ROLLING ELEMENT BEARING STATUS USING FREQUENCY ANALYSIS

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ABSTRACT

It has been said that if one has perfect information, then one can make perfect decisions. In the daily operation of a production facility, many decisions are made each day concerning the mechanical condition of production machinery. Often these decisions are made based on opinions and not facts. Condition monitoring, using vibration analysis, will provide the decision makers with better information so that they can make better decisions. Because all the rotating forces are carried through the bearings, knowledge of the condition of these bearings and the machine is important in the daily production decisions. This paper will demonstrate with case histories how condition monitoring can provide the decision makers with better information for better decisions.

INTRODUCTION

In the 17 years the author worked as a plant engineer, one common problem encountered was trying to answer the questions concerning which machine to rebuild and which one to leave alone. If you look at five similar machines and you have time to overhaul two of them during the next shutdown, which two do you select? Do you work on the two that have been in operation the longest, the two with the poorest performance numbers, or the two that the operators feel need rework? At various times each of these criterion has been used to pick the next candidate for overhaul. Along the same line of thought, how many times have we seen a smooth operating piece of equipment taken out of service for overhaul simply because it has reached its time limit as set by the manufacturer? This paper will provide the reader with information that will show how condition monitoring can provide the information needed to make the correct decision in providing the proper maintenance at the right time to the right machine.

BACKGROUND

All rotating equipment has one thing in common, bearings. In monitoring the health of our equipment, the condition of the bearings is of prime importance. Consider that if the bearings are good, even an out-of-balance, misaligned machine will operate. However, if the bearings are damaged, the machine will soon fail,
even if properly assembled and balanced. Today technology has developed new techniques for nonintrusive determination of the bearing's physical condition. Early bearing fault detection usually consisted of an experienced mechanic placing one end of a screwdriver on the bearing cap and the other end on the bone structure behind his ear. Sometimes he was right and sometimes he was wrong. With the advent of portable vibration measuring equipment, some operators noted that the high frequency energy generated by a failing bearing would excite the natural frequency of the bearing and would call a bad bearing based on this information. Again, sometimes they were right and sometimes they were wrong.

The next step in this evolution was to look for specific frequencies generated by the bearing elements as they rotated, using velocity measurements. With this improvement, the accuracy increased but even the good technicians would often miss bearing flaws on the very slow rotating machinery, considering anything below 100 rpm to be slow. In the last few years, with the inclusion of enveloping algorithms, the accuracy has improved to nearly 100 percent. A few bad bearings still get misdiagnosed, but they are rare.

The techniques explained in this paper apply to all rolling element bearings and can provide some information about the condition of sleeve or journal bearings. And, it applies to all bearing manufacturers' products. What is unique is that each vibration data collector manufacturer uses different algorithms in processing the electronic signal generated by the accelerometer. Therefore the results and reliability of other data gathering equipment may not be equal to that used by the author.

The mathematical processing of an electrical signal known as enveloping has been in existence for over 20 years in the laboratory. Only in the past few years, with the advent of portable equipment with sufficient storage and computer power, has the technology been made available to the plant technician and engineer in the field. A simple explanation for the process is that by using selective high frequency bypass filters, it mathematically enhances the repetitive signals generated as the rotating elements pass over a flaw and degrades the nonrepetitive. Then this processed signal is demodulated and presented to the user in the frequency range he desires. Therefore if you have a pump with a bad bearing, the bearing signals, which are repetitive, will be enhanced, while the nonrepetitive flow and possible cavitation noise will be degraded. It is not the purpose of this paper to provide a full mathematical explanation of the process but if the reader is interested, there are numerous other sources available.

DATA GATHERING TECHNIQUES

Just as you hear a sound, which is a vibration, when you run your thumbnail down a comb, rolling element bearings generate a vibration as they roll over a defect in the race of a bearing. If the flaw is on the inner race, it will generate a specific frequency different from the outer race frequency because the relative speed of the rolling elements is different for the two races. (Faster on the inner race than the outer, when the inner is rotating). In like manner, if there is a flaw on the rolling element, it will also generate a vibration although it will be at a different frequency. And it follows that if the cage has a defect, it will generate another frequency. So it is possible that a defective bearing could generate

four specific frequencies, all at the same time, although the author has rarely seen more than two. Experience has shown that a stationary outer race, which is always in the load zone, is usually the site of a "normal" initial degradation location. The inner race is rotating, so the load zone is spread over the entire race rather than at one point as in the outer race.

Common to most modern portable electronic data collectors is the accelerometer. These are generally constructed with a manmade piezoelectric crystal that generates an output voltage directly proportional to the acceleration force applied. The accelerometer is usually placed on the bearing cap, or if not accessible, as near as possible. Since one of the analysis techniques involves trending of vibration levels, it is important that the data collection location be marked and the same location be consistently used each time.

