or velocity pickups that are mounted on a machine's outer casing. Those sensors are seismic devices that respond to the total motion of the structure at the point of transducer attachment. They are simple to install on operating machinery and for that reason are very popular.

With housing-mounted seismic sensors the vibration of the machine is measured instead of the bearing. That complicates the task of acquiring meaningful bearing information. An accelerometer mounted on a machine casing senses all of the natural modes of casing vibration that exist at the sensing location, plus all of the rigid body modes of vibration of the machine, plus all of the vibrations that are transmitted to the sensing location from and thru other structural elements. All of those vibrations constitute nothing more than background noise when one is interested in detecting the signal from a bearing. The strength of the bearing signal as it appears on the machine casing is not normally assessed in terms of its absolute level but rather in terms of its relation to the level of background noise (casing vibrations).

Vibration analyzers are used to trend data and to separate the vibration signal into its discrete frequency components for detailed analysis. In large, low speed equipment where bearing signal strength is normally very low and in machines such as turbines that normally have high noise levels, state-of-the-art vibration techniques fail to extract reliable bearing information from the overall vibration signal.

Some investigators have shown that increases in the level of casing vibration can be experienced when bearings degrade. It is also found however, that similar increases in casing vibrations can be detected when there is no change in bearing condition. In fact, any energy source that generates impact energy can and does stimulate the entire spectrum of vibrations on the machine casings. Coupling and cross-talk among rigid structural elements is normally quite strong and therefore difficulties are usually encountered in sorting out the cause of increased vibration levels.

Other devices which have been specifically designed as bearing monitors have appeared on the market over the past decade or more. Many of those devices indicate bearing degradation by providing a measure of the impact energy on the "high side" of the vibration spectrum. Those devices have gained popularity because they trend well with certain types of bearing degradation and are easy to apply to operating machinery. Drawbacks of those devices are that they provide only a limited amount of bearing information and that the information they do provide is sensitive to measurement location.

The development of the Fiber Optic Bearing Monitor was initiated at the U.S. Navy's David Taylor Naval Ship Research & Development Center to overcome the technical inadequacies of general purpose vibration analyzers and other bearing monitoring devices that derive their inputs from casing-mounted sensors. A description of the Navy prototype unit was given in 1982 (1). The FOBM was designed to provide a simple and absolute measure of bearing condition and also to provide an instrument that could uncover bearing operational deficiencies so that they could be corrected before they lead to bearing damage. Unlike other devices that only detect the degradation of a bearing as it occurs, the FOBM could be used to prevent failures from occurring.

An improved FOBM, the subject of this paper, has been developed for commercial use. A drawback of the FOBM is that it requires sensors to be embedded in the housing of the bearing to be monitored. Application to operating machinery is not possible without modification of the bearing housings. However, the installation of fiber optic sensors can easily be accomplished in new machine designs, in laboratory test stands, or in plants where critical machines are out of service for any reason.

DESCRIPTION OF THE FOBM AND SENSORS

The present Fiber Optic Bearing Monitor, shown in figure 1, is a portable battery operated instrument weighing 6 pounds. Powerful bearing diagnostic programs are included which allow a user to instantly analyze most bearing problems on site.

Inputs are derived from fiber optic displacement transducers having a variety of tip configurations. Where bearings are readily accessible and only periodic inspections are required, non-contact probes can be used. These probes have a 3/16" diameter and a nominal displacement sensitivity of 1 µin./mv. In order to use these probes, a fitting must be installed at each measurement location. Examples of fittings and probes, which can be supplied with detachable tips, are shown in figure 2.

Successful operation of the non-contact optical probes is contingent upon having an unobstructed optical path from the sensor to the bearing. Operating bearings commonly develop fretting corrosion such as is illustrated in figure 3. As bearing lubricant migrates into the sensing area it mixes with the corrosion debris to form a metallic-based sludge. That sludge fouls the optical path of the non-contact optical probes. And, since the sludge is a conductive medium, it will also foul the sensing path of non-contact sensors such as eddy current or capacitance devices which operate by virtue of sensing proximity to conductive objects.

Where fouling is encountered using the non-contact optical probes, a cotton swab is usually sufficient for cleaning of the target area. In those applications where bearings are not easily accessed, where probe fouling is chronic, or where continuous monitoring or a permanent installation is desired, encapsulated fiber optic displacement sensors (patent pending) should be used.

The encapsulated fiber optic sensor shown in figure 4 has been developed to overcome the fouling problem. It is a contact displacement transducer with high frequency capability. The fiber optics are sealed inside of the sensor casing where they monitor the motion of contact tip that is biased against the bearing outer ring.

This sensor is permanently installed and locked into position at the bearing. At the opposite end, a quick-disconnect is provided which can be mounted on the outer casing of the machine. The portable FOBM can be connected for periodic or continuous monitoring as necessary.

COMPARISON OF BEARING AND HOUSING SPECTRA

One of the major advantages to be gained from use of the Fiber Optic Bearing Monitor is that the vibration signal to be processed from the sensor is comprised mainly of bearing information. Consequently, the bearing data from the FOBM is far more reliable than the bearing data derived from casing mounted sensors. An example of the difference in the nature of the signals derived from casing mounted sensors and fiber optic sensors mounted at a bearing/housing interface is shown in figure 5. The upper trace shows the vibration signature from an accelerometer mounted on a bearing housing, one inch from the bearing. The lower trace shows the signal from a fiber optic displacement probe mounted at the bearing/ housing interface. The machine was a large vertical pump motor.

The frequency content of the two signals is strikingly dissimilar. The primary component of the fiber optic spectrum is the load dependent deflection of the outer ring which occurs at the outer roller pass frequency. That component is barely discerned on the bearing housing. All other major frequencies appearing in the fiber optic spectrum are harmonics of the load dependent deflection. This is a characteristic feature of rolling element bearings and is one that can be used to trigger synchronous spectrum analyzers.

Synchronous averaging with respect to shaft speed is a technique vibration analysts use to study rotational frequency problems. Now, the analog signal of bearing vibrations can be used to study how bearings may be influencing vibrations in other points on a machine.

FOBM DISPLAYED OUTPUTS

Five primary outputs are available from the Fiber Optic Bearing Monitor: Noise Level, Defect Level, Bearing Speed Ratio, Component Orders and Amplitudes, and Impact Activity. These outputs allow the user to make fast on-site assessments of bearing condition and mechanical operation.

