Application Note

Monitoring of Slow Speed Bearings Using the SKF Microlog CMVA 60 ULS (Ultra Low Speed)

By Dr. Bob Jones • SKF

Abstract

With the advent of Enveloped Acceleration, it is possible to monitor the operation of slow speed equipment and its rolling element bearings. For purposes of this paper, we will consider slow speed to be anything rotating less than 100 r/min. The author has collected and analyzed the condition of bearings in a range from 0,1 to 8,3 r/min with satisfactory results. This involves the use of the time domain as well as the frequency domain. This paper will discuss techniques for setting up the data collection and give examples collected in the field. With the release of the SKF Microlog CMVA 60 ULS (Ultra Low Speed), slow speed equipment may be monitored, in velocity, down to 6 r/min. Examples will also be shown using this equipment.

Introduction

Monitoring of slow speed equipment bearings is a mixture of engineering and art. Some would say it is black magic and just let it go at that, but in fact it is a finely tuned engineering process that relies on some of the latest electronic processing technology. This technology allows us to enhance the extremely low level signals generated by the bearing rotating elements as they make contact with a damaged area of the bearing ring or cage. In the past, we used the measurement of velocity to attempt to analyze the condition of slow speed bearings. Sometimes we were successful and sometimes we were not. Everyone in this business can probably recall a horror story where, after carefully monitoring a bearing over a period of several weeks and declaring it to be in acceptable condition, have it fail shortly thereafter. The weakness of using a velocity measurement for bearings is in the mathematics.

Fig. 1. SKF Microlog CMVA 60 ULS (Ultra Low Speed) data collector.

Mathematically, velocity is a product of dividing distance by time, V = d/t. This gives you inches per second, millimeters per second or miles per hour, whatever units you wish to use. In any rolling element bearings, the “d” is a very small number, in the order of 0,0005 in. or less. If the time element is relatively large, 0,5 seconds for example, this would result in an element velocity of 0,001 IPS.

In large machinery, as in paper mills, screw conveyors or large slew bearings, the bearing elements do not have a large mass relative to the machine. The velocity generated has to be transferred to the bearing housing and it is like tapping on it with a tiny hammer, the bearing housing movement is even smaller and the vibration measurement probe just doesn't detect it. In laboratory work, we have taken velocity measurements on severely damaged bearings that would have to be replaced in an operational environment. The readings we obtained on these damaged bearings was in the order of 0,0027 IPS, at 1 770 r/min! Certainly not an amplitude that would cause concern, and yet we knew the bearings needed replacement.

We can see then that at the site of the damage, the elements just don't have enough distance to develop any velocity (speed) or mass to transfer an energy pulse that is consistently measurable with any portable data collector. This does not say that one can never see a bearing problem using velocity, but our experience has been that when you can see it in velocity, you are already in trouble and probably have been for awhile, you just did not know it.

This means that we need another method to measure what is happening inside the bearing while it is in service. Using proprietary algorithms, SKF Condition Monitoring has produced in the CMVA 55 and the CMVA 60 SKF Microlog data collectors instruments that have the ability, by using enveloped acceleration processing, to detect initial damage in rolling element bearings that are of a size that literally cannot be seen without magnification.

Enveloped acceleration (gE)

Before we examine case histories of slow speed equipment, it is important that we understand why and how enveloped acceleration is a superior method for analyzing bearings versus using velocity measurements. We will do this without delving into the specific mathematical algorithms and electronic methodology that is used in the process.

If we recall our high school physics, we remember that F = MA, force is equal to mass times acceleration. Of these three units, we can measure the acceleration using an accelerometer. If we arbitrarily set the mass to equal one, then the force is equal to the acceleration and we now have a method to measure the forces occurring inside the bearing. Therefore, what we will be measuring is the repetitive forces generated as a rolling element impacts a flaw or damaged site inside the bearing. If we attempt to measure this force with standard acceleration (G's), we will be attempting to capture a single event of such small amplitude that, as with velocity, may not be observable.

In a nut shell, enveloping allows us to enhance the repetitive signal produced as a bearing element passes over a damaged area in a bearing and degrade the non-repetitive signals. This is accomplished by using one of four specific filters to capture the harmonic energy in the range of that filter.