In those instances where it is not possible to safely position the accelerometer by hand, the accelerometer may be permanently stud mounted to the machine and the signal wire terminated in a safe location. Generally the accelerometer will be mounted using a magnet. Both methods are acceptable for general vibration monitoring. In rare instances, a stinger may be attached to the accelerometer to reach a bearing cap located in a tight space, but stingers will alter the signal amplitude and frequency and are not recommended for general usage.

For continuous monitoring of a machine, all the points of interest use a stud or epoxy mounted accelerometer. The signal wires are then terminated at a common point where they are multiplexed and routed to a permanently mounted data collector. The signals from the data collector are then passed to a computer controller that is programmed to store and process the data. One accelerometer signal can be processed into four presentations; acceleration, velocity, displacement, and enveloped acceleration, and these may be processed for different frequency ranges as needed. In other words, the velocity signal may be presented in one spectrum from zero to 30 Hz to check for balance and alignment. A second spectrum may be generated with a range of zero to 1000 Hz to disclose the rotor bar pass frequency, checking for stator damage. In addition, other types of sensors can collect operational data such as shaft position, speed, temperature, flow, pressure, etc. Generally any sensor that provides a voltage output can be monitored. The signal can then be collected and stored for evaluation.

Historically, velocity measurements are used to monitor general machinery conditions and various engineering groups have derived acceptable amplitude limits for warnings and shut downs. Also, it was accepted that slow speed equipment was very difficult to monitor because the signals were usually so low that they would be buried in the data collector's noise floor. There are good physical reasons for this; velocity is the resultant of dividing distance by time. In slow speed equipment, the distance it moves divided by a relative long time results in a velocity of extremely low amplitude. Since we have difficulty measuring velocity, measuring the acceleration enables us to measure the amount of forces being generated inside the bearing. One can apply a force to a machine, which can be measured, but the machine may not move (no velocity). When a rolling element passes over a defect in a bearing, there is a force vector generated. As stated before, these minute repetitive forces are then processed in a manner that allows them to be evaluated with reference to their severity.

Unlike velocity measurements, which are not speed related, the evaluation of an enveloped signal requires knowledge of the rotating speed. "Speed related" means that a velocity reading of 0.35 inches per second (ips) indicates a "rough running" machine, and it does not matter if the rotation speed is 1785 rpm or 3560 rpm. However with enveloped (gE) readings, the speed of the machine is very important. A damaged conveyor bearing rotating at 10 rpm with an amplitude of 0.03 gE would be of concern, where if this reading were taken on a pump bearing rotating at 1780 rpm, there would be no concern.

As will be seen in the section on bearing analysis, comparisons will be shown between measurements using the various methods available, and the value of enveloping is easily seen.

BEARING AND VIBRATION TERMINOLOGY

Bearings are constructed of four parts: rolling elements, an inner ring, an outer ring, and the cage. As previously stated, each of these components will usually generate a unique frequency if damaged. As can be seen in the following frequency calculations, the frequency generated is based on the number of rolling elements, the shaft rotation speed, ball diameter, pitch diameter, and the contact angle. These formulas are provided although all the major data collection software will do the calculations if the user provides the bearing ID, i.e., an SKF 6309 or FAG 22222.

Bearing Frequency Formulas

$$BPFO = (N/2)(RPM/60)(1-Bd/Pd)(\cos\varnothing) \qquad (1)$$

$$BPFI = (N/2)(RPM/60)(1+BD/Pd)(\cos\varnothing) \qquad (2)$$

$$BSF = (N/2)(RPM/60)(1-[BD/PD]^2)(\cos\varnothing) \qquad (3)$$

$$FTF = (1/2)(RPM/60)(1-Bd/Pd)(\cos\varnothing) \qquad (4)$$

where:
BPFO = Ball pass frequency outer race
BPFI = Ball pass frequency inner race
BSF = Ball spin frequency
FTF = Cage frequency

and:
N = Number of balls or rollers
Bd = Ball diameter (in or mm)
Pd = Bearing pitch diameter (in or mm)
∅ = Contact angle, ball to race

These formulas are for the bearing mounted on the shaft and a rotating inner ring. If the outer ring is rotating, reverse the (+) and (−) in the formulas. Another handy rule-of-thumb to use when in the field, the computer is back at the office, and a close approximation is needed:

$$BPFO = (RPM)(n)(0.4) \qquad (5)$$

$$BPFI = (RPM)(n)(0.6) \qquad (6)$$

The first four formulas will give the frequency results in Hertz (Hz). Hz is cycles per second. If you desire them in cycles per minute, (cpm), multiply by 60.

Vibration amplitudes are measured in the following units:

• Displacement (distance) is measured in mils, one mil equals 0.001 inches. Metric measurements are in millimeters.

• Velocity (speed) is measured in inches per second, ips. For metrics, the units are mm/sec. For a quick approximation, 1 mm/sec equals 0.04 ips.