The Noise Level, Defect Level, and the impact activity are used in combination to characterize the condition of a bearing's wearing surfaces. The Noise Level provides an rms measure of bearing quality and it is sensitive to vibration sources that are more or less uniformly distributed about the bearing. Examples of anomalies that can alter bearing Noise Levels are surface roughness, bearing wear, lubricant oxidation, and roller skidding. Isolated defects do not significantly add to the Noise Level in their formative stages.

The Defect Level provides a measure of the amount of impact activity within a bearing. Good bearings have no impact activity. Smooth balls and rollers rolling on smooth raceways with an adequate supply of clean lubricant will have the lowest Defect Level which is 1.0 by definition.

Damaged bearings and bearings with hard particle contamination in the lubricant will exhibit high Defect Levels. The Impact Activity Display is used to identify the source of high Defect Levels and also to provide a measure of the magnitude of the damage inside the bearing.

Bearing Speed Ratio and other frequency orders are used to detect bearing installation problems and deficiencies that could lead to early bearing failures if left uncorrected. These outputs relate to the mechanical performance of the bear-system and are helpful not only for detection of developing bearing problems but also as quality control checks of machine assemblies.

Noise Level

The balls (or rollers) and raceways of all ball and roller bearings are geometrically imperfect and those imperfections result in noise and vibration. The Noise Level provides a measure of the roughness of the bearing's wearing surfaces. The quality rating of a bearing is directly proportional to the amount of radial displacement of the outer ring.

Bearing manufacturers measure bearing noise levels as a means of checking the overall quality of their products. A machine used for this purpose is known as the Anderometer. The U.S. Navy conducts lot sample Anderometer vibration tests on all lots of bearings that are intended for quiet service applications. The Navy has developed a military specification that contains vibration limits for all sizes of bearings that are tested on the Anderometer. Until now, the Anderometer has only been used to check bearing quality before installation. With the development of the Fiber Optic Bearing Monitor, this military specification test of bearing quality can be extended to in-service bearings.

A Noise Level chart, figure 6, has been developed to provide limits for vibration levels of high quality ball bearings. Those bearings will operate in the quiet region if properly installed and lubricated. High quality bearings stay quiet until wear or lubricant degradation or a dynamic problem such as skidding causes a rise to the noisy region. Low tolerance grade bearings will generally be found to operate at higher noise levels than super-precision bearings. Generally, the highest quality bearing will generate the lowest Noise Level.

Vibration limits for quiet operating bearings are given in the Military Specification (2). The quiet bearing threshold in the Noise Level Chart is related to the Mil-Spec limits. When in-service bearing vibration levels exceed the quiet bearing threshold, there is 95% confidence that the bearing would fail to pass the Mil-Spec vibration test for quiet operating bearings.

When in-service bearing vibration levels exceed the mechanical failure threshold, there is 95% certainty that degradation has progressed within the bearing to the point where it is visible to the unaided eye. Once this noise level has been reached, failure is considered to be imminent. Depending upon the type of service a bearing is under, the remaining bearing life can be several hours to several days or weeks. Due to the uncertain nature of bearing failures, it is recommended that bearings be replaced as soon as possible once this noise level has been reached!

Defect Level

The Defect Level provides a measure of the impact activity within a bearing. It does so by measuring the shape of the bearing displacement function in a high frequency window. By definition, a new bearing of high quality that has been properly installed and is adequately lubricated with clean grease or oil, has a Defect Level of 1.0.

For example, figure 7 shows the vibration pattern of a good ball bearing. The upper trace shows the high frequency broad band noise of the bearing. The lower trace shows the classic low frequency load-dependent deflection pattern of the bearing outer ring.

Flaws on bearing component parts and hard particle contamination of the bearing lubricant generate impact activity within the bearing. Flaws generate impacts at regularly repeated intervals. Contamination generates randomized impacts.

Figure 8 shows an oscilloscope trace for a ball bearing with an outer ring flaw. Each ball impacts the flaw as the ball complement advances, therefore the vibration pattern shows an impact associated with each ball passage.

Figure 9 shows the pattern of a ball bearing with an inner ring flaw. The amplitude of the impacts is modulated because the flaw is on the rotating ring.

Figure 10 shows the pattern of a bearing with a defective ball. Impacts are observed at the ball defect frequency and repeatedly appear and vanish from the deflection pattern at a rate equal to the ball train period.

The Defect Level provides a measure of how much the peak level of bearing vibration exceeds the rms level of bearing vibration over the non-flawed surfaces. The Defect Level Chart shown in figure 11 has been developed to provide limits for Defect Levels in high quality ball bearings. Early stage defect growth are indicated by readings between 1.0 and 1.5. Defects of this magnitude are of only secondary concern since one half or more of the remaining useful bearing life may still be achieved. The flaw is considered to be of a significant size when the Defect Level exceeds 1.5. Plans should be made to replace a bearing at the next regularly scheduled shutdown when the Defect Levels are in the range 1.5-2.0.

Defect Levels above 2.0 are generally measured when the flaw has progressed to the point where metal is flaking out of the damaged component. Failure is considered to be imminent at this point. To avoid a potentially catastrophic failure, a machine should be shut down and the bearings replaced when flaws generate Defect Levels greater than 2.0.

Impact Activity

The Impact Activity Display presents the high frequency noise pattern from the bearing in a bar graph format. The time base of the display is set by the user be synchronous with any of the bearing component periods of motion. This display can be used to positively identify the source of high Defect Levels as bearing flaws or as contamination. It can further be used to provide a measure of the length of the damage on the flawed component.

Flaws generate regularly repeating impacts while contamination generates randomized impacts. When viewing the display, patterns of high and low bars synchronized to a period of bearing operation provide positive identification of flaws. Randomly distributed high and low bars indicate contamination problems.

The bar pattern can also be used to give a measure of the length of bearing damage along the direction of rolling of the damaged component. Figure 12 gives an example of this display feature for outer ring damage. The width of the display is set to be precisely equal to the spacing between two adjacent balls. By comparing the width of the number of high bars with the width of the display, the user can infer what the length of the flaw inside the bearing is. In the figure, the large flaw illustrated is shown to be approximately equal to one half of the distance between two adjacent balls.

