Proximity Transducer Technique for Bearing Health Monitoring

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This paper describes a new, effective method developed at the National Research Council of Canada for rolling element bearing incipient failure detection. This method can detect not only outer race damage (described previously), but also inner race damage with a 100% detection rate based on a sample size of 32. The prediction of the exact angular location of the damage spot along the raceway is illustrated and experimental confirmation is presented. For the first time, a statistically measurable parameter for inner and outer race damage is introduced as a means of verifying other techniques that do not offer absolute proof, but resort only to "overwhelming evidence." A brief comparison with other methods such as the shock pulse method, kurtosis analysis, cepstrum analysis, and high-frequency resonance technique is presented. A computerized automatic monitoring system utilizing the new method is described and experimental results are presented.

Introduction

IN recent years, there has been a proliferation of rolling element bearing condition monitoring instrumentation. The obvious objectives of employing condition monitoring devices are to reduce losses due to machinery downtime and to improve maintenance, productivity, and safety by detecting degrading bearings before they cause catastrophic failure. Methods of rolling element bearing monitoring have been reviewed by many scientists[1-7] and can be categorized in different ways. The new method described in this paper can be classified as one of the vibration analysis methods.

With very few exceptions,[8,9] most vibration analysis methods are based on either acceleration[7] or velocity measurements.[10] Among the bearing health monitoring methods based on acceleration measurements, two are particularly prominent, namely, the high-frequency resonance technique (HFRT)[7] and kurtosis analysis.[11] McFadden[7] presented an excellent review paper on HFRT and stated that there was only one published work on inner race damage identification using HFRT. That work was on the inner race damage of angular contact bearings under thrust load, not deep groove bearings under radial load. Bearings under radial load present more difficulties and, therefore, no method seems to be 100% dependable. The method described in this paper is based on displacement measurement under radial load and exhibited not only 100% dependability in both inner and outer race incipient failure detection, but also accurate identification of the damage spot along the raceway.

The application of displacement transducers to rolling element health monitoring was introduced for the first time by Philips.[8,9] He used a fiber optic sensor to measure the elastic deformation of the bearing outer ring caused by the rolling balls under thrust load. Philips used two sensors and developed the concept of bearing speed ratio (BSR). He reported interesting work on the detection of inner and outer race damages and improper installation of bearings based on BSR monitoring.

The work reported in this paper usually utilized a single transducer instead of two. Therefore, the detection of bearing damage is not based on the "bearing defect factor"[9] or BSR values. Although Philips did not mention it explicitly, his work seems to have been based on a thrust loading where the load zone spans the entire 360 deg. The present work is based on a radial loading where the detection of inner race damage is much more difficult because the load zone does not cover the entire 360 deg, but rather only a portion of the periphery of the bearing.[7]

Bently and Harker[12] introduced a highly sensitive eddy current sensor in place of a fiber optic sensor. Harker and Hansen[13] reported case histories using the eddy current proximity sensors for the purpose of rotating machinery health monitoring. It was not possible to identify the failure mode or the exact location of damage without disassembling the bearings until Kim[14] reported his preliminary test results with the eddy current proximity transducer technique.

This paper summarizes previous work on outer race damage detection and then describes additional findings on aspects such as inner race damage detection, identification of damage location with experimental confirmations, a statically measurable parameter as a proof of bearing damage without disassembly, and comparison with other methods such as the shock pulse method, kurtosis analysis, and HFRT. Also described here is a quantification of the incipient failure that was not possible in previous work.[14] This quantification of the damage signal has been applied to a test facility and a computerized automatic monitoring system has been commissioned. The automatic monitoring scheme as well as the experimental confirmation are also described in this paper.