After this capture, the energy is electronically processed to provide the enhanced signal by mathematically summing these harmonic signals. Since the user has set up a specific frequency range to examine, this captured energy is then demodulated and presented to the user in the frequency range selected. Please note that there is no connection between the specific filter range selected prior to the data capture and the frequency range selected for the displayed spectrum.

Figs. 2 to **4** illustrate the four filters and how the flaw generated energy "moves" around and may be detected better in one filter today and another next month. It may be in all four filters, but probably one will show it better. These examples do not show the overlap between filters, e.g., the first filter ends at 100 Hz and the second filter begins at 50 Hz., but are satisfactory for this depiction. The data has since been lost, but we once examined a 27 r/min machine where we had a good bearing defect signal in each of the four filters; the choice is yours.

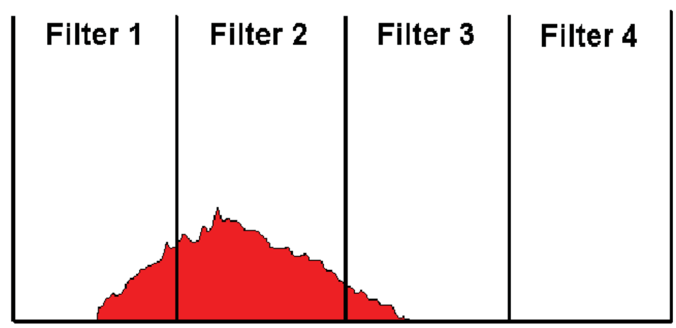

Fig. 2. A possible energy location for slow rotating bearing with flaw.

If this is where the energy is located, then it would be possible to display a spectrum using the first three filters, but the best choice would be to use the second filter because that is where the most energy is located and will produce the best spectrum.

In the case shown in **fig. 3**, the best choice would be filter 3, since that is the filter that would capture the most energy and produce the best spectrum.

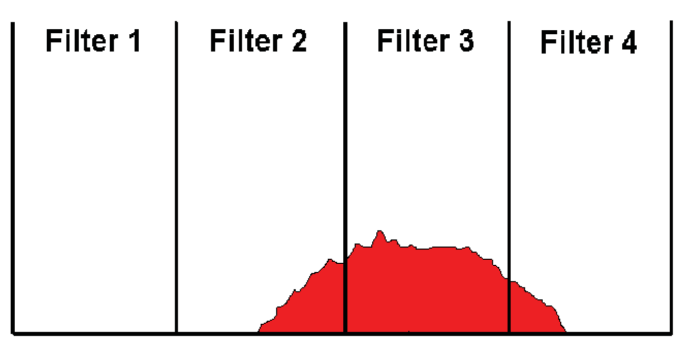

Fig. 3. Another possible location for the energy from the same bearing in fig. 2.

The example in **fig. 4** would be a case where you could use any of the first three filters and even the fourth filter will produce a spectrum. This could be an example of the machine that was rotating at 27 r/min and produced acceptable bearing flaw signals using any of the four filters.

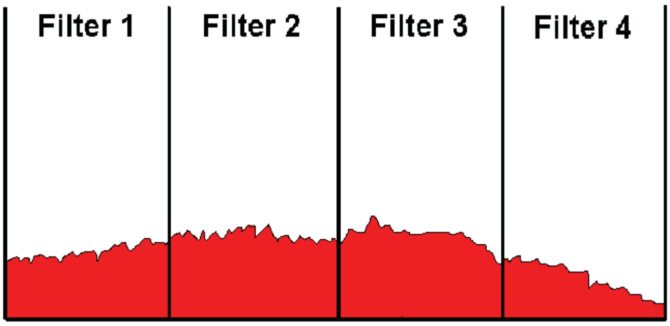

Fig. 4. A slow rotating bearing with energy in all filter ranges.

It is mandatory in collecting vibration signals from slow speed equipment that the user save the time domain spectrum. The data collector has already produced one in order to convert it into the frequency domain using a Fast Fourier Transform (FFT). The user only has to setup the point to save the information. In one example we will look at later, the bearing is rotating at 0,5 r/min. The bearing race defect frequency was calculated to be 6,9 CPM, which means that a roller passed over the flaw every 12 seconds, or five impacts for the 60 seconds it took to collect the 500 CPM spectrum. In the frequency spectrum, it is not possible to see the defect frequency, and due to time constraints, we could not decrease the Fmax or increase the number of lines for improved resolution. The solution is in the time domain, as will be shown.

