CONDITION MONITORING OF ROLLING ELEMENT BEARINGS INSTALLED IN CENTRIFUGAL PUMPS

by

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ABSTRACT

Monitoring the condition of bearings in centrifugal pumps continues to be an important concern to pump users, especially in critical pump installations. Additionally, pump users are interested in simple, easy to use, moderate cost, reliable bearing condition instruments. Bearing condition monitoring methods, such as vibration analysis, shock pulse, and bearing outer race deflection have proven successful in laboratory tests, but direct comparisons have often been lacking.

The results of tests conducted on an ANSI Type 1.5x3-8 centrifugal process pump using these bearing condition monitoring methods are presented. Installation and operational considerations which need to be addressed when using the various bearing condition monitoring methods on centrifugal pumps are discussed.

It is considered noteworthy that the system that monitors bearing outer race deflection had the greatest success in detecting bearing defects while the traditional case mounted velocity transducer system was the least successful in detecting the same bearing faults.

INTRODUCTION

Given the necessary training, sophisticated instruments and experience, maintenance personnel can monitor pump bearings and predict when these bearings are beginning to fail. However, this takes a substantial investment of time and money. The concept of being able to identify the condition of a bearing using instruments that give one or two general numbers or a "go/no-go" status is attractive. Continuous efforts are underway towards the development of instruments which may make this concept a reality.

A variety of sensors have been used for bearing condition monitoring systems. Velocity pickups, accelerometers, piezoelectric crystals and proximity probes have all been successfully used as sensors of bearing condition in laboratory and quality assurance environments. However, when these same bearing condition monitoring systems are used on the bearings of a centrifugal pump installed in the field, reliable indications of bearing condition are not consistently obtained. This is due to the fact that not only the condition of the bearing, but also the size, construction and support of the bearing frame, type and condition of the mechanical seal, amount of impeller unbalance, impeller radial and thrust loads, and type and condition of lubrication may affect the actual vibration level at the bearing. A better understanding of the type and magnitude of vibration produced by each of these sources would help in the determination of the actual bearing condition.

The purpose of the testing program covered by this paper was twofold. First, it was to determine what effects, if any, normal changes in pump related parameters such as speed, flow or suction pressure might have on the output of several bearing condition monitoring systems. The second purpose was to determine the capability of each measuring system to detect bearing defects.

A suitable bearing condition monitoring system is one which is relatively insensitive to normal pump operational changes while being relatively sensitive to bearing condition changes. As a bearing begins to deteriorate the signal level of an ideal monitoring system should increase. This early detection of a defective bearing would give maintenance personnel more time to schedule corrective action.

The scope of our testing included pump hydraulic changes as well as bearing condition changes. The impeller was operated in both a balanced and unbalanced condition. The pump was operated at different speeds, flows and suction pressures. The bearing frame was operated under normal conditions, without oil, with contaminated oil, and with defects etched on the bearing outer race.

DESCRIPTION OF BEARING MONITORING SYSTEMS

Velocity System

The simplest bearing monitor tested consisted of a general purpose case mounted velocity pickup and a readout. The velocity transducer selected has a linear frequency range of 20 to 1000 Hertz. The location of the velocity transducer is shown in Figure 1, mounted vertically on the pump bearing frame between the thrust and radial bearings. It was connected to a vibration monitor set to indicate unfiltered peak velocity on a 0 to 3 in/sec scale.

Acceleration System

The second bearing monitor system tested consisted of an acceleration transducer system and a readout. The acceleration transducer system was made up of a standard accelerometer, interface cable and an interface module. The accelerometer has a linear frequency range of 2 to 20,000 Hertz. The location of the accelerometer is shown in Figure 1, mounted vertically on the bearing frame between the radial and thrust bearings, adjacent to the velocity transducer. The acceleration transducer system was connected to an acceleration monitor set up to indicate unfiltered peak acceleration on a 0 to 10 g scale.