Description of Experimental Arrangement

The transducer used in this study is the same type of highly sensitive eddy current proximity transducer described by Bently and Harker.[12] The sensitivity of the probes is approximately 2 V per 0.001 in. (25 μm). The sensors can be used in the same manner as were the fiber optic probes by Philips. A typical installation of the probe is shown in Fig. 1. A very slight relief of the housing in the load zone is provided to allow the probe to observe not the walls of the hole, but rather the elastic deformation of the outer race as each rolling element passes, under load, over the observed point. The relief can be small enough such that normal life of the bearing is not affected.[12]

A schematic for the experimental setup and the data acquisition system is shown in Fig. 2. The displacement signal from an eddy current sensor is directed, through appropriate filters and signal conditioning, to an LPA11-K (laboratory peripheral accelerator), and eventually to an IBM 3033 via minicomputers. This and other analog signals are converted

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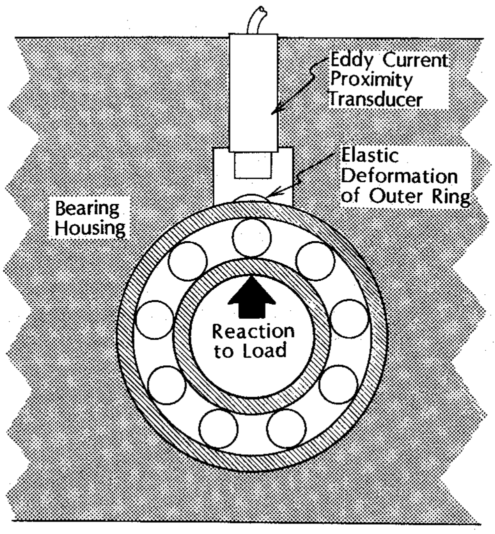

Fig. 1 Transducer installed in line with load.

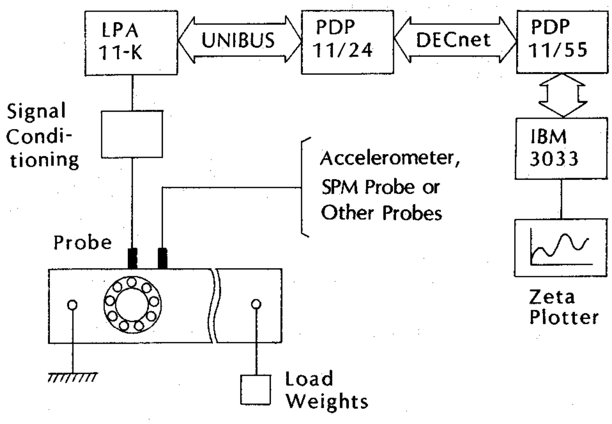

Fig. 2 Data acquisition and processing system.

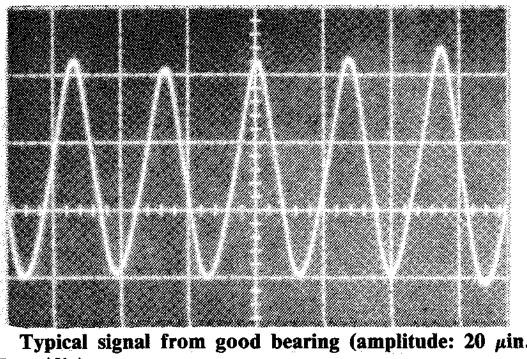

Fig. 3 Typical signal from good bearing (amplitude: 20 μin./div, time: 5 ms/div).

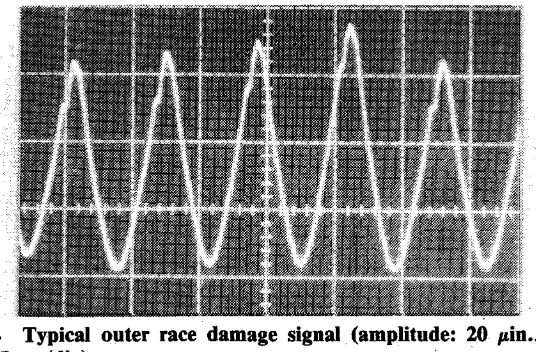

Fig. 4 Typical outer race damage signal (amplitude: 20 μin./div, time: 5 ms/div).

to digital data by the LPA11-K up to a maximum rate of 111 kHz. The digital data are then transferred to a hard disk for storage. Because of the limited capacity of the minicomputer, the majority of data is transferred to a mainframe computer (IBM 3033), via a PDP 11/55, for further analyses and processing.