In the early development and testing of the enveloping process, the criteria for selecting which of the four filters to use was based on the rotating speed of the machine. These criteria are still valid for machines operating above 500 r/min, but experience has shown us that when analyzing slow speed equipment, the rules have to be modified. For example, with the 0,5 r/min machine, using early guidelines, we would have selected the first filter with a range of 5 to 100 Hz. If we had only used that one filter, we probably would have missed the call. The filter that displayed the best results was the third filter, 500 to 10 000 Hz. However, on other similar occasions, it has been seen that the first filter was the best to use. And recently with equipment at 2,4 r/min, the best filter to use was the second. This experience leads to the conclusion that with slow speed equipment it is necessary to collect three readings for each bearing, each reading using a different filter. After it is determined which filter is providing the best spectrum, the data collection setup should be used and the other two disabled. However, if over time the signal changes with either an increase or a decrease in amplitude, the disabled points should be enabled and another evaluation conducted.

Laboratory testing disclosed the reason for this shifting. Early on it was assumed that slower speeds would generate lower frequency signals, and as the speed increased, the energy would move upward to the higher frequencies. This has proven not to be the case in all situations. At 0,5 r/min, the energy was clearer in the 500 to 10 000 Hz range (third filter) than it was in the 5 to 100 Hz range (first filter).

However, that was confirmed only for that day and that damage site. Further damage may cause the clearest energy to move to a lower or higher frequency. Therefore, for plant personnel it is imperative that they plan on multiple readings for critical slow speed bearing.

Fig. 5 is a typical setup screen for collecting enveloped acceleration readings. The important points to note are the filter selection, FFT and time selected, one average and the start frequency set at "0". It is possible to set the start frequency at "0" because you are using an acceleration signal and there is no integration to produce the ski slope that is seen and influences the overall amplitude in velocity.

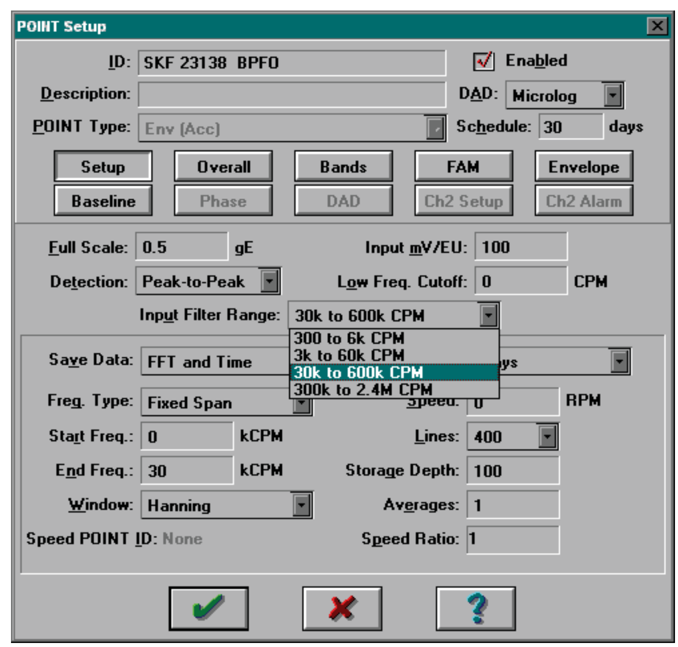

Fig. 5. Typical setup screen for enveloped acceleration.

In addition to learning how to look for the energy, the user needs to understand some of the characteristics of an enveloped spectrum. We are all familiar with the widely published alarm limits for velocity measurements: alarm 1 is generally 0.25 IPS and alarm 2 is 0.35 IPS. And importantly, these are not speed dependent. In other words, these alarms apply to a machine operating at 600 r/min as well as the machine operating at 3 600 r/min. It is mandatory that the user understand that this is not the case with enveloped measurements. The rolling elements inside a machine rotating at 100 r/min are going to generate significantly less energy, because less forces are present, than the elements from a machine rotating at 3 600 r/min. Therefore, the user is required to associate the speed with the observed amplitude.