• Acceleration (force) is measured in Gs, for both English and Metric units.

• Enveloped acceleration (derived force) is a special measurement, eG, of acceleration, and there is no comparison or conversion to the standard acceleration measurements.

SIGNAL PROCESSING

Although this paper is not about signal processing, it is necessary to examine some of the characteristics of the process. All the major data collectors receive the accelerometer signal and

either store or display it as a time versus amplitude signal. If one were looking at an oscilloscope, this is the signal one would see, amplitude on the "Y" axis and time on the "X" axis. In order to see this same presentation in the frequency domain, a Fourier transform must be applied. The resultant is a display with the amplitude again in the "Y" axis, but the "X" axis is now displayed as a frequency range that the user can select in either Hz or cpm. For history buffs, Jean Baptiste Fourier was a famous French mathematician who developed the basic theories for signal analysis. One great help in using an enveloped Fourier transform is that not only is the very low signal enhanced by the enveloping process, the transform itself provides positive evidence of the presence of bearing damage.

Although the only place in real life where a pure sine wave exists is in the laboratory, a loaded rotating bearing will generate an approximation. If there is no damage, and the bearing is heavily loaded, the Fourier transform (FFT) will produce a single frequency spike of energy at the bearing BPFO. The process is sensitive enough to detect the minute outer ring movement that takes place as three, then four, then three rolling elements pass through the load zone. If the bearing is not heavily loaded, no signal will be generated, so there will be nothing in the spectrum. However, if there is damage, the sine wave is clipped or truncated. An FFT of a clipped sine wave will result in the fundamental frequency, BPFO for example, plus harmonics of that frequency. The results then are that when the user examines the FFT display, if there is no BPFO signal or if it is present and there are no harmonics, then there is no damage in the bearing. If harmonics of the bearing components are present, there is damage. Then the user has to evaluate these damage indicators based on amplitude and shaft speed. For general machine condition, if the FFT displays multiple harmonics of the *shaft* rotation speed, this indicates looseness in the machine parts and not damage in the bearing.

CASE HISTORIES

Cage Problems

It is all too common to observe at a new construction site, many new pieces of production equipment sitting at various locations covered with plastic or a tarp. They have arrived before the building was completed so are stored in the field. If this occurs over an extended period of time, the end results will be damaged bearings. No matter what time of the year, metal gets warmer in the daytime and cooler at night, producing condensation. When this condensation occurs inside the bearing, trouble begins in two forms. First the hydrogen molecule in the water attaches to metal molecules, resulting in hydrogen embrittlement. Second, the oxygen oxidizes the metal and you have rust. Then several months later when the equipment is installed and activated, loud grinding and scraping noises emit from the bearings. This was the case at a new plant in Richmond, Virginia. They were able to obtain seven of the needed eight replacement bearings from the local bearing shop, but could not locate the eighth from any of the bearing shops in the area. In desperation, they obtained a bearing from a junk shop and proceeded with the installation. When this machine ran, it was vibrating much more than the other three and the author was called in to determine the cause.

He was told that the bearings were SKF 22222s and that the fan speed was about 1600 rpm. Figure 1 is the frequency spectrum collected on the suspect bearing. Using the integral bearing frequency program, the frequency markers for each of the bearing components can be overlaid on the spectrum. What is immediately seen is that the cage frequency (FTF) lines up with an energy spike. For clarity, the other three bearing frequency markers are not shown. The secret to frequency analysis is identifying the sources for the energy seen in the spectrum. In this case, the only thing in this machine that would generate 675 cpm is a damaged cage in an SKF 22222 bearing.
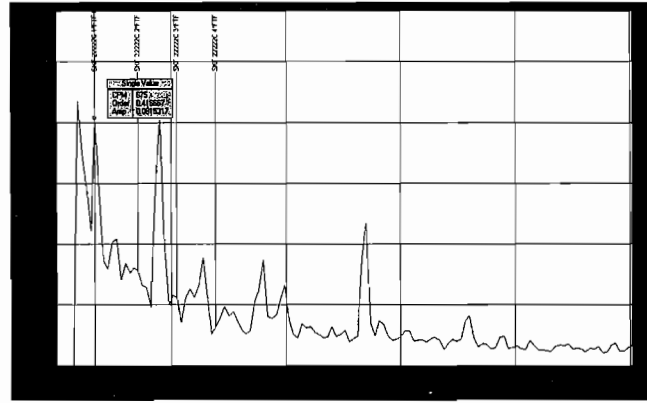

Figure 1. Velocity Spectrum Indicating a Damaged Cage.