SKF 6002 bearings were selected as test bearings because of their lower load capacity and potentially low noise at low speed. The load was 700–900 lb (3100–4000 N) and rotational speed maintained at 2450 rpm.

Good Bearing

The signal from a good bearing (Fig. 3) resembles a sinusoidal curve in the time domain. The characteristics of a good bearing signal or waveform can be summarized as "smooth."

Damaged Bearing: Outer Race Failure

A typical waveform for outer race failure is shown in Fig. 4. There is a slight "peakiness" or "nonsmoothness" in the wave shape. The most prominent characteristic of outer race damage is that the time series wave shape shows exact periodicity. This means, in a physical sense, that every time the rolling elements pass the damaged region in the outer race, the signal exhibits a small (and local) peak for every ball-passing cycle.

Figures 5 and 6 illustrate the identification process for outer race damage location. A detailed description can be found in Ref. 14. The time duration between the crests of the waveform represents the period of ball-passing frequency as well as the physical angle between the rolling elements. The time duration between the damage signal and the crest of the ball-passing waveform was measured as 2.93 ms. This corresponds to 17.3 deg when calculated from the geometry of the test bearings.

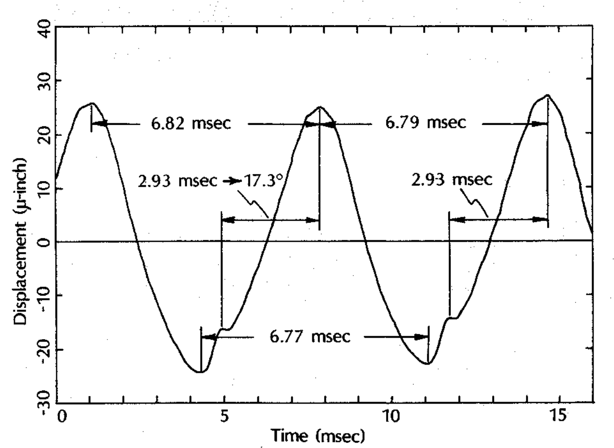

Fig. 5 Identification of precise location of outer race damage.

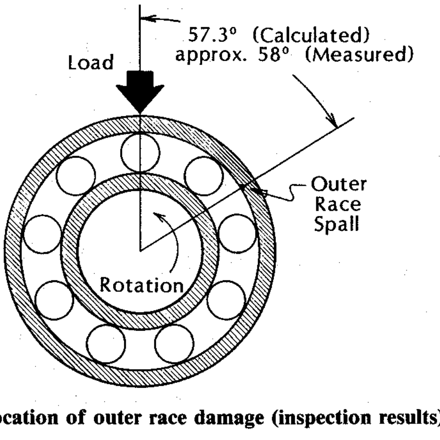

Fig. 6 Location of outer race damage (inspection results).

Since the angular distance between the balls is 40 deg, the above-measured value of 17.3 deg means that the location of outer race damage is either 17.3 deg before top dead center (BTDC) or $17.3+40=57.3$ deg BTDC. Actual measurement of the angular location of the outer race spall revealed the value of approximately 58 deg. Other combinations such as $17.3+80$, $17.3+120$ . . . deg were not possible because they were out of the "load zone," except for the cases of "after" top dead center (ATDC), such as $17.3-40$ and $17.3-80$ deg. Although these two locations of ATDC are within the load zone under the radial load, somehow no failure at the ATDC occurred during the whole series of tests.

Damaged Bearing: Inner Race Failure

Typical inner race damage signals are shown in Figs. 7 and 8. For bearings with inner race damage:

1) The "peaky" damage signal appears concurrently with "good" wave shapes.

2) The damage signals are not exactly periodic, but rather "approximately" periodic in the peaky signal groups.

3) Two prominent characteristics when the waveform is recorded for a reasonably long period are "split signals" and "TDC signals."

On a radially loaded bearing, the signals due to inner race damage do not repeat on every ball-passing cycle. With a thrust load on an angular contact bearing, the damage signal may be periodic due to the fact that the load zone covers 360 deg, that is, all of the rolling elements are under load.