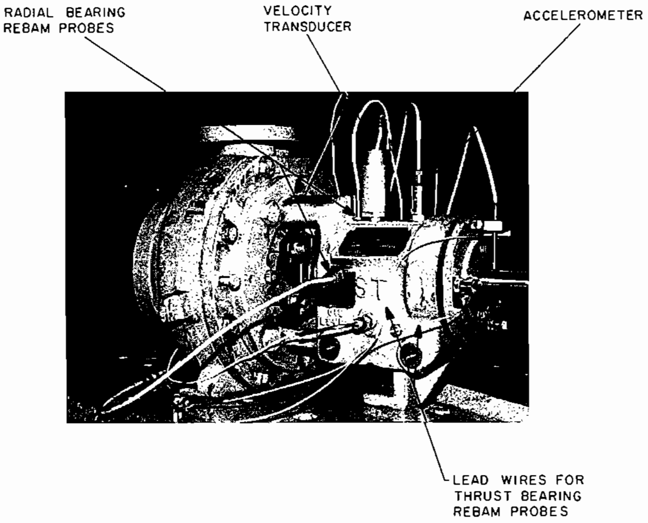

Figure 1. Sensors Installed on Test Pump.

REBAM System

REBAM stands for Rolling Element Bearing Activity Monitor. This system is built and marketed by a large US company specializing in vibration monitoring products. This bearing monitor system is based on a relatively new concept. By measuring the deflection of the outer race of the bearing and separating that displacement signal into two frequency bands, the pump and bearing condition can be identified. The deflection of the outer race is measured using a REBAM proximity transducer system. It consists of a proximity probe, a very high sensitivity eddy current proximity transducer and a monitor. The probes have a linear frequency range of 0 to 10,000 Hertz and can measure deflections from 2.0 to 1000 μin. The proximity probes installed in the radial bearing and also the lead cables for the special miniature proximity probes installed in the thrust bearing housing are shown in Figure 1. The signal from the REBAM proximity transducer system was fed into the REBAM monitor.

The monitor separates the input signal into two separate channels. The first channel is low pass filtered to observe frequencies in the range of one-forth to three times (1/4-3×) running speed. This is called the rotor related (RR) vibration region. It provides detection of rotor vibration malfunctions such as unbalance and misalignment. For this application, the low pass filter was set at 270 Hertz. The readout full scale for the rotor related channel was set at 500 μin peak to peak.

The second channel of the REBAM monitor is high pass filtered to observe frequencies in the range of one to seven times (1-7×) the rolling element passage rate. This frequency range is call the prime spike (PS) region. It provides detection of defects in the rolling elements or bearing races. For this application, the high pass filter was set at 634 Hertz. The readout full scale for the prime spike channel was set at 100 μin peak to peak. RR channel signal variations of 10 μin are known to be normal while PS channel signal variations of 5.0 μin are considered acceptable.

SPM System

The forth bearing condition monitoring system tested was the Shock Pulse Method (SPM) system. The entire SPM system is housed in a gun like instrument as pictured in Figure 2. This instrument is a microprocesser controlled device capable of identifying lubrication quality as well as bearing condition. By inputting the speed and size of the bearing in the form of a "NORM" number and the type of bearing in the form of a "SPM TYPE" number, the SPM bearing analyzer is completely programed and ready to use. This instrument was used in the vertical position on the thrust bearing and the horizontal position on the radial bearing. Once the analyzer was in position a press of the trigger activated the analyzer and it displayed lubrication and bearing condition numbers.

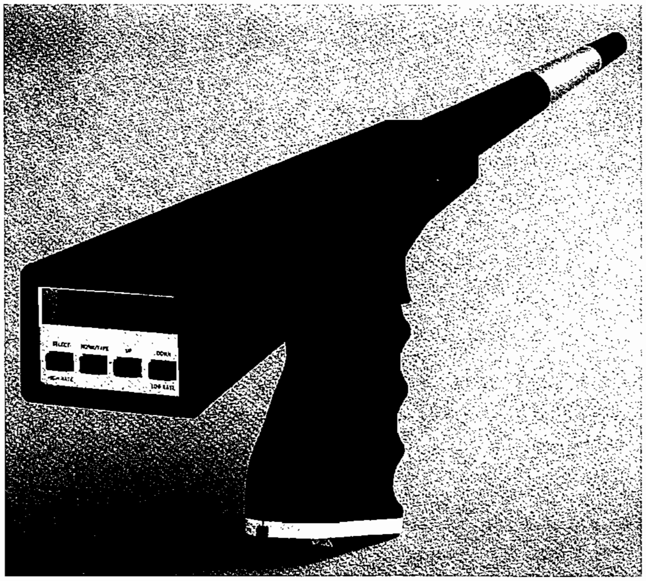

Figure 2. SPM Bearing Analyzer Model BEA-52.