Based on this analysis, the bearing was removed and inspected. Figure 2 is a photograph of the bearing showing the damaged cage. Using the serial number on the bearing, it was determined that it was over 21 years old! Sometime during its life, someone had struck the brass cage and deformed it, either during an installation or in removal.
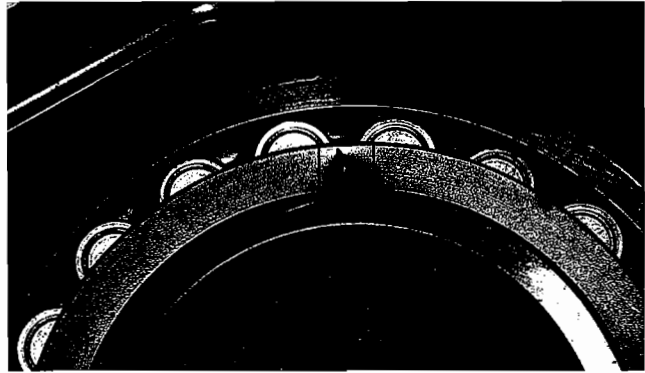

Figure 2. Damaged Cage.

This case illustrates how damaged components are found using frequency analysis. It also points out the need to use care where bearings are purchased, even if under pressure to get the machine back in service. The major bearing manufacturers provide customer training on the care and handling of rolling element bearings. Somewhere in the past, someone had not learned that one should not mount and dismount bearings with hammers and drift pins.

Cracked Inner Race

There are very specific tolerances for bearing fits on the shaft and in the housings. If they are followed, one can expect a long life from the bearings. However, if, as in the next example, shaft fits are not maintained, the results can be disastrous.

If a bearing is loose on the shaft, it will slowly rotate. The friction will generate heat, which in turn will cause the shaft and inner ring to expand. In this case, the shaft expanded more than the ring, to the point where all the fit tolerances were exceeded and then the ring cracked. Figure 3 is the enveloped spectrum collected while the unit was in operation.

The owner said the unit was operating at 1200 rpm and the installed bearing was an SKF 2222. When the author first looked at this spectrum without the bearing frequency overlay, it appears that there were multiple harmonics of the shaft speed, 1203 rpm, which would indicate looseness in the machine assembly. Figure 4 shows the value of further evaluation.
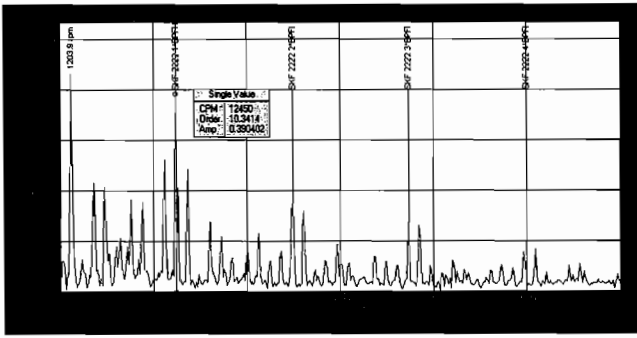
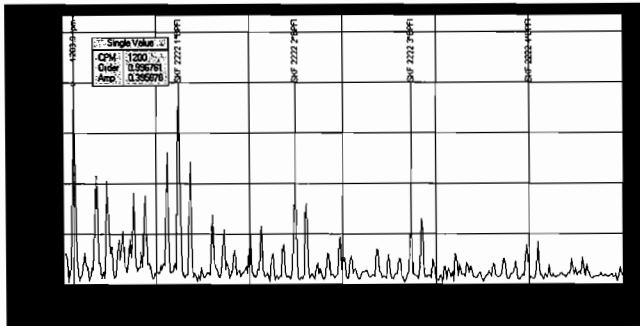*Figure 3. Enveloped Acceleration, Suspect Bearing.*

Figure 4. Suspect Bearing with Bearing Frequency Defect Markers.

The bearing frequency overlay clearly shows that there is a problem with the inner ring. The fundamental inner ring frequency with harmonics can be seen. Inner ring defects have a unique characteristic in that they will almost always produce sidebands of the shaft speed (Figure 5). Using the software, one can overlay sideband markers and see that they are the shaft speed. These sidebands are created by the natural modulation caused by the flaw rotating in and out of the load zone.

With this evidence in hand, the author reported that the bearing had a damaged inner ring and the overall amplitudes indicated a need for immediate action.
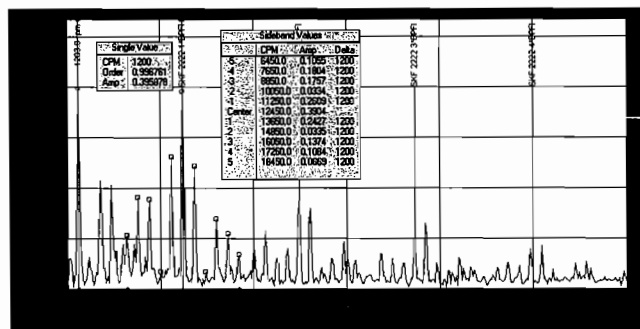
Figure 5. Suspect Bearing with Shaft Speed Sideband Markers.