In the radial load case, the inner race damage does not appear until it comes into the load zone. Only when the damage is in the load zone does the irregular wave appear and then, as soon as the inner race damage passes out of the load zone, the "good bearing" wave shapes reappear.

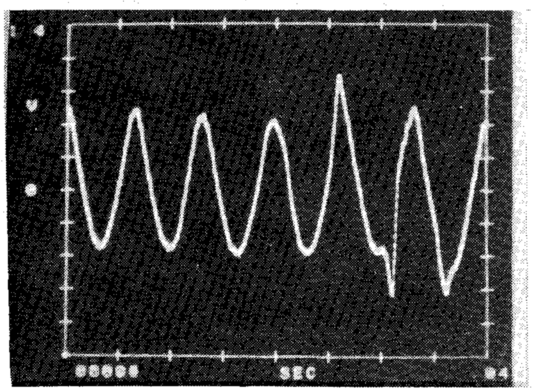

Fig. 7 Typical inner race damage signal (amplitude: 14 μin./div, time: 5 ms/div).

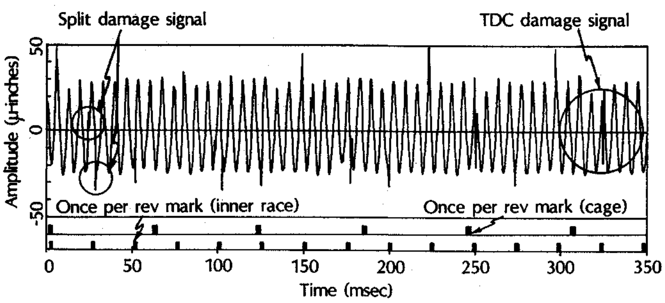

Fig. 8 Characteristics of inner race damage signals.

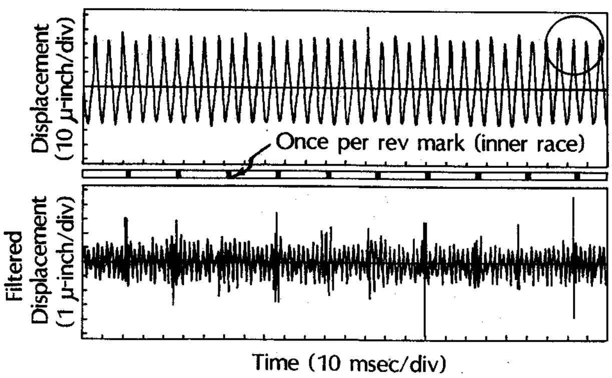

Fig. 9 Identification of inner race damage spot.

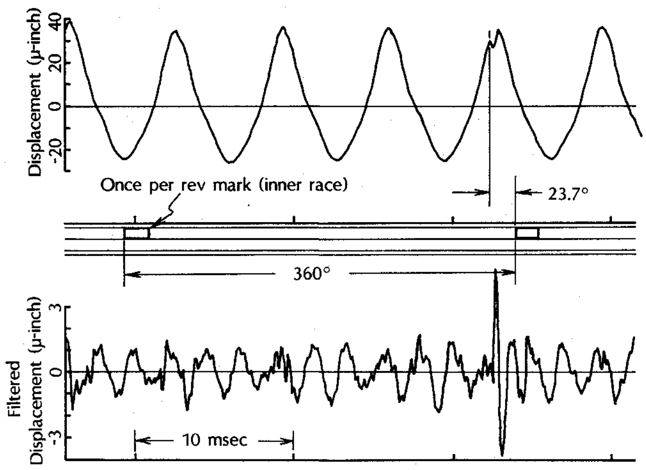

Fig. 10 Expanded plot of the circled region in Fig. 9.

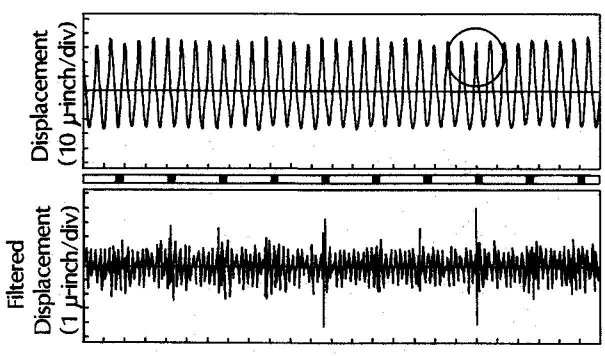

Fig. 11 Installation of new OPRM.