Bearing Speed Ratio

Bearing rings have relatively thin cross-sections and are subjected to high stresses at the rolling element contacts. These stresses cause deformations on the outer surface of the bearing as shown in figure 13. As bearings operate the deflection pattern travels around the stationary bearing ring and is measured by the FOBM. Bearing Speed Ratio, (BSR), is defined as the ratio of the bearing retainer speed times the number of rolling elements divided by the shaft speed.

The utility of BSR measurements were reported in reference (3). Both the value of the BSR and the amplitude of the load dependent deflection component are used to determine whether the bearing is properly installed and correctly loaded. Excessive loading causes high ball passage amplitude readings. Underloading causes a reduction of the ball pass amplitude and can also result in skidding of the ball train. Skidding can be detected by measuring the value of the BSR and comparing it to the normal or expected value that can be calculated assuming the bearing is properly lubricated and installed correctly.

Frequency Orders and Amplitudes

The FOBM contains a narrow band pass filter which can be used to perform a spectral analysis of the bearing signal. The filter is set as any multiple or fractional part of the shaft rotational frequency. Using this feature, any component of vibration at the bearing from train frequency up to 9 times rotational frequency can be measured and displayed.

The 1/REV amplitude indicates the peak-to-peak value of the rotational frequency vibration. This reading provides a measure of the fitup between the bearing and its housing. When excessive readings are indicated, the bearing housing will be found to be oversized. Limits for acceptable 1/REV values are obtained from equipment design drawings. The FOBM displays the amplitude of this component and of all component orders of bearing vibration in microinches, pk-pk.

BEARING DAMAGE ANALYSIS

Taylor (4) discussed how bearing defects may be identified by spectral analysis. The appearance of one or more of the five frequencies associated with motions of the bearing component parts indicates the defective bearing component. Severity of the defect is indicated by the amplitude of vibration. He also discussed a method for estimating the size of defects by noting the number of frequency spikes that are modulated by the speed of the rotating unit. A more exact method for determining the severity of bearing damage is presented below.

One of the difficulties of Taylors' approach is that the amplitude of vibration is used to indicate damage severity. He correctly states that "so many variables affect amplitude that it is only used to describe relative conditions". Another problem with his method lies with the computation of bearing defect frequencies. All the defect frequency formulas require the bearing contact angle to be known. In reality, the operating contact angle is not known. It is dependent upon the bearing loading, shaft and housing fits, temperature distribution, and shaft speed for large or high speed bearings where centrifugal forces are significant compared to the applied forces. Therefore, nominal values of contact angles are used for purposes of estimating the bearing defect frequencies.

A precise measure of the operating contact angle is had with the FOBM by virtue of having measured the Bearing Speed Ratio. Precise bearing damage equations are presented here in terms of the BSR and where;

f_o = outer ring defect frequency,

f_i = inner ring defect frequency,

f_t = train frequency,

f_r = shaft rotational frequency,

f_s = spin frequency of a rolling element,

f_b = roller defect frequency,

and

n = number of rolling elements.

By definition,

$$BSR = nf_t/f_r \qquad (1)$$

$$f_o = nf_t \qquad (2)$$

$$f_i = n(f_r - f_t) \qquad (3)$$

and

$$f_s = D_o f_t/d \qquad (4)$$

where,

D_o = the diameter of the outer ring track.

Also,

$$f_b = 2f_s = 2D_o f_t/d \qquad (5)$$

Substituting equation (1) into equations (2), (3), and (5) yields the following bearing damage equations

$$f_o = f_r BSR \qquad (6)$$

$$f_i = f_r(n - BSR) \qquad (7)$$

$$f_b = \frac{f_r BSR}{n}\left[\frac{OD+ID}{d} + 2\right] \qquad (8)$$

where D_o is assumed to be equal to the mean value of the bearing O.D. and I.D. plus one roller diameter.

The Fiber Optic Bearing Monitor measures the shaft frequency, f_r, and the BSR. Therefore, it is very simple to perform a bearing damage analysis. To check for outer ring flaws, the BSR number is keyed into the Impact Activity Display. That synchronizes the display to the period of outer ring damage activity. To check for inner ring flaws, the quantity (n-BSR) is keyed into the display. That synchronizes the display to the period of inner ring damage activity. Inner ring damage that has progressed to a point where it is equal to or greater than the length along the raceway between two adjacent rollers can be measured by keying in the number 1.000 which synchronizes the display to the period of shaft rotation. Ball or roller defects are detected by keying in the value f_b/f_r. Ball or roller defects can also be observed by keying the value BSR/n into the display, thereby synchronizing the display to the period of the cage rotation.

The length of damage in the rolling direction on any flawed component is determined from the Impact Activity Display by reading the duration of the impact activity and comparing it to the width of the display. For example, if f_r(1.0) has been keyed into the display, and 5 of 20 bars indicate impact activity, then 25% of the bearing inner ring should be damaged.

CLOSURE

It has been shown that a great deal of useful and important bearing information is available at a bearing-housing interface, and that much of the data is either not available on a machine casing or is retrievable only with much difficulty and with less accuracy.

The Fiber Optic Bearing Monitor, which has been developed to process bearing information so obtained, is a powerful bearing diagnostic tool that can improve plant efficiency and operation, help OEM's improve quality control in their manufacturing processes, and provide research laboratories with new opportunities to expand their understanding of the tribological processes involved in bearing operations.

REFERENCES

(1) Philips, G.J.,"The Fiber Optic Bearing Monitor", Proceedings of the 28th International Instrumentation Symposium, ISBN 0-87664-689-5, pp.379-395, Instrument Society of America, 1982.

(2) Military Specification, "Bearings, Ball, Annular, for Quiet Operation," Mil Spec MIL-B-17931D(SHIPS), 15 Apr. 1975.

(3) Philips, G.J.,"Bearing Performance Investigations Through Speed Ratio Measurements," ASLE Transactions, Vol.22,No.4,1979,pp.307-314.

(4) Taylor, J.I.,"Identification of Bearing Defects by Spectral Analysis," Transactions of the ASME, Journal of Mechanical Design, Preprint #79-DET-14.