Without programing the "NORM" and "SPM TYPE" numbers the SPM bearing analyzer can be used as a shock pulse meter that counts pulses which exceed two different threshold levels. Low rate (LR) is an indication of the shock pulses that exceed a low threshold while high rate (HR) is an indication of the shock pulses that exceed a high threshold. Although the SPM system was used both as a shock pulse analyzer and shock pulse meter the latter was an excellent way to trend changes that occurred during this testing program.

DISCUSSION OF RESULTS

Effects of Speed Variation on Signal Levels

The completely assembled pump was operated at 1750 rpm and 3550 rpm to investigate signal level changes due to speed variations. Both the velocity and acceleration signals were found to be sensitive to speed variations. More specifically, the velocity signal levels doubled and the acceleration signal levels more than tripled when the speed of the pump was doubled. These results are reasonable since a 200 percent increase in velocity and a 400 percent increase in acceleration are anticipated for a given rotating system when the speed is doubled [1]. The REBAM rotor related signal level changes were due to data scatter as no trend could be established between the low and high speed signal levels. However, the REBAM prime spike signal levels did not change with the speed change. Likewise, the SPM system signal levels did not change with the change in pump speed. No change in the REBAM system or the SPM system signal levels was anticipated because there was no change in bearing condition or lubrication.

Mechanical Seal Effects Examined

Test runs with and without a mechanical seal were aimed at determining whether a mechanical seal in good condition would create sufficient "rubbing noise" to affect either the piezoelectric crystal or REBAM signal levels. None of the four systems exhibited any signal level changes due to the presence of the mechanical seal.

Baseline signal levels for all four systems were obtained by running the bearing frame alone. The stuffing box and mechanical seal were then added to the bearing frame. This configuration was run twice, first with the mechanical seal spring tension set per manufacturer specifications and again with the spring tension set at maximum. Signal levels from all four systems did not change from their baseline levels during either run. The results of these tests demonstrate that at least in the configuration tested the mechanical seal has no effect on piezoelectric crystal or REBAM signal levels. However, we wish to emphasize that these findings relate only to a mechanical seal in good condition and frequencies below 20 khz. Kataoka, et al. [2], and Bloch [3], clearly documented that higher frequency measurements can detect defective mechanical seals in centrifugal pumps.

Impeller Unbalance Effects

A series of tests were conducted to determine the effects of mechanical unbalance on the signal levels of the various monitoring systems. An impeller was selected with an unbalance of ten times the manufacturer's maximum allowable unbalance. The impeller was first run in air for the unbalance test. After being balanced to within acceptable limits the same impeller was used for the balanced signal response test. The velocity and acceleration systems did not exhibit signal level changes between the unbalanced and balanced impeller tests. This was true for both high and low speeds and must be attributed to the fact that ten times allowable unbalance is still moderate, in absolute terms. There was also no effect on REBAM prime spike signal levels. The REBAM rotor related signal levels increased by amounts greater than normal variations. Similar REBAM rotor related signal level increases occurred during low speed testing. This demonstrated that the REBAM rotor related signals can detect an impeller unbalance condition. The SPM system was not available during this phase of testing.

Baseline Data for Good Bearings

High speed baseline data for the velocity, acceleration and REBAM systems were obtained for three new bearing sets. The high speed baseline data for the SPM system were documented on two new bearing sets. These tests were performed to identify differences, if any, in signal levels between good bearing sets and also to determine variations in signal level with changes in flow.

Signal levels for the velocity, acceleration and REBAM prime spike and SPM systems were similar for each bearing set tested. This indicates that there is little variation in signal levels among good bearings.