This point is illustrated in **fig. 6**. Again in the laboratory, using a DC motor, a flaw was induced in the motor bearing. With the speed set at 50 r/min, the amplitude of the enveloped reading was 0,004 gE. As the speed was increased, the amplitudes can be seen to increase to the point where at 3 600 r/min, the amplitude had increased to 1,8 gE. That is an increase from low to high speed of 450 times, all from the same flaw. Clearly the user has to consider the machine speed and be careful not to apply limits to Machine A that were developed for Machine B that operates at a different speed.

At this point, we have selected a bearing to monitor, built three points using each of the three filters with the time waveform saved, assigned the bearing to the point and are ready to go collect some data. Once you have the data, here is what to look for.

From the bearing defect frequency data base, you should be aware of what frequencies you are looking for. But, in many cases, you will not be able to know for certain what bearing is installed because the machine has been overhauled numerous times and no records have been kept. On the basis that a good engineering guess is better than no information at all, do the following: look in the frequency spectrum for harmonic signals. Harmonic content in the frequency spectrum tells us that the energy from the time wave is being clipped or truncated. A Fourier transform of a clipped sine wave will produce harmonics. If there is no damage, there is no clipping and no harmonics. Therefore, if we have harmonic energy that is not associated with such things as rotation speed, gear mesh or twice line frequency, we are probably seeing energy from a damaged bearing.

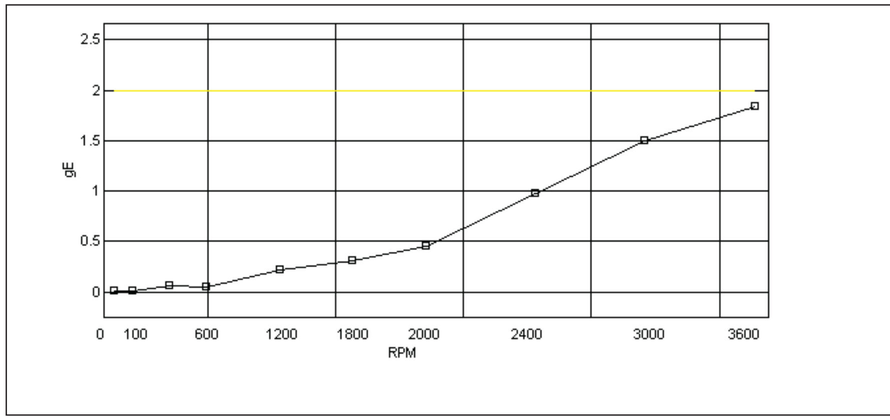

Fig. 6. Increase in gE amplitudes with increase in speed, constant size outer ring flaw.

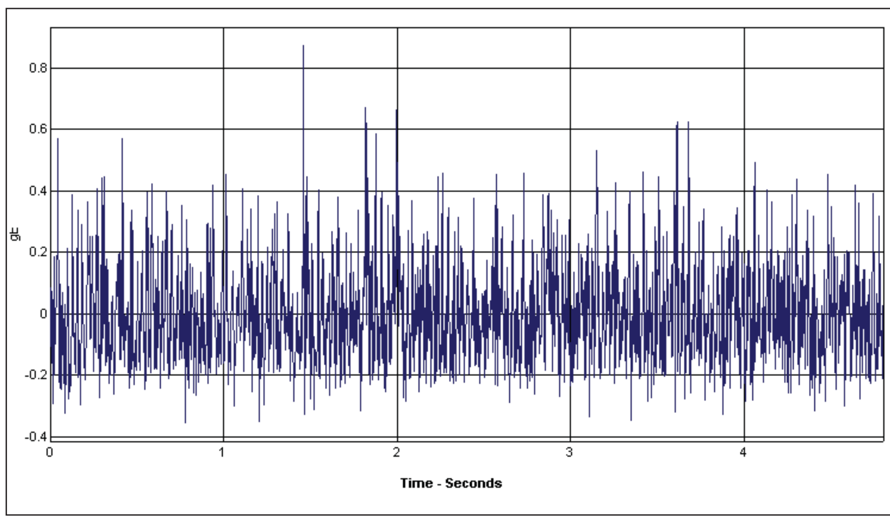

Fig. 7. Typical enveloped time domain spectrum of damaged bearing.