Figure 6 is a photograph of the bearing. A piece of paper has been inserted into the crack to make it more visible. Proof that the bearing had been turning on the shaft is seen on the inside of the ring. It is scratched, has black and blue heat marks, and is coated with fretting corrosion. Of course this is one of those "which came first" problems, the crack or the looseness. Once the ring cracks, it will certainly turn on the shaft and if it were not scratched and blued before, it soon will be. In any event, the bearing was damaged when first inspected and it needed replacement.
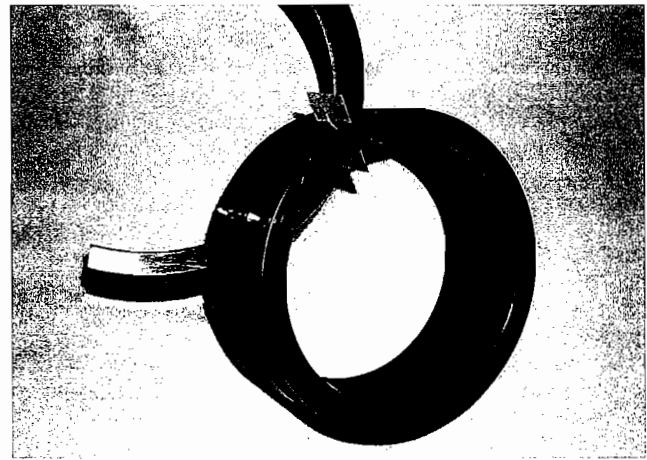

Figure 6. Bearing with Cracked Inner Ring.

Figure 7 is a spectrum taken on the same bearing at the same location and at the same time as those above. The only difference, besides the upper frequency limit, is that the acceleration signal is processed to read out in velocity. Compare Figure 4 with Figure 7. The cursor is placed on the bearing frequency and the amplitude reads 0.0004 ips. No one would ever consider changing a bearing with this low an amplitude, but enveloped acceleration readings show a problem and the visual proof is the photo of the inner ring after it was removed. This should convince anyone that enveloped acceleration is a much more sensitive method of analyzing bearing conditions.
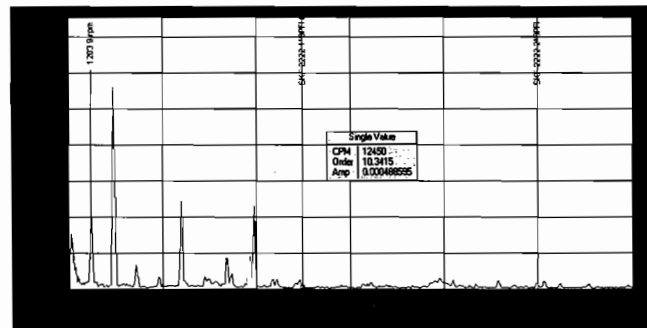

Figure 7. Bearing Velocity Measurement, Cracked Inner Ring.

Figure 6 shows a photograph of the bearing with a cracked inner ring. In black and white the fretting corrosion does not show as well, but the inner surface of the ring should be as clean and shiny as the outer surfaces. A clean, straight across crack is characteristic of over stress caused by an oversized shaft. This is often seen in applications where the shaft is hollow and used to carry steam to the interior of the machine, as in a papermill. If the shaft is not allowed to heat up slowly, so that the bearing ring can heat up at the same rate, the expanding shaft will crack the inner ring.

Damaged Outer Raceway

It is not often that we are able to obtain damaged bearings after they have been replaced. As a matter of fact, it was hard to save the damaged bearings even when the author was the plant engineer. Seems like repairs always take place on the off shifts and by the time you come in the next morning, someone has "cleaned off the bench" and they are gone. In these first few examples, the customer was interested in having a first-hand look and comparing the original assessment with what was found at tear down.

On a cooling fan operating at approximately 1480 rpm, data were collected that indicated possible damage in the outer ring of an SKF 2218, a double row ball bearing. Figure 8 is the velocity

spectrum collected. The amplitude of the velocity measurement for the BPFO is only 0.021 ips but there is a harmonic present. Although there is damage, the harmonic can be seen, with just the velocity reading no action would normally be taken.
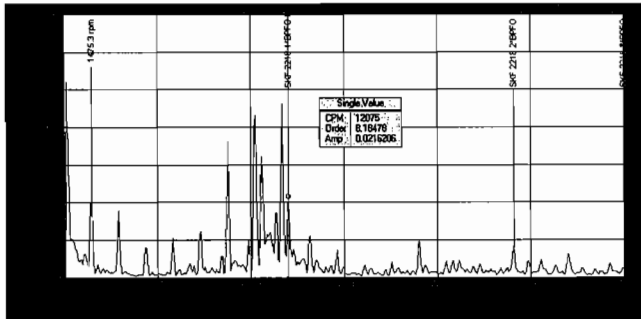

Figure 8. Bearing Velocity Measurement, Cracked Outer Ring.