Average velocity, acceleration, REBAM and SPM signal levels with changes in flow are shown in Figure 3. Flow is plotted in percentage of pump Best Efficiency Point (BEP). Each signal level is plotted as a percentage of its level at 100 percent BEP. Each system signal level had the same trend, i.e. higher signal levels at both extremes of flow. Restated, the signal levels were higher the further from BEP the pump was operated. There are two possible reasons for this result. First, amplitude variations of radial and axial forces on the impeller vary with flow. These force variations are minimum around BEP and increase to either side of BEP [4]. As the excitation force increases the sensor output is expected to increase. Second, the direction of the radial force is a function of flow. The radial force in this pump is normally away from the cutwater at low flows and toward the cutwater at high flows. The cutwater in this pump is close to the vertical position. Most of the measurements were taken in the vertical direction. Having the sensor in the load plane of the bearing in order to get improved readings was stressed by the installation instructions of both the SPM and REBAM systems.

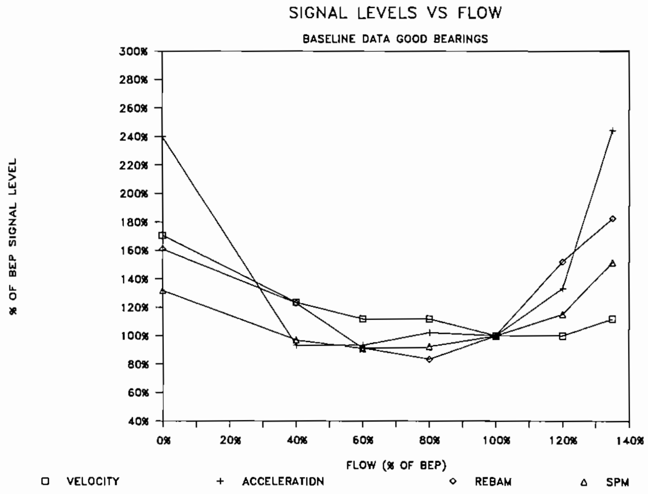

Figure 3. Average Baseline Signal Levels for Good Bearings.

A list of average baseline levels of the four systems are presented in Table 1 as they were installed and tested on good bearing sets. These levels are for the 100 percent BEP of the pump and should be used only as a guide.

Table 1. Baseline Levels.

Monitoring System	Baseline Data Good Pump
Velocity	0.20 in/sec peak
Acceleration	1.4 G peak
REBAM	50 μ in rotor related 5 μ in prime spike
SPM	37 low rate 33 high rate

Suction Pressure Variation Tests

Tests varying the pump suction pressure at a given flow were performed to determine if the signal levels varied with suction pressure changes and identify what happens to signal levels when the pump begins to cavitate. These Net Positive Suction Head (NPSH) tests were conducted at 40 percent of BEP and at 100 percent of BEP flows. The velocity, acceleration and

REBAM systems' signal levels remained relatively constant as suction pressure was reduced (Figure 4). This demonstrated that the velocity, acceleration and REBAM systems were insensitive to changes in pump suction pressure providing the pump was not cavitating. During cavitation the signal levels of the acceleration and REBAM systems increased. A plot of typical velocity, acceleration and REBAM signal levels, *vs* suction pressure in feet of water absolute is presented in Figure 4. The SPM system was not available during this phase of testing.

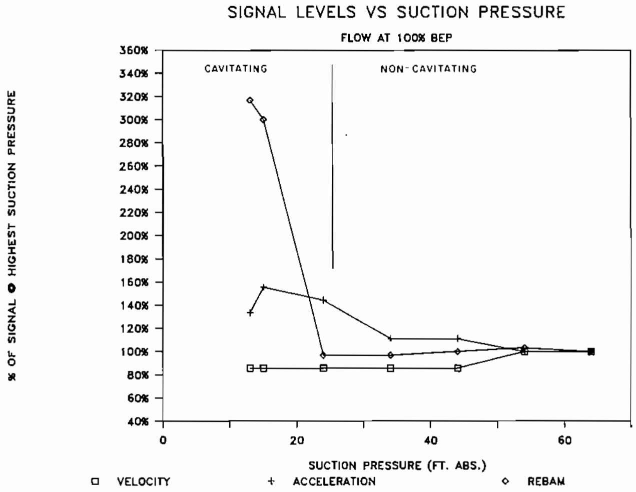

Figure 4. Signal Level Variations due to Suction Pressure Changes.