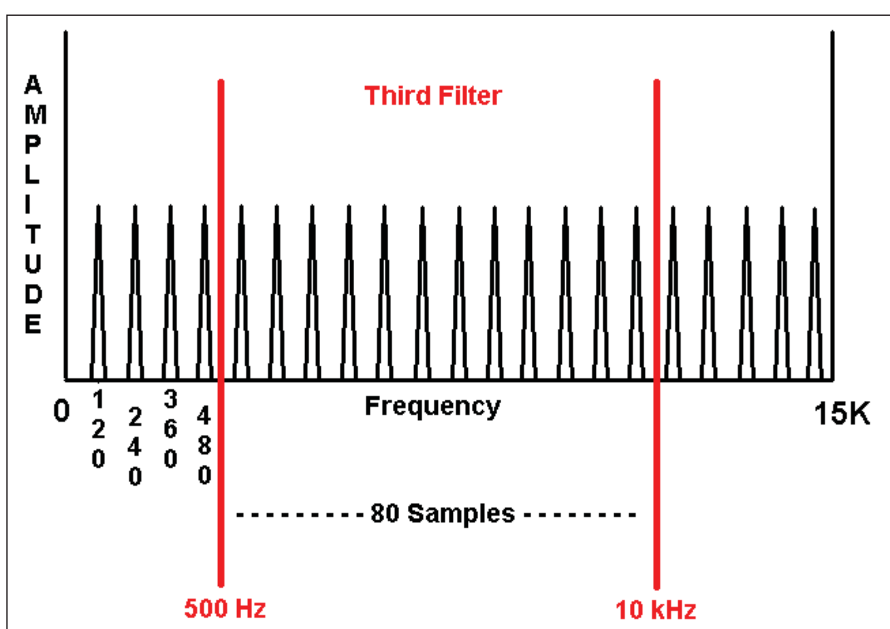

Fig. 8. Envelope processing.

The envelope process, non-technically

We have discussed the filters and the energy they capture. Now we will examine how this energy is processed to provide us the spectrum used for evaluation. Although the time domain (→ **fig. 6**) has time as the "X" axis, the algorithms enable the data collector to select the desired filter frequency range data from this time information. The Fmax was set to 80 Hz in order to collect five seconds of data. If you need more time, the Fmax is reduced. If less time is needed, the Fmax is increased.

Fig. 7 is a representation of what is happening inside the data collector in processing this energy into the enveloped spectrum based on using the third filter, which has a range of 500 to 10 000 Hz.

The filter has now assembled, out of the collected data, the harmonic content of the energy being emitted from the bearing.

In the **fig. 8** example, the bearing has a fundamental frequency at 120 Hz. The harmonics then follow out to the limit of the accelerometer, although we cut it off at 15 kHz. The filter has captured 80 harmonics, which are then mathematically processed to produce an enveloped spectrum similar to the next example that is from a damaged paper roll bearing turning at 88,5 r/min.

To continue the process with another spectrum, we see in **fig. 9** what appears to be multiple harmonics. Using "Set Speed", mark the rotating speed of the shaft exactly as possible; this is 1X. Then set the single cursor on the first harmonic and observe how many orders of running speed are shown in the "Single Value" window. If the orders shown are a non-integer number, e.g., 6,532 or 4,575 orders, you probably have a damaged bearing. The reason for this is in the mathematics of calculating bearing defect frequencies. It is not true in all cases, because some defect frequencies will be seen to be 4,012 or 5,991, so close to an integer that this evaluation is not valid. It is also not valid if you are working with a gearbox with multiple internal shafts. However, we have called bad bearings based solely on the order information when the owner did not know what bearing was installed.

Fig. 10 is a spectrum from a recently rebuilt 500 HP with a variable frequency drive motor turning a screw mixer at 674 r/min.