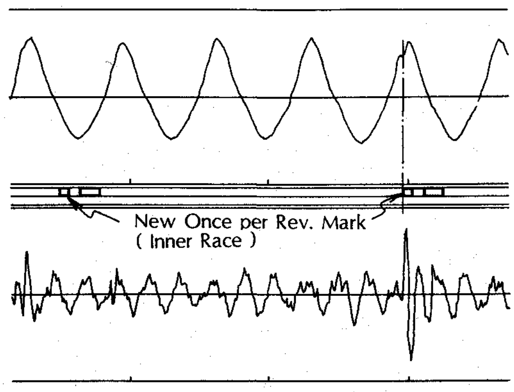

Fig. 12 Expanded plot of the circled region in Fig. 11.

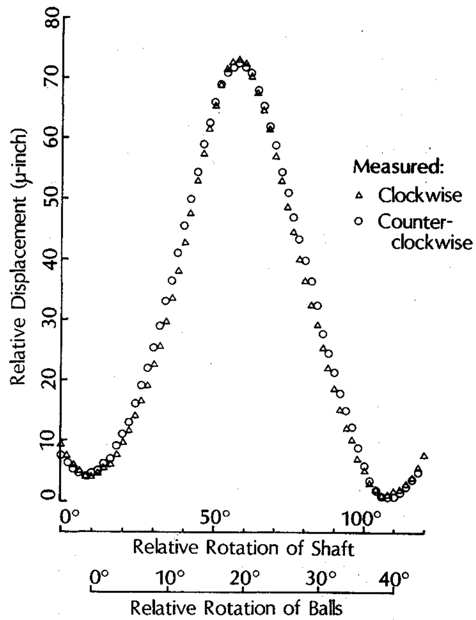

Fig. 13 Static measurement of good bearing.

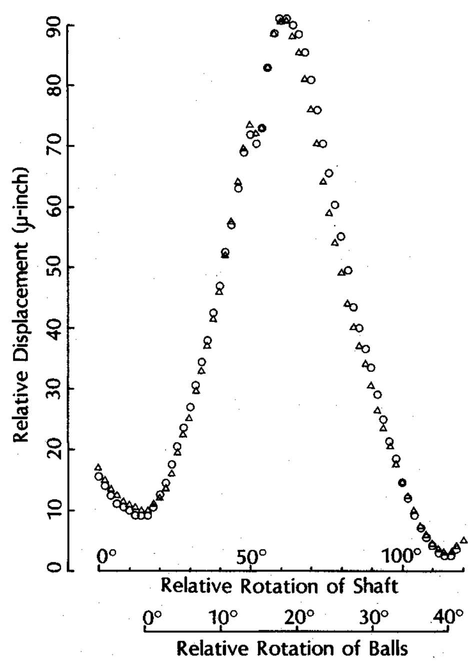

Fig. 14 Static measurement of outer race damage.

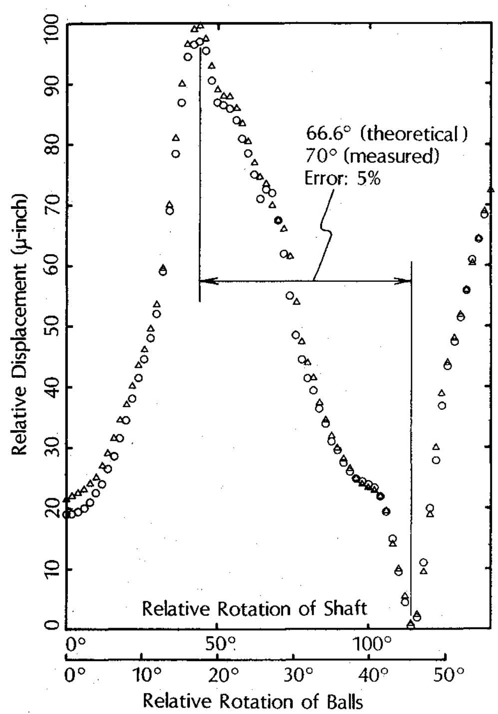

Fig. 15 Static measurement of inner race damage.