Tests with Bearings Deprived of Lubrication

With the test pump running at high speed and set at 100 percent BEP, the oil was drained from the bearing frame. This test was conducted to identify changes in signal level due to lack of lubrication. After a period of time the oil was poured back into the bearing frame. Data were recorded before the oil was removed, after it was removed and after it was poured back. This test was performed twice. The first test time with no oil was 45 minutes. The second test time with no oil was 120 minutes. A third test was run after the bearing frame was cleaned of all residual oil. Results were similar for all three tests.

The velocity monitoring system did not indicate any change in signal level when the oil was removed. The acceleration system signal level increased to 140 percent of its baseline level after the oil was removed. When oil was added back into the bearing frame, the acceleration level returned to its original value. The REBAM system signal levels increased with the removal of oil and returned to the same signal levels when the oil was poured back into the bearing frame. Average signal levels were 240 percent of baseline for rotor related and 295 percent of baseline for prime spike with the oil removed. Results of the no oil test using the SPM system were similar. The low rate and high rate shock pulse levels increased when the oil was removed and returned to their normal levels when the oil was added back. The average signal level for both the low rate and high rate shock pulse levels was 150 percent of baseline values. Figure 5 is a plot of typical velocity, acceleration, REBAM and SPM signal levels *vs* time with no oil in the bearing frame. Visual inspection of the bearings revealed no deterioration or damage. Independent testing of similar bearing sets and extensive experience with oil mist lubrication have shown that rolling element bearings operated under moderate load conditions can last several hours without lubrication before damage occurs.

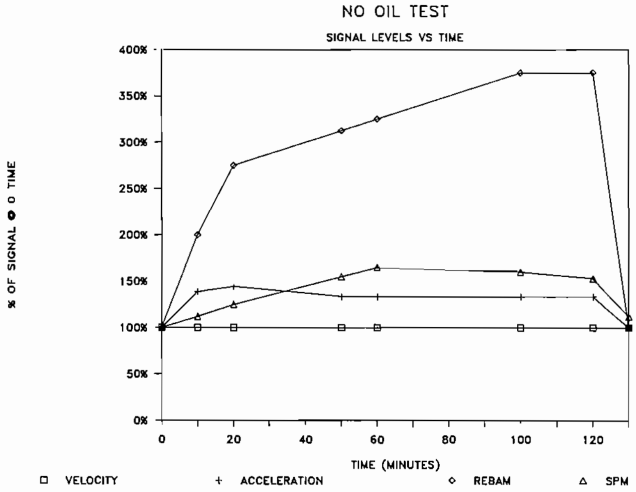

Figure 5. Changes in Signal Levels Caused by Removal of Bearing Lubrication.

CONTAMINATED OIL TEST

In order to determine the signal level changes due to contamination in the oil a contaminated oil test was conducted. This test was accomplished by pouring fine sand into the bearing frame oil while the pump was running. The pump was operating at high speed and the flow set at 100 percent of BEP when the sand was introduced. During a 60 minute run the velocity system signal level increased to 300 percent of its baseline value while the acceleration system signal level increased to 680 percent of its baseline value and the REBAM prime spike signal levei increased to over 1000 percent of its baseline value. Figure 6 is a graph of all three signal levels versus time after the sand was added to the oil. Of interest are the slopes of the acceleration and REBAM prime spike signals showing considerable sensitivity and early detection of damage caused by the sand. As bearing damage increased the signal levels also increased.