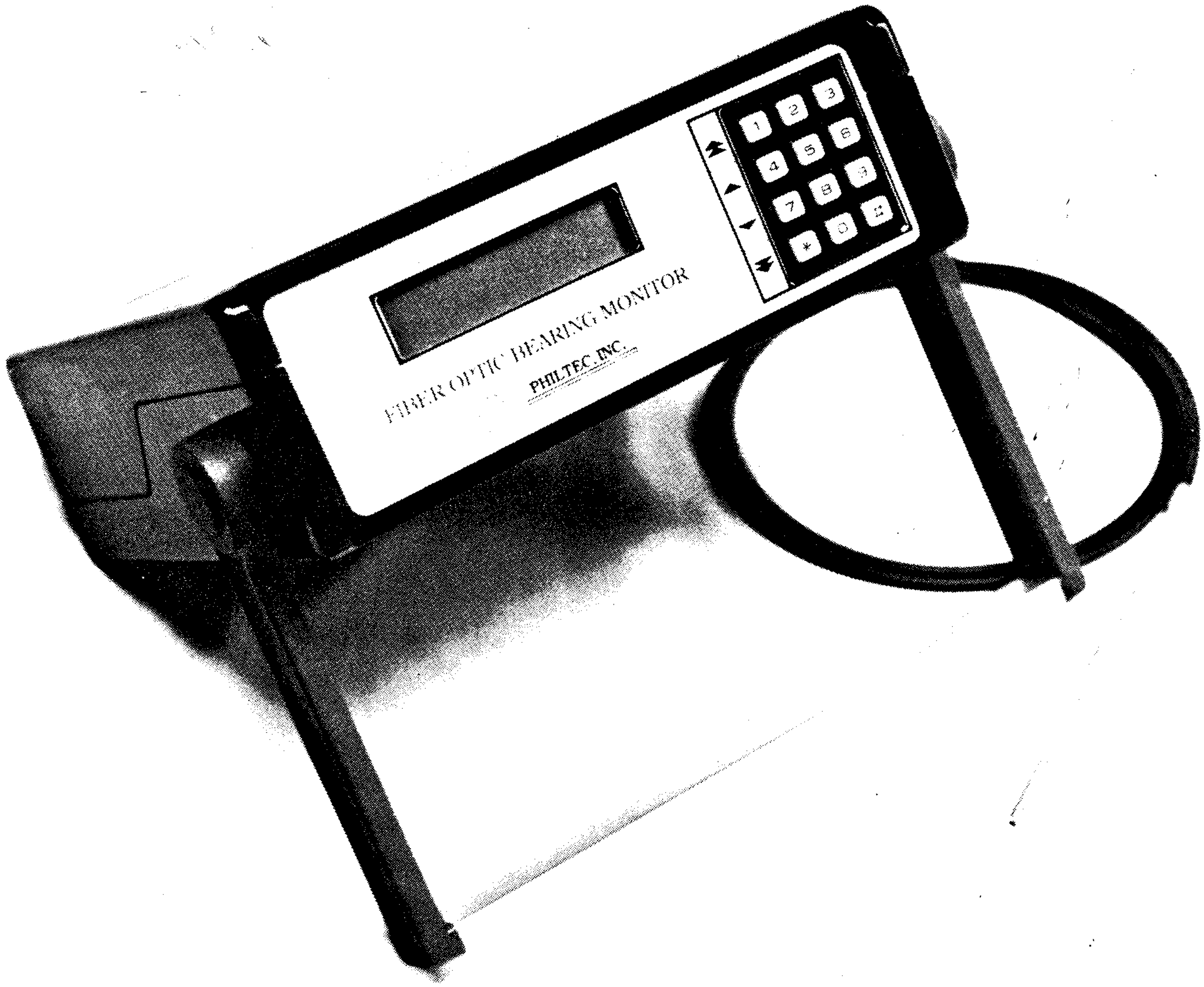

Figure 1 — The Fiber Optic Bearing Monitor

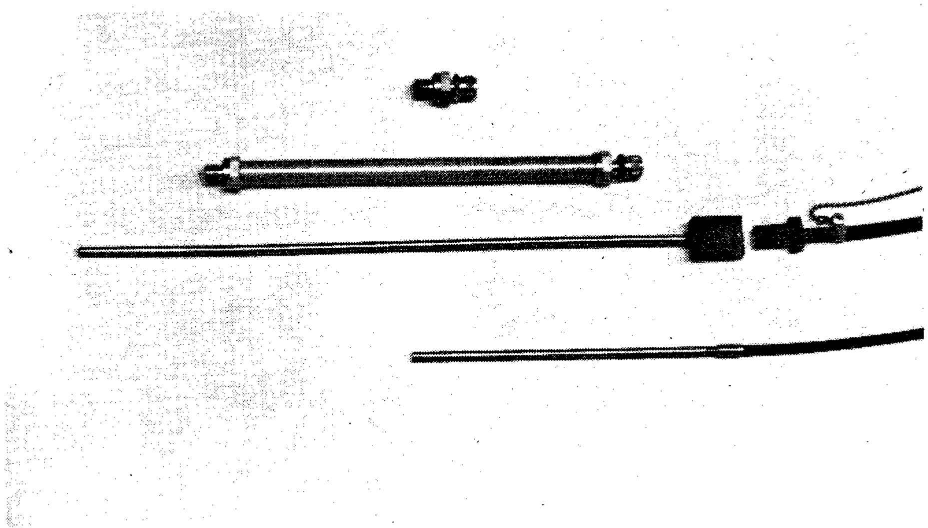

Figure 2 — Non-Contact Probes and Fittings

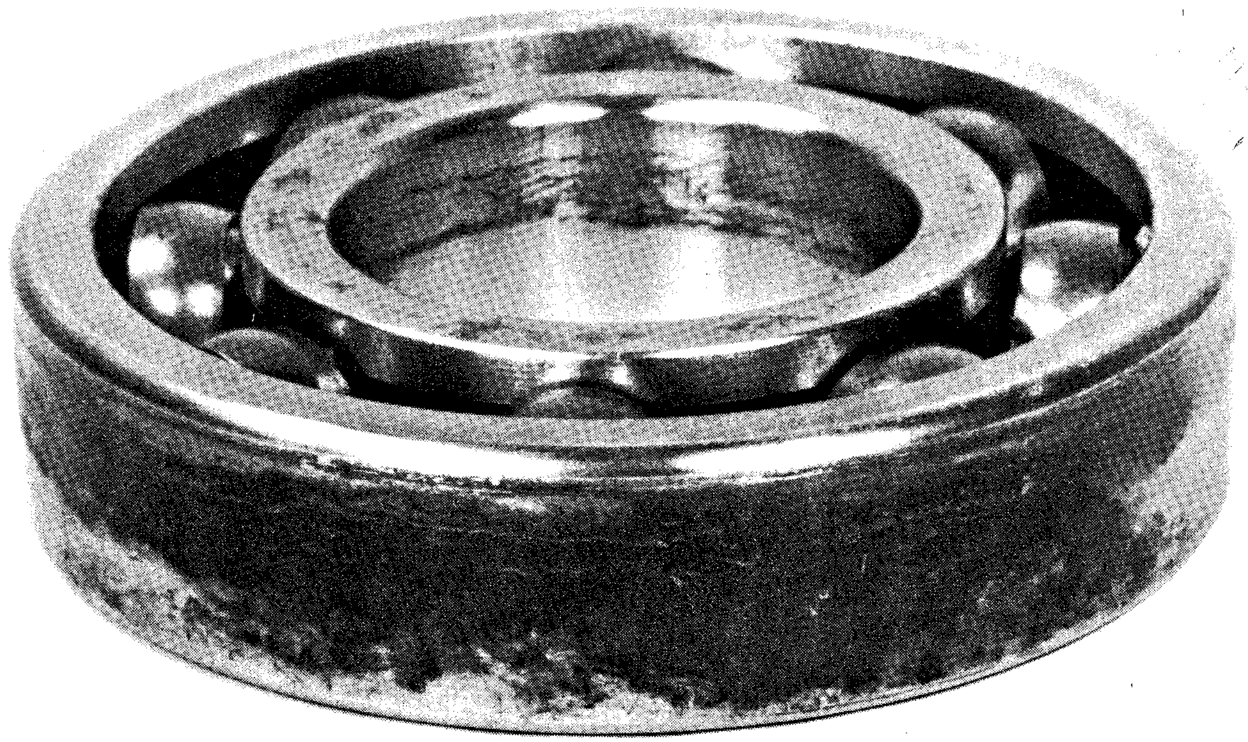

Figure 3 — Fretting Corrosion On Bearing Outer Ring