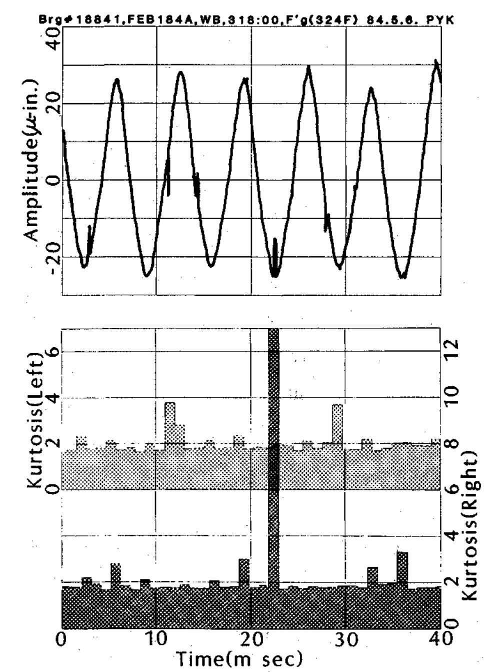

Fig. 16 Effect of sampling intervals on kurtosis values.

The "split signals" (Fig. 8) occur when the inner race damage comes to the TDC of the load zone and the rolling element is approximately one-half a ball-passing cycle away from TDC. On the other hand, "TDC signals" are generated when the inner race damage and the rolling element coincide with the sensor location at TDC. Vivid examples of "split signals" are documented in the paper by Harker and Hansen.[13]

Identifying the angular position of inner race damage is illustrated in Figs. 9-12. This is done by scanning two channels at the same time, one channel for the waveform and the other channel for the reference mark (Fig. 9). The reference mark may be placed at any arbitrary location on the periphery of the shaft or inner race.

Figure 10 focuses on the circled area of Fig. 9, which contains a prominent damage signal. In Fig. 10, the distance between two consecutive once per revolution marks (OPRM) represents one complete revolution of the inner race. Noting that the damage spot occurs 23.7 deg before the OPRM, a "new" reference mark is placed approximately 24 deg from the "old" OPRM in the direction of rotation. The effect of both OPRM signals and the relative location to the damage spot can be seen in Figs. 11 and 12. The "new" OPRM is now located at the same angular location as the inner race damage. Damage location measurement in the disassembled bearing revealed good agreement with the prediction. Results to date are based on five consecutive samples.

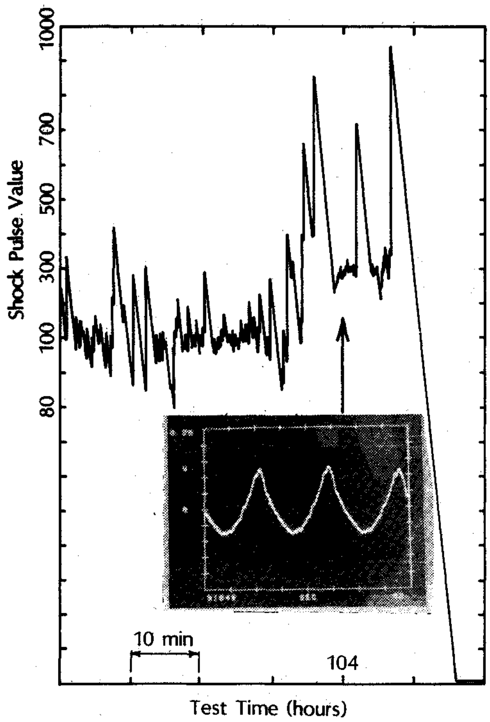

Fig. 17 Comparison with SPM.