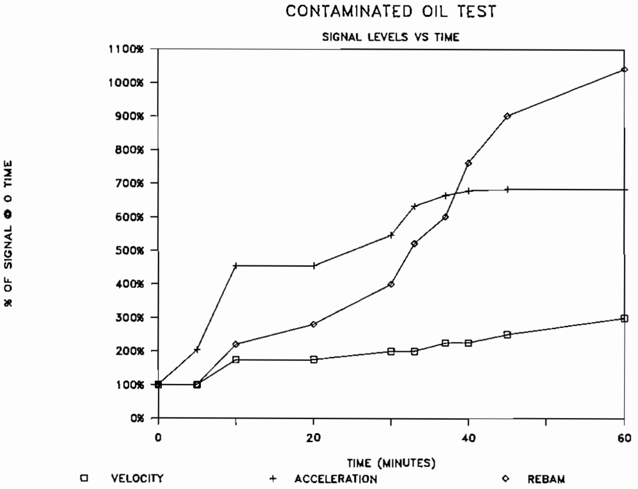

Figure 6. Signal Level Increases with Time Due to Contaminated Oil.

The REBAM signal levels between the radial bearing and the thrust bearing varied. Figure 7 is a plot of the REBAM prime spike signal levels for both bearings. The signal level increases for the thrust bearing were substantially higher than the level increases for the radial bearing. The signal level of the thrust bearing increased to 300 percent and 1000 oercent of their baseline levels for rotor related and prime spike signal levels respectively. This is compared to the increased radial bearing signal levels of 100 percent and 150 percent of baseline for rotor related and prime spike signal levels respectively. Disassembly of the bearing frame revealed that most of the sand had moved toward the thrust bearing and little had gotten into the radial bearing. Visual inspection of the bearings confirmed that the radial bearing was in better condition than the thrust bearing.

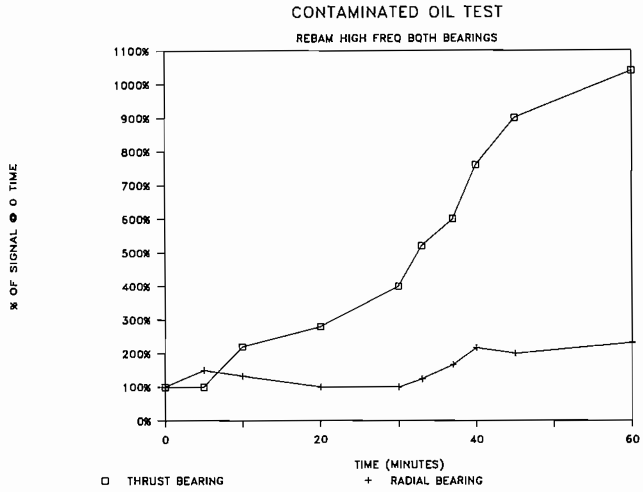

Figure 7. Difference in Thrust and Radial Bearing Damage Caused by Contaminated Oil as Sensed by REBAM.

The increases in signal level for all three systems as the contaminated oil entered the bearings were greater than signal level increases caused by flow variations. During the sand test the pump became audibly noisier. The severity of the thrust bearing defect due to the contaminated oil was enough to be detected by any monitoring system. The advantage of an individual bearing monitoring system is evidenced during this test. The velocity and acceleration systems did indicate a pump problem, but the REBAM system indicated which bearing was deteriorating. The SPM system was not available for this test.

Test of Bearing Defect Severity

To measure the sensitivity of the various systems to detect a bearing defect, bearings with a known defect were installed. A defect measuring approximately 1/16 of an inch square and 0.003 inches deep was ground into the outer races of both the radial and thrust bearing. A complete head capacity test was performed with these bearings installed and with normal lubrication.

Since the signal levels from the velocity system for the defective bearing test were found to be no higher than the baseline signal level obtained with good bearings we opted not to provide an illustration with this paper. However, the acceleration signal level increased to 300 percent of baseline levels as shown in Figure 8. The REBAM rotor related signal levels did not exhibit any consistent level increase or decrease. The REBAM prime spike signal levels were greater than 800 percent of baseline levels (Figure 9). The SPM system indicated spike energy rate increases of 150 percent and 185 percent of their baseline values (Figure 10). There was no change in the noise level of the pump when it was operated with the defective bearings as compared to the pump operating with known good bearings.