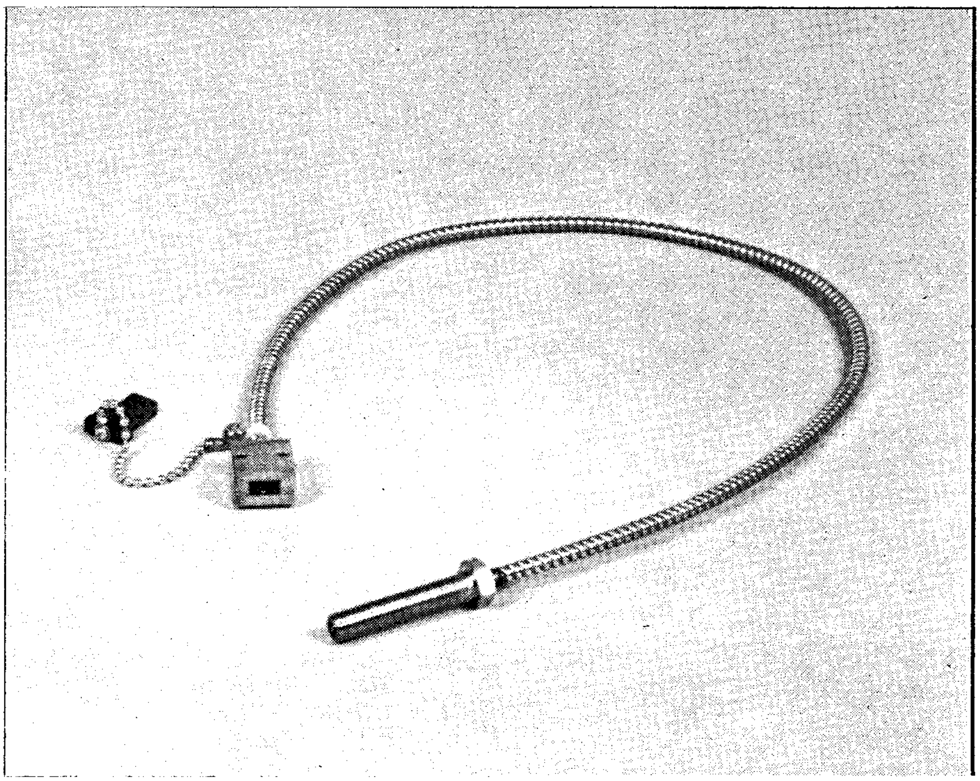

Figure 4 — Encapsulated Fiber Optic Sensor*

*Patent Pending

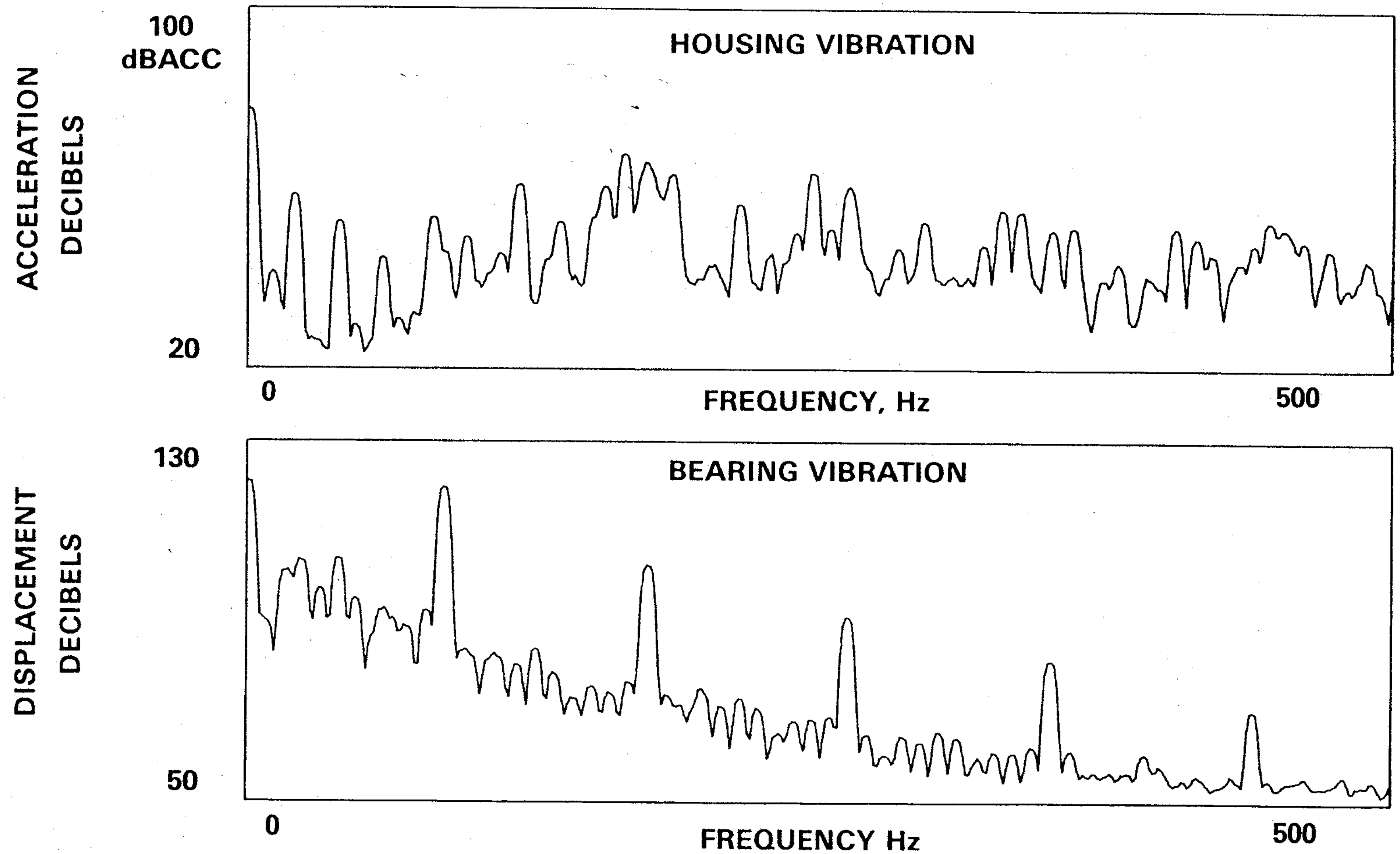

Figure 5 — Comparison of Housing and Bearing Vibration