As in the previous case, another spectrum was collected processing the signal using the enveloped acceleration algorithm. This process only requires the user to press the enter button one more time, and if one wants too, the collection program can be set up so that all the different data parameters from one point are collected with just one press of the enter key. It all depends how the route is set up in the host computer.

This time both the BPFI and BPFO were overlaid to verify that the damage was only in the outer ring (Figure 9). Note that the amplitude of the fundamental BPFO is nearly 1.25 eG. At this rotation speed, any amplitude over 1.0 eG is cause for concern. Figure 10 is a photograph of the damaged bearing's outer race. The photograph only shows two small ball tracks, but examination with a 20× lens revealed pitting and spalling primarily in the load zone but with some carryover around the entire ring. Once spalling begins, the degradation process can be very rapid as the small particles stick to the rolling elements and are imbedded and over rolled throughout the remainder of the bearing ring. At this point, a prediction of remaining bearing life would only be a guess, there are too many variables and any amplitude trends would be approaching a nonlinear function. Again, this is damage that is readily apparent using enveloped acceleration, which would not be of concern using only velocity measurements.
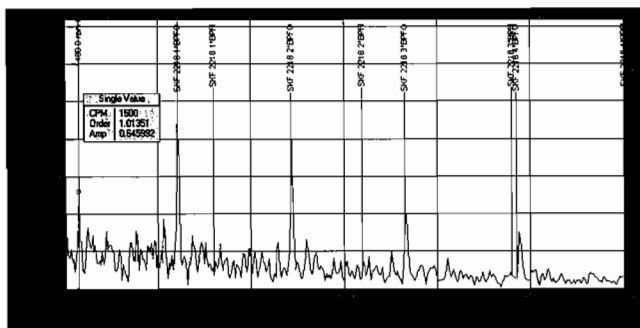

Figure 9. Bearing Enveloped Acceleration Measurement.

Loose Bearing Installation

There are occasions where velocity is the best measurement. If you have ever been in a room where an extremely loud sound is being created, you know how difficult it is to point to the source. It seems to be coming from everywhere. When looseness becomes extreme, the same effect occurs with the accelerometer and what is found with the enveloped signal are a lot of frequency spikes that are somewhat difficult to interpret. Figure 11 is the velocity spectrum of a taper lock bearing that was not only loose on the taper, the taper
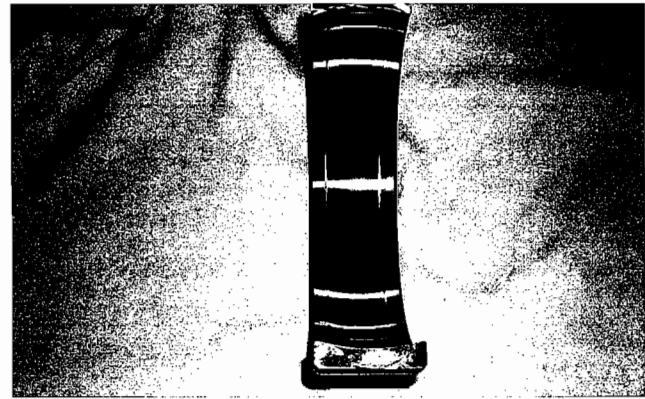

Figure 10. Bearing Outer Ring Damage.

was loose on the shaft. From a diagnostic point, multiple harmonics of the shaft speed are usually an indication of machine component looseness. Note in the velocity spectrum that the fourth harmonic is larger than the others. Generally when the fourth harmonic of shaft speed is larger, it is an indication that the bearing is loose in the housing. Also if the third harmonic is largest, it usually means the bearing is loose on the shaft. Here was a situation where the bearing was reported loose in the housing, when in fact everything was loose.
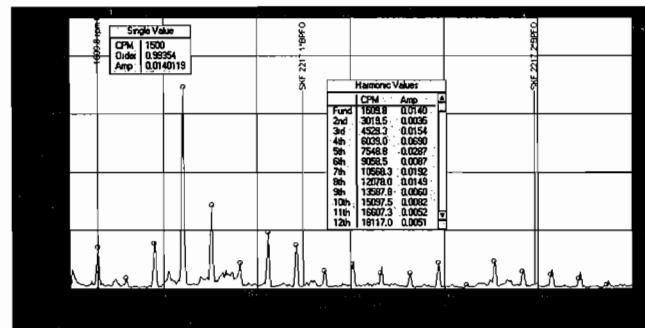

Figure 11. Velocity Spectrum with Multiple Harmonics of Shaft Speed.