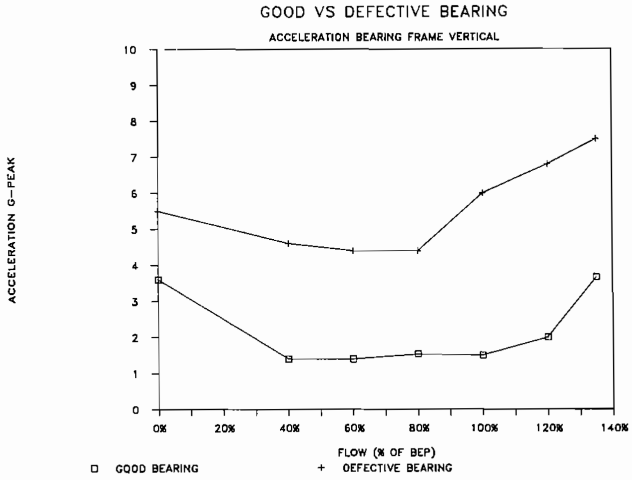

Figure 8. Acceleration Signal Level Changes Between a Good and Defective Bearing with Respect to Flow.

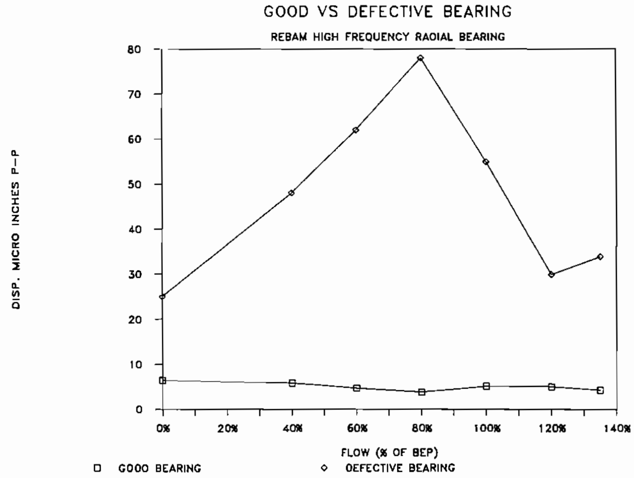

Figure 9. REBAM Signal Level Changes Between a Good and Defective Bearing with Respect to Flow.

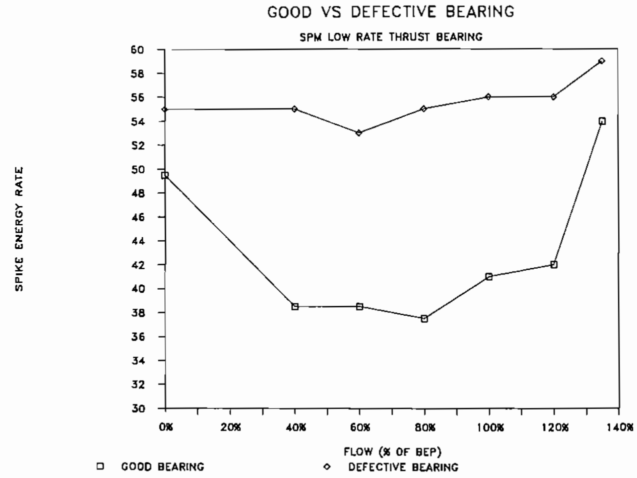

Figure 10. SPM Signal Level Changes Between a Good and Defective Bearing with Respect to Flow.

INSTALLATION AND OPERATIONAL CONSIDERATIONS

Considering the four systems tested for a continuous bearing condition monitoring installation the velocity and acceleration sensors would be the simplest to install. It would require drilling and tapping one hole per pump bearing frame. If the casting surface was rough a surface machining operation would also be required. For this testing the SPM system was used as a portable system moving the instrument from point to point. The SPM manufacturers recommend that a half spherical cavity be machined at each measuring point. For permanent installation of a the SPM sensor a stud arrangement is recommended. This would require drilling and tapping each measurement location. The REBAM sensors are the most difficult to install. They require drilling and tapping through the bearing frame at each measurement location on the radial bearing. Because the thrust bearings on the pump tested are located in a housing inside the bearing frame, special miniature REBAM probes were manufactured and epoxied into the bearing housing.

The velocity, acceleration and REBAM systems are all similar in operation. Once the system is installed, one or two analog signals indicate the condition of the bearing. No other adjustments are necessary to the system. This would also be the case if a dedicated SPM system were available. However, the SPM bearing analyzer used during this testing required reprograming each time a different speed or bearing was monitored.