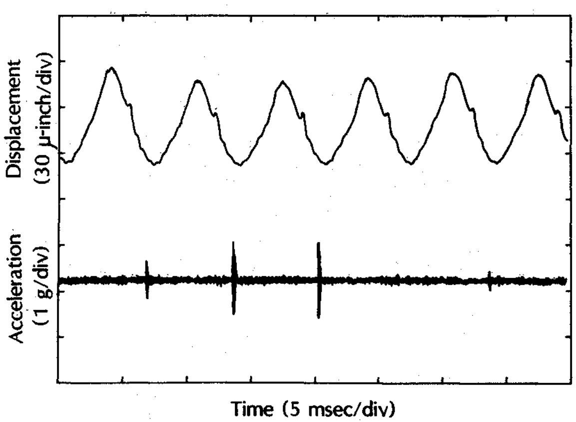

Fig. 18 Comparison with HFRT.

Statically Measurable Parameter

Although claims for many fault detection techniques have been made, no definitive proof, experimental or analytical, is available to show that "irregular" signals are indeed due to the damage itself. One of the main difficulties is that most of the techniques rely on either velocity or acceleration measurements, both dynamic phenomena. Therefore, as soon as the rotating machinery is stopped for examination, the dynamic signals cease.

The method presented here offers a physically measurable parameter for rolling element damage detection without disassembly of the test bearing. The method can ascertain that the irregular "peaky" signal is indeed coming from the physical contact of the damage spot with the rolling element. Proof was achieved by measuring the elastic deformation of the outer race while the shaft was rotated in increments of 2 deg. The measurements thus obtained were static, not dynamic, as the deformation was measured when the shaft was at rest.

Figure 13 shows the static measurements of the elastic deformation of a good bearing. The shape is in complete

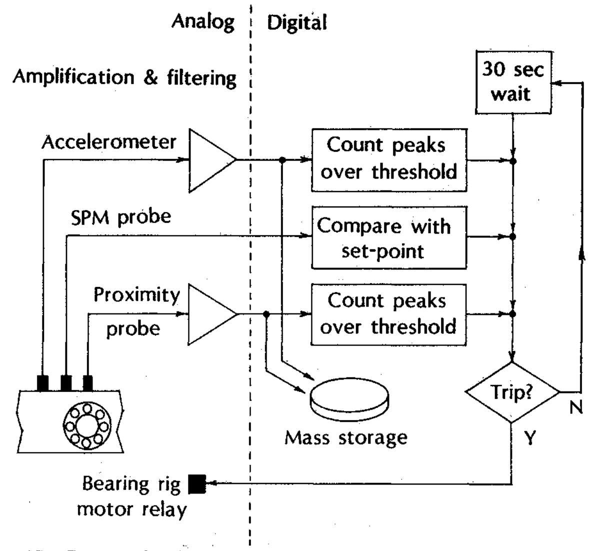

Fig. 19 Schematic diagram for computerized automatic monitoring system.

agreement with the dynamic measurement of Fig. 3. Figure 14 shows the static measurements of the elastic deformation of a bearing with outer race failure. The dynamic waveform of the identical bearing was shown in Fig. 4.

The elastic deformation of the outer race of a bearing with inner race damage as statically measured is shown in Fig. 15. The dynamic waveform of the identical bearing was shown in Fig. 7. Again, the agreement between statically and dynamically obtained data is very good.

These measurements can be carried out statically as well as dynamically without disassembling the bearing. Thus, the deformation of the outer race of rolling element bearing is a physically measurable parameter for inner and outer race damage detection that does not require bearing disassembly. To date, visual inspection after bearing disassembly has been the only available method to confirm bearing spalls.

Comparison with Other Methods

The concepts of kurtosis[11] and cepstrum[15] analyses were applied to the eddy current proximity transducer signals for the purpose of quantification. However, they did not yield any significant information. As a result of the attempt it was found that the value of kurtosis can be extremely sensitive to sample size and sample interval. Figure 16 shows the basic waveform from a damaged bearing and the results of two kurtosis analyses of the same signal. "Kurtosis (left)" shows the values for each consecutive group of 50 samples, that is, kurtosis calculations were applied to samples 1–50, 51–100, 101–150, and so on.