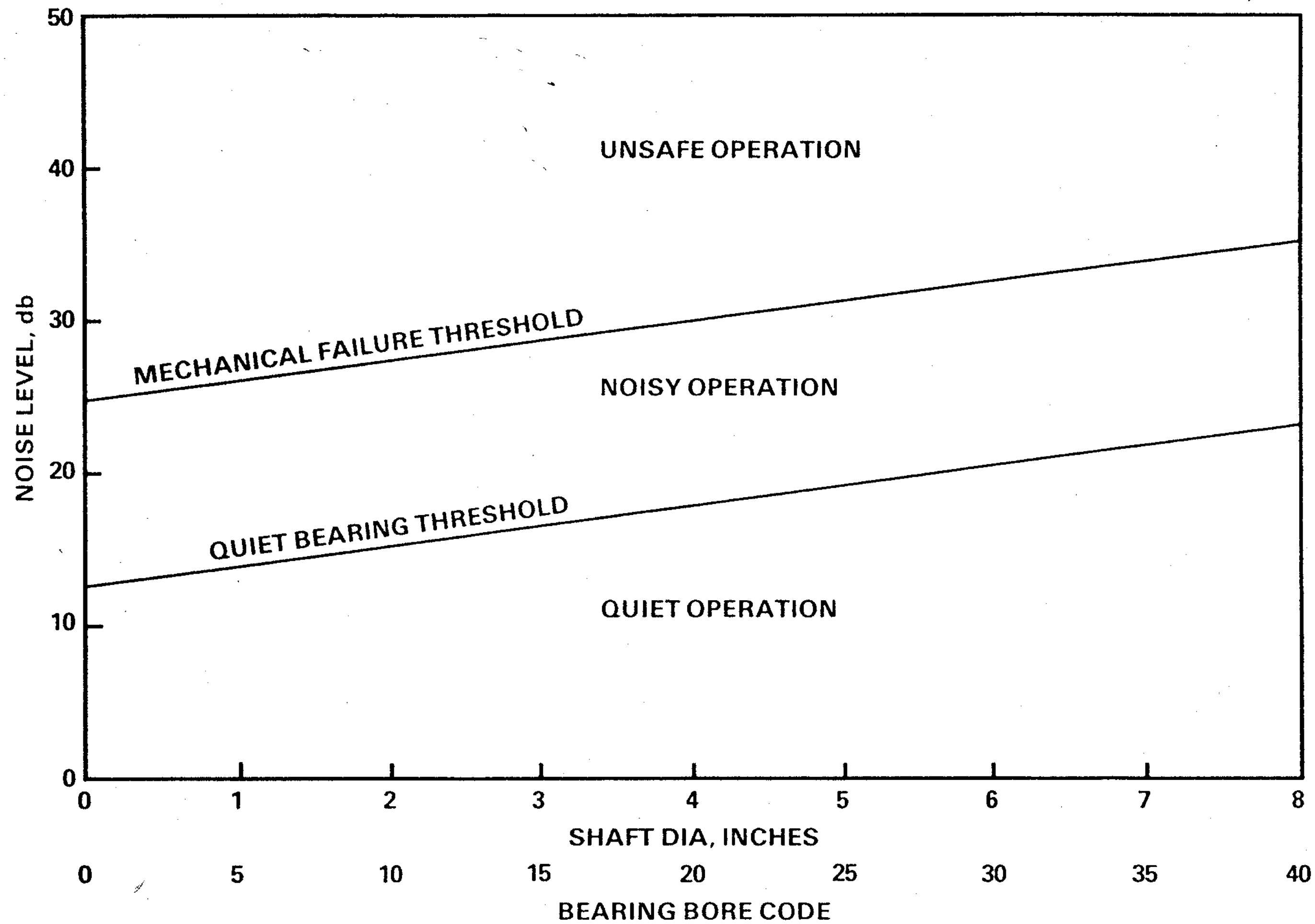

Figure 6 — Noise Level Chart For Ball Bearings

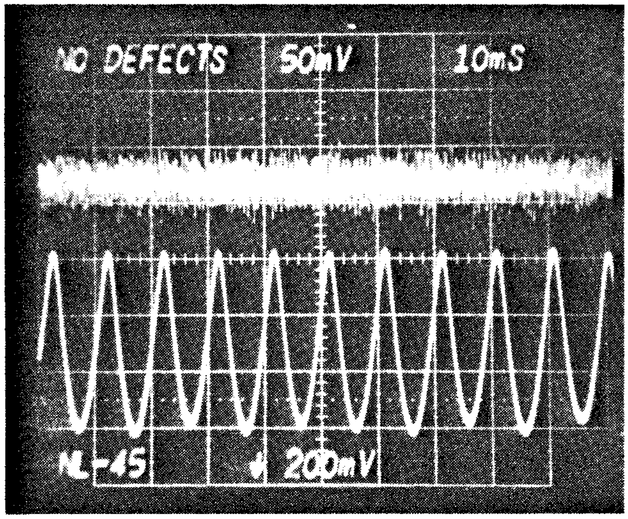

Figure 7 — Typical Vibration Pattern for High Quality Bearing Without Defects

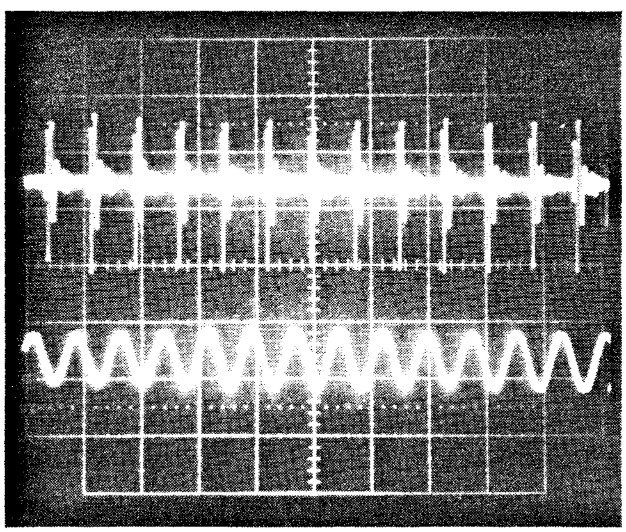