It is important to determine the baseline, alarm level or danger levels of any given system. As stated earlier, Table 1 shows is a list of the baseline levels of the four systems as they were installed on the test pump. These levels are for the BEP of the pump tested and should be used only as a guide. Other pump installations may give different baseline values due to bearing frame size and installation practices. Percentage increases given in Table 2 could be used as a guide for setting alarm and danger levels.

At roughly $2000 per channel, the initial cost of each of the four bearing condition monitoring systems was about the same. Permanently installed monitoring systems will, of course, require wiring or telemetry equipment costs which could add substantially to the overall price tag.

Table 2. Comparison of Different Monitoring Systems. Reponse is Expressed in Percent of Baseline Value at 100% of BEP.

	MONITORING SYSTEM			
Pump Condition	*Velocity*	*Accel.*	*REBAM*	*SPM*
1750 rpm to 3550 rpm Variation	200%	300%	RR 100% PS 100%	L 100% H 100%
Mechanical Seal	100%	100%	RR 100% PS 100%	L 100% H 100%
0% to 140% of BEP Flow Variation	150%	200%	RR 200% PS 150%	L 166% H 180%
40% to 110% of BEP Flow Variation	125%	115%	RR 150% PS 125%	L 115% H 125%
Suction Pressure Variation	86%	110%	RR 105% PS 105%	NA NA
Fault Condition				
Pump Cavitation	86%	150%	RR 320% PS 230%	NA NA
Impeller Unbalance	100%	100%	RR 175% PS 100%	NA NA
No Oil Test	100%	140%	RR 240% PS 295%	L 150% H 150%
Contaminated Oil Test	300%	680%	RR 300% PS 1000%	NA NA
Defective Bearing	100%	300%	RR 100% PS 800%	L 150% H 185%

RR = Rotor Related
PS = Prime Spike
NA = Instrument Not Available for Test

CONCLUSIONS AND SUMMARY OF RESULTS

A tabulated summary is given in Table 2 for each of the bearing monitoring systems tested and how they compared to each other. The table is divided into two categories. First, pump-related variables which the pump would encounter during normal operation. Second, pump fault conditions which would require identification and correction to ensure reliable pump operation.

As discussed earlier, all four systems exhibited increased signal levels at flows to either extreme of BEP. Only in the flow range between 40 percent to 110 percent of BEP were the four systems able to distinguish between signal level increases caused by a flow variation or the inception of a pump fault condition. Hence, frequency spectrum analysis would be required to conclusively establish fault conditions outside the 40 percent to 110 percent of BEP flow range.

The velocity system is the least effective bearing condition monitoring system. It was only effective in identifying bearing deterioration during the contaminated oil test. The bearings were defective to the point that total pump failure was imminent.

The acceleration system was more sensitive than the velocity system. It was responsive to pump cavitation and loss of lubricant conditions, providing the flows were kept between 40 percent and 110 percent of BEP. The acceleration system also indicated bearing defects and contaminated oil at signal levels higher than were obtained from extreme flow variations.

The REBAM system proved to be the most sensitive of the four systems tested. The rotor related signal levels could indicate impeller unbalance (10 times the normally accepted unbalance limit). The prime spike signal levels although responsive to flow variations indicated higher signal levels when pump cavitation, lack of oil, contaminated oil and bearing faults existed. The REBAM system exhibited its highest response during tests where the bearing condition was deteriorating.

A complete test was not conducted on the SPM system. This system would be useful if the pump flow was kept between 40 percent and 110 percent of BEP. Its baseline signal level is relatively constant over this flow range and signal level increases during the no oil test and the defective bearing test were greater then baseline fluctuations.

From cost, installation and operation points of view, all four systems were the same except for installation. The REBAM system is the most difficult to install because it requires the disassembly of the bearing frame in order to drill, tap, and clean the bearing frame and install the probes. This is offset by the fact that it is the most sensitive of the systems tested.

No definite conclusions can be drawn in regards to the length of time between the first indication of a bearing deterioration and final failure.

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