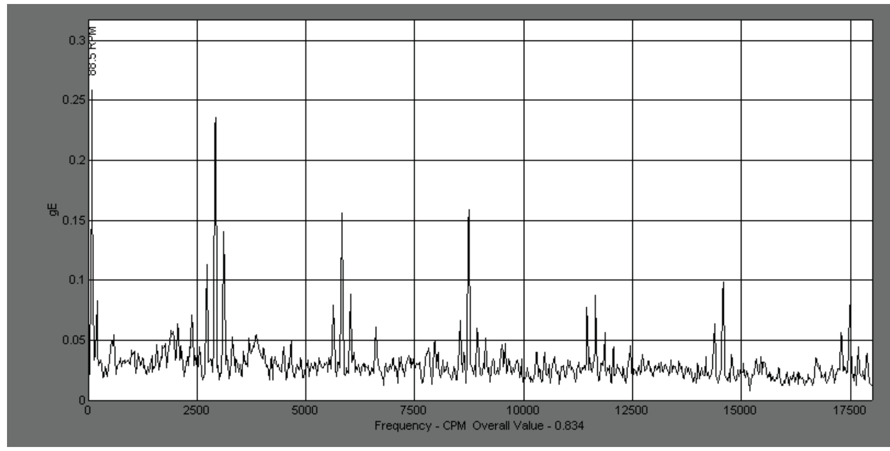

Fig. 9. Final product, the enveloped spectrum showing possible bearing damage.

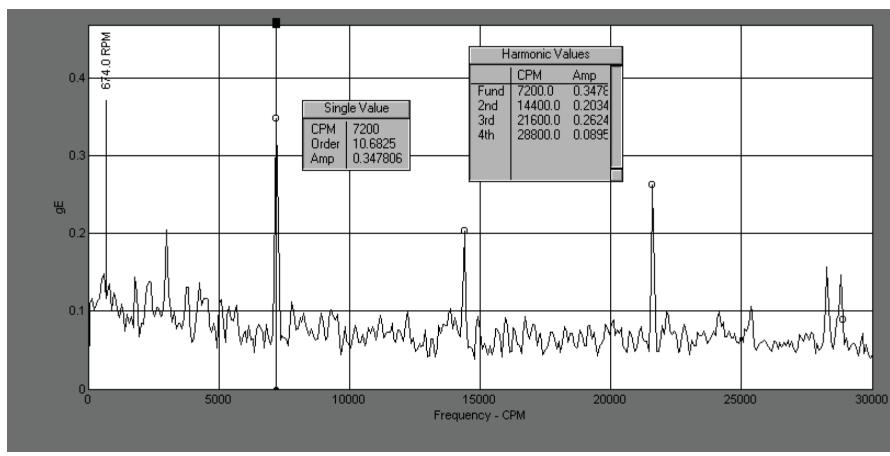

Fig. 10. Spectrum of unknown bearing with fundamental frequency at 10,6825 orders.

The frequency spectrum, with harmonics, and the first harmonic at 10,6825 orders of shaft speed led to the call of a bad bearing, although at the time the owner did not know what type of bearing was installed. The motor shop, using velocity measurements, did not agree, but the owner insisted. When the bearing was pulled, the damage was found. Apparently on installation, the installer had slipped and damaged the lip of the inner ring. As the rolling elements passed over the area, the inner race defect frequency (BPFI) was generated. Score one for the good guys.

Now some of you sharp eyed readers are going to notice that the CPM in the Single Value window is 7 200 CPM and will say that is twice line frequency and indicates an electrical problem in the motor stator. There is another thing you check for in cases like this. When you use the "Set Speed" marker, place it on the first harmonic and check the exact frequency. Remember the single cursor goes from line to line and this frequency is between lines. "Set Speed" check showed it to actually to be 7 211 CPM, too high to be an electrically induced problem. When we examine some slow speed bearings, you will see similar examples using the orders as a clue.

There is a characteristic of enveloping that will often give us a problem when we are trying to use the "Set Speed" and mark the 1X on an enveloped spectrum. The enveloper is looking for harmonic content. If the unit is well balanced and there is no looseness, the rotating forces will not generate any 1X forces and will not display a clear peak at the rotation speed. Even if the unit is unbalanced, the once per rotation out of balance forces do not generate harmonics. So the question is: How do we know where to mark the rotation speed on an enveloped spectrum? The solution is to also collect a high resolution velocity spectrum immediately after collecting the enveloped spectrum. All rotating equipment has some out of balance forces that can be seen in the velocity spectrum. Put the cursor on this 1X signal, use "Set Speed" and determine the exact speed. Return to the enveloped spectrum and again open the "Set Speed" window. Type in the exact speed from the velocity spectrum, hit the green check mark and this speed will be marked on the enveloped spectrum at 1X, irregardless of the position of the cursor.

Some examples of this technique are shown in **figs. 11** and **12**.