Figure 12 is the same location measured with enveloped acceleration. This is a case where the velocity spectrum provides clearer information. It is there in the enveloped acceleration, but so is a lot of other "stuff." And, this is the reason when troubleshooting is done that data are collected using several parameters.
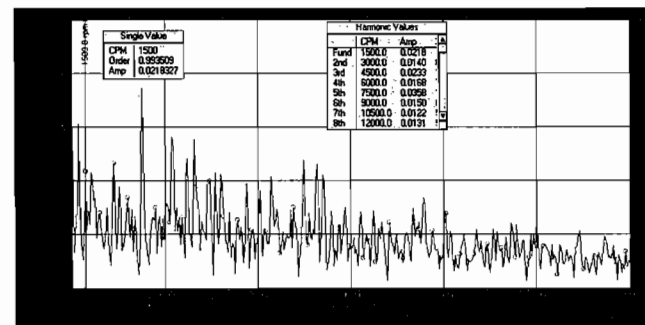

Figure 12. Enveloped Spectrum of Loose Bearing.

When one can look at the bearings, one can see what was really going on when it was in service. Figure 13 is a photograph of the taper. It is scratched and has the fretting corrosion on both inside and outside, physical evidence the taper was loose on the shaft and the bearing was loose on the taper.
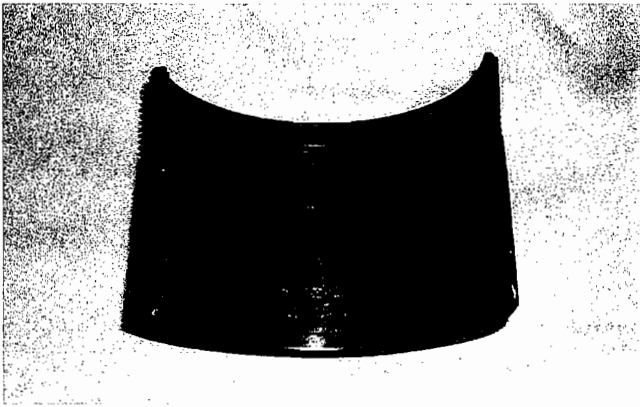
Figure 13. Fretting Corrosion on Taper Lock.

Slow Speed Applications

The most efficient way to reduce the shaft speed from a 900 rpm motor for example, is to pass it through a reduction gearbox. One of the more common applications is on conveyor belts where slow speed is required to move materials. Figures 14 and 15 are velocity and enveloped acceleration spectrums from a reduction gearbox where the output shaft speed is 8.4 rpm. As stated earlier, on slow speed equipment the mathematics of velocity prevent it from providing useful information on bearing conditions.
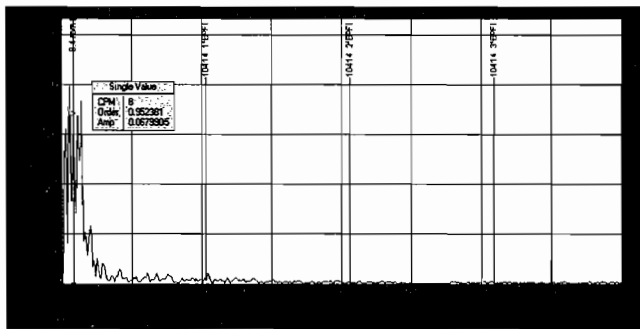

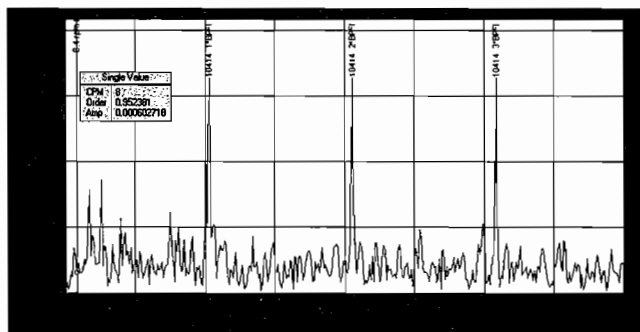*Figure 14. Velocity Measurement at 8.4 RPM.*

Figure 15. Enveloped Acceleration at 8.4 RPM.

The signals at the low end of the spectrum are not valid. When an accelerometer signal is integrated to obtain velocity, the internal electronic noise in the data collector is also integrated, producing a false vibration signal. This is common to all data collectors. The usual practice is to filter out the signal by starting the spectrum at 60 or 120 cpm. In this case, we started at "0" to show where the 8.4 rpm would be.

Clearly there is a problem on the inner race of this bearing. The fundamental BPFI has harmonics and at a speed of 8.4 rpm, the

amplitude of 0.006 eG is severe. From a production standpoint, the replacement time for this bearing is 2.5 days. When this amount of time can be scheduled instead of interrupting production, the operating costs will be reduced. On average, unscheduled repairs cost 10 times the cost of a scheduled repair.