Figure 8 — Bearing With Outer Race Defect

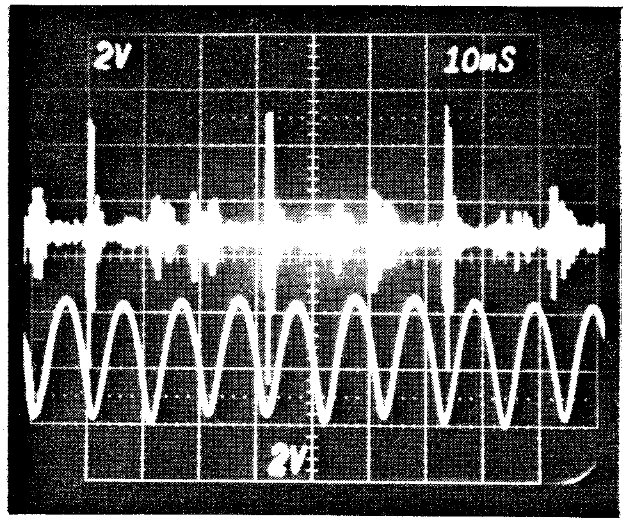

Figure 9 — Bearing With Inner Race Defect

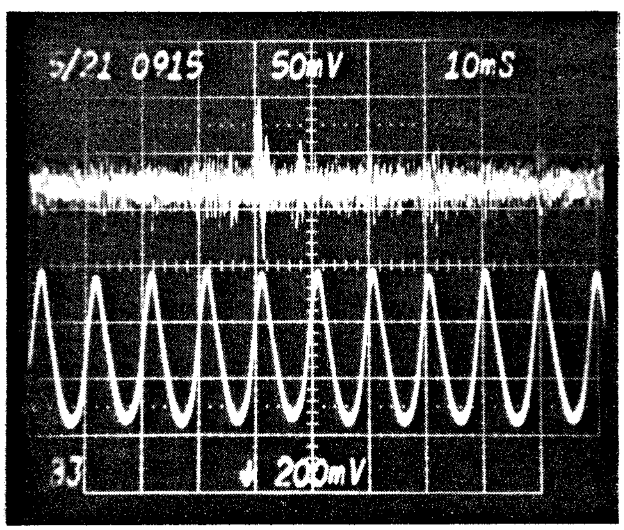

Figure 10 — Bearing With Ball Defect

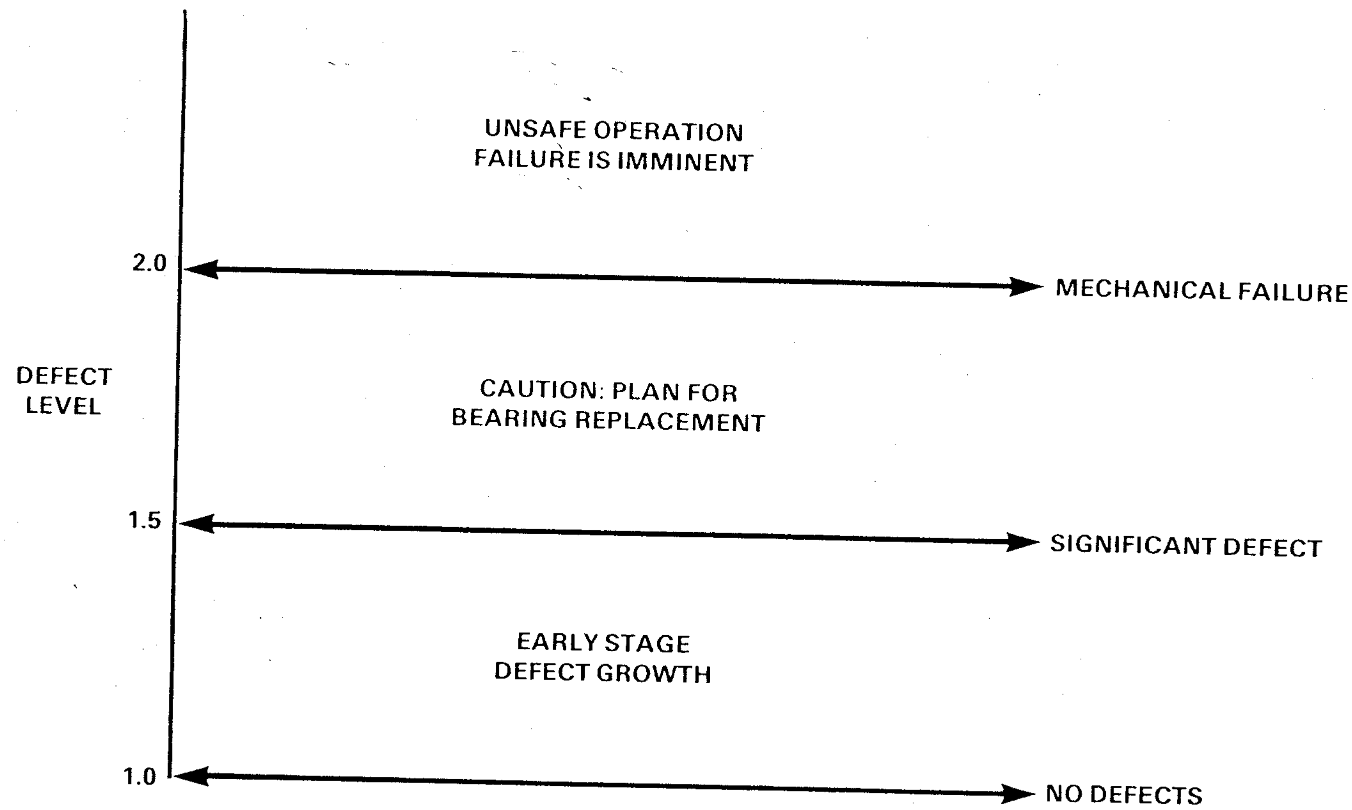