Taking the original spectrum, we have added in **fig. 13** the harmonic marker, the rotation speed as determined from the velocity spectrum, and displayed the "Set Speed" window with the cursor on the suspect frequency. Here you can see what we discussed earlier, the cursor is on the line at 7 200, but in actuality is at 7 210,6 CPM. And the "Single Value" window shows the orders at 10,6825. In this case, since the motor had been rebuilt recently, we did know the bearings that were installed so to seal the inspection, the next spectrum is with the bearing frequencies (BPFO) overlaid.

One point needs to be noted here. This was a fairly new bearing and so does not have any significant wear. Therefore, the bearing frequency overlays match up very well. This may not be the case when you are testing old, worn bearings. The Frequency Analysis Module (FAM) contains frequencies for new, perfect bearings. If the spectrum is from a worn bearing, it is probable that they will not match up as in this example. The answer is to also use the other information you have to arrive at a conclusion; don't use just the overlays.

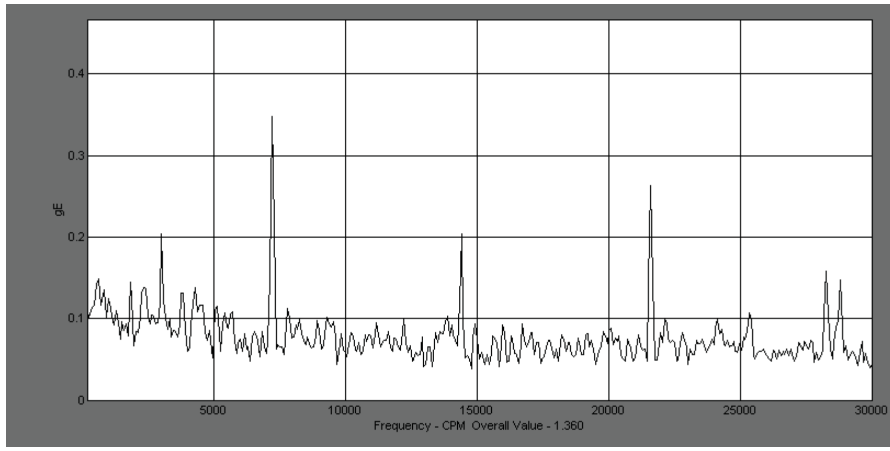

Fig. 11. Initial spectrum with what appears to be harmonic content.

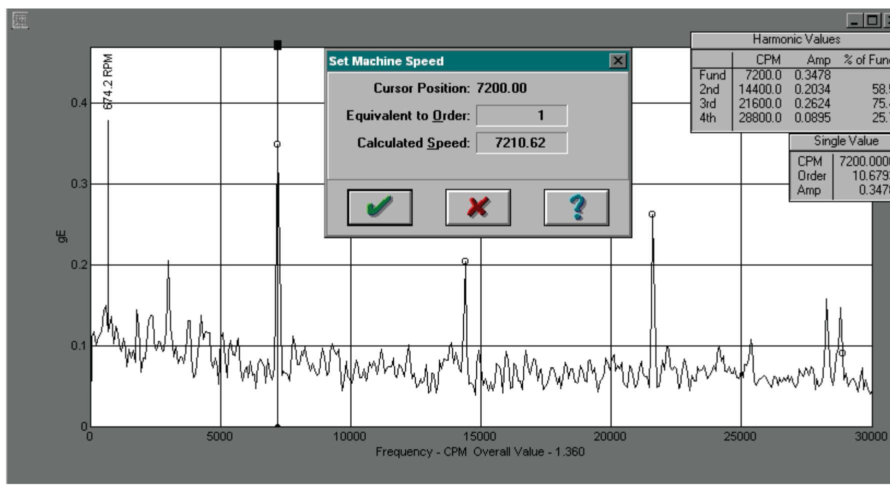

Fig. 12. Initial spectrum after processing and annotating the exact harmonic frequency at 7210,6 CPM.