Journal Bearings

Journal bearings, also called sleeve bearings, are best monitored by the use of an oil analysis program. Theoretically, if the proper oil film is maintained between the shaft and the journal, there will never be any wear. In real life, this does not happen. Therefore oil analysis will be the first indication of excessive wear. If the owner does not have an oil analysis program, then the first indication of a problem will probably be an increase in the vibration level at a frequency equal to the shaft speed. As the bearing continues to wear, the shaft will not be properly supported in the bearing and will begin to "bounce around," generating a spectrum with multiple harmonics of the shaft speed. In addition, it has been found that oversize or worn journal bearings will produce these harmonics with the fourth harmonic having a greater amplitude than the others.

Figure 16 is a velocity spectrum of a screw compressor that had been recently overhauled. The overall amplitude was excessive and it was recommended that the machine be shut down and inspected. Although they were reluctant to take it offline because it reduced the plant production capacity, it was fortunate they did because the journal bearing that had been installed during the overhaul was oversize. The male rotor movement exceeded the screw mesh clearances, which could have resulted in a catastrophic failure if it had been allowed to continue.
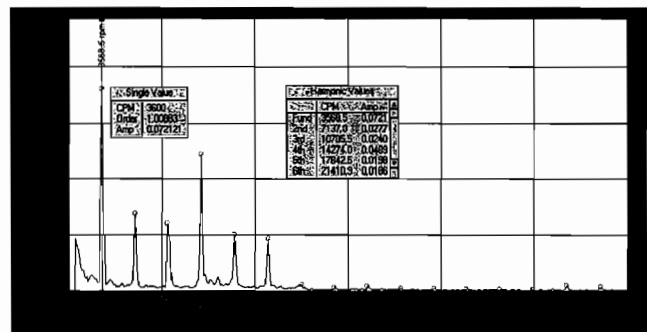

Figure 16. Oversized Journal Bearing with High Fourth Harmonic.

Odds and Ends

The author's experience has been that many times the owner of the machine has no idea what bearings are installed. Usually the machine has been in service many years, with several overhauls by several people and no one wrote down what bearings were used. A helpful characteristic of the bearing fault frequency calculations is that when the contact angle is greater than "0," the multiplier will result in a frequency that is a noninteger multiple of the shaft speed. In Figure 17, the cursor is placed on an unknown frequency spike and the "Order" information in the "Single Value" box tells us it is 7.263 orders of rotation speed. Then the harmonic marker can be placed on this mystery frequency and harmonics can be seen. Based on this information, it would be prudent to do a physical inspection of the bearing. The author has found a number of damaged bearings using this technique. In Figure 17, the bearing had been deliberately damaged by the owner before the author's arrival. He wanted to see if the author could find it among several others in the machine. The author did.

Remember that the computer bearing fault frequencies are calculated based on new bearing dimensions. The bearings being inspected are probably worn and consequently the actual frequencies generated may not fall exactly on the observed frequency.
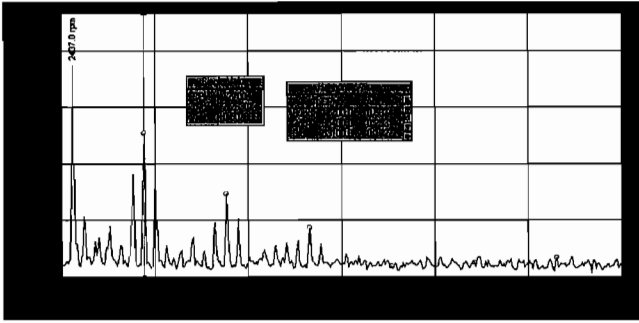
Figure 17. Unknown Bearing with Energy at 7.263 Times Shaft Speed and Harmonics.

The author has found through experience that approximately 90 percent of inner ring failures are caused by poor installation techniques. When the bearing is placed on the shaft by pushing on anything but the inner ring, damage will occur. Force on the cage will damage the cage and push the rolling elements against the lip of the races, causing damage to the rings. Even if the damage does not affect the machine operation, it will result in noisy bearings.

Care should be taken to prevent water from entering the lubrication. One percent water in the lube system will reduce the life of the bearing by 90 percent.

And finally, over 60 percent of machine failures are caused by the loss of the rolling element bearings. Why? Because of misalignment! Other than thrust bearings, rolling element bearings are designed to carry a radial load. When misalignment occurs, an axial component is generated. When this becomes excessive, the bearings begin to fail. Probably the one procedure that would save the most money in any maintenance department would be to improve the alignment methods. For this, laser alignment equipment is strongly recommended, a straight edge just does not do the job.

CONCLUSION

Any technology or methodology that will provide better information about the condition of machine bearings will enable more efficient operations to be conducted. This efficiency will be seen in better scheduling of overhauls, a reduced overtime budget, an increase in time between failures, and an increase in production. Whether it is publicly or privately owned, the usual purpose of operating a business is to make a profit. Knowing the condition of bearings will provide the information needed to increase those profits.