Figure 11 — Defect Level Chart for Precision Ball Bearings

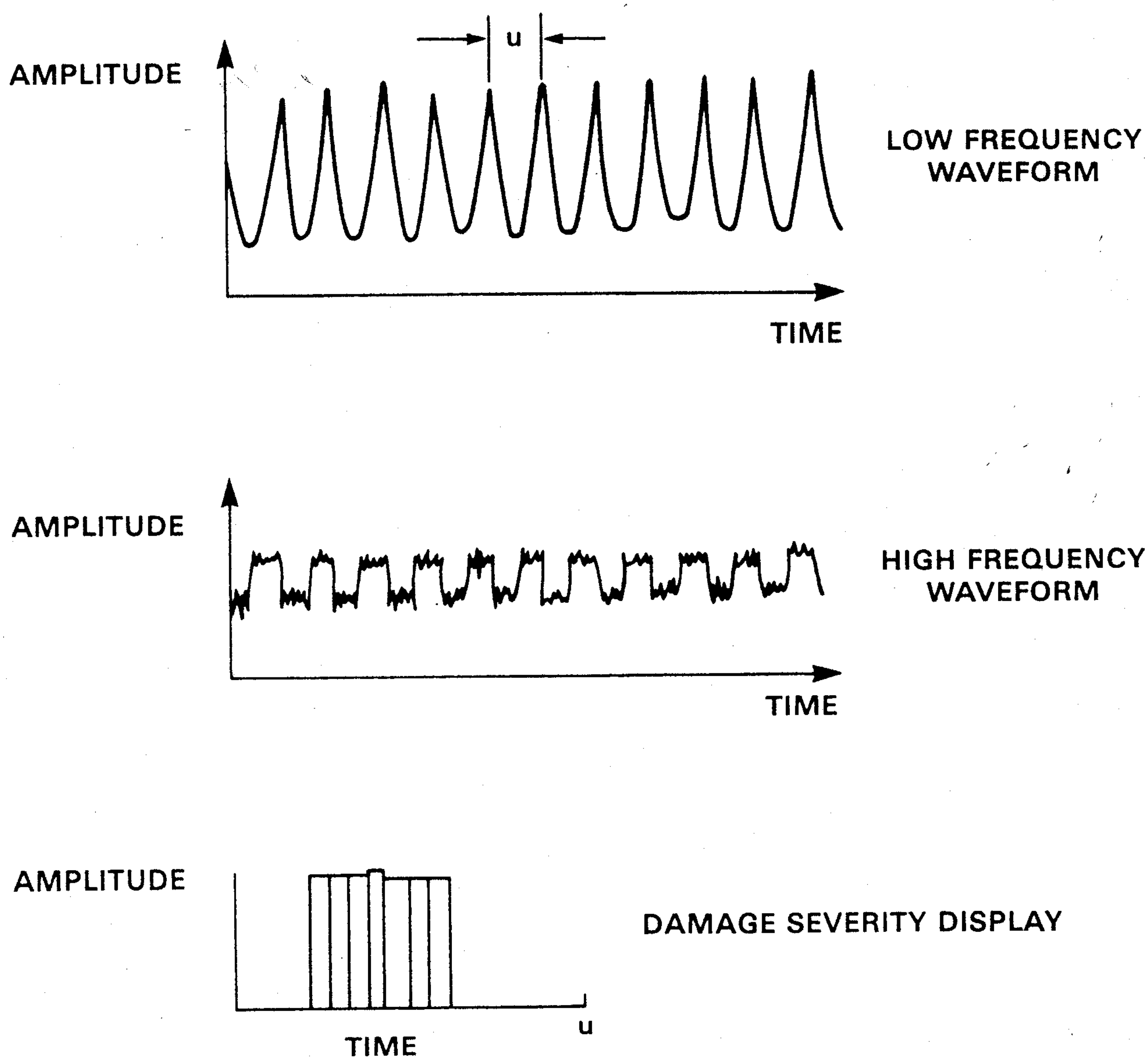

Figure 12 — Impact Activity for a Large Outer Ring Flaw

Figure 13 — Holographic Interferogram Showing Contour of Outer Ring Deformation