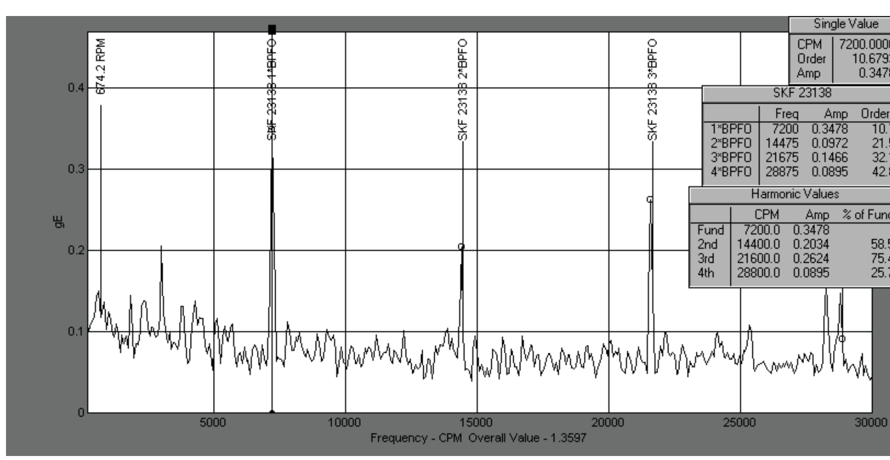

Fig. 13. Final results of process and analyzed spectrum.

Slow speed applications

A major automobile parts plant produces diesel engines. The production line is moved by four very large gear drives with an output shaft speed of 8,3 to 12,0 r/min. The output shaft bearings were a constant maintenance problem in that they were internal and on the bottom of the gear case. Although the plant has an excellent vibration monitoring program with numerous “saves” on other equipment, this particular gearbox would fail without warning, causing a three day unscheduled outage for replacement. The automotive business operates on a “just-in-time” assembly basis, so they were required to maintain in stock a three day supply of engines to ship while the repairs were made.

We demonstrated to them with the following spectrums just what enveloped acceleration could do for them in monitoring slow speed bearings. As part of the demonstration, we collected three readings: acceleration, velocity and enveloped acceleration. The spectrums speak for themselves (→ **fig. 14**).

We overlaid the inner race defect to show that although there may be a slight amount of energy at these frequencies, not many people are going to push for action with an amplitude of 0,00005 G’s!!!

The velocity spectrum (→ **fig. 15**) shows us nothing of concern. And this was their problem, they had a large amount of velocity data that did not show them anything of value. As will be seen in the enveloped spectrum (→ **fig. 16**), there is damage in this bearing, but there is nothing of concern showing in the velocity measurement.

There was a speed change to 11,1 r/min, but as can be clearly seen, there is harmonic activity and the FAM overlay aligns very well to show us that there is damage in the inner race. One of the first comments made was that the amplitudes are too low to worry about. This is not true. Return to **fig. 6** and note that this amplitude 0,006 at 11 r/min would be probably be equal to 1,5 to 2,0 eG at 3 600 r/min, certainly a cause for alarm. We knew the bearing that was installed, but our first clue was while collecting the data we saw the apparent harmonic signals.

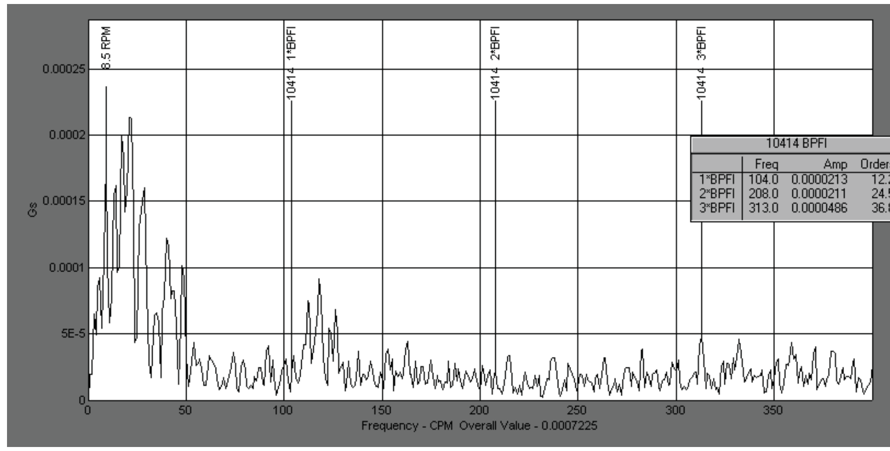

Fig. 14. Acceleration spectrum.