"Kurtosis (right)" was found by displacing the sampling interval by 25. Kurtosis calculations were applied to samples 26–75, 76–125, 126–175, and so on. The data indicate that an individual waveform can generate two different values by displacing the sampling intervals. "Kurtosis (left)" shows a kurtosis value of approximately 2, while "Kurtosis (right)" shows a value of approximately 14.

Figure 17 compares the eddy current proximity signals with those of the shock pulse method (SPM). Excellent agreement between the two methods was found. However, the eddy current probe technique yielded slighlty earlier detection capability and, most importantly, 100% reliability in 32 consecutive cases. On the other hand, SPM seemed to indicate some capability to detect poor bearing lubrication.

Figure 18 presents the comparison between the eddy current proximity transducer technique and the HFRT. The resonant frequency of the accelerometer was chosen as the "carrier frequency." Both techniques showed good agreement; however,

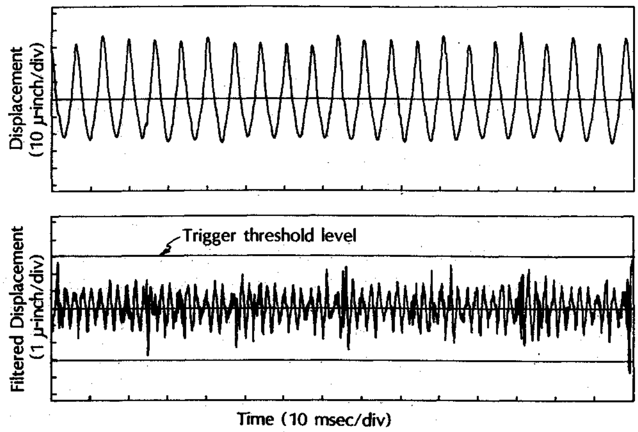

Fig. 20 Bearing signals 30 s before tripping.

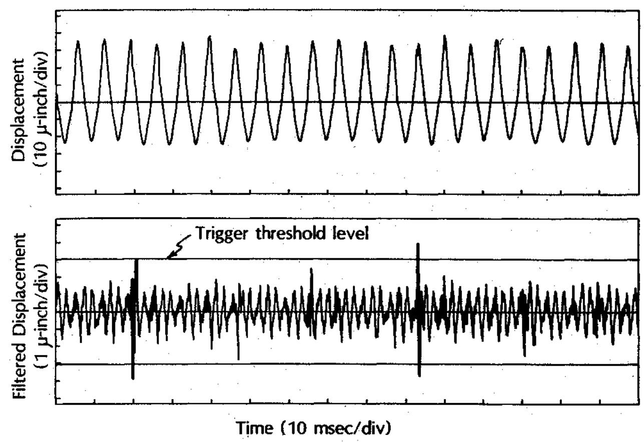

Fig. 21 Bearing signals at tripping.

as shown in Fig. 18, HFRT damage signals experienced dropout. If, however, the envelope detection technique is incorporated, a few missing signals may not be significant.

Quantification of Damage Signals and Computerized Automatic Monitoring System

To date, identification of bearing damage has been based upon "pattern recognition" of the characteristic damage signals. Quantification of damage characteristics is essential for computerized automatic monitoring systems. This has been achieved by removing up to the third harmonic of the ball-passing frequency from the original waveform. It was found by trial and error that subtraction of harmonics higher than the third did not result in an improvement of the signal-to-noise ratio. A schematic of the automatic monitoring system is shown in Fig. 19. To date, the eddy current proximity transducer technique has proved to be 100% reliable. Figure 20 shows the original waveform as well as the filtered waveform (up to the third harmonic subtracted from the original waveform) 30 s prior to automatic tripping due to inner race failure. Figure 21 shows both wave shapes at the time of tripping.

Conclusions

The eddy current proximity transducer technique has been successfully applied to rolling element bearing incipient failure detection with 100% reliability.

A method of identifying either inner or outer race damage and the damage location has been illustrated. A statically measurable parameter for detecting inner and outer race damage without a need for disassembling the bearings has been introduced. A favorable comparison with other methods such as the shock pulse method, kurtosis analysis, and high-frequency resonance technique was presented.

A computerized automatic monitoring system utilizing the eddy current proximity transducer method was demonstrated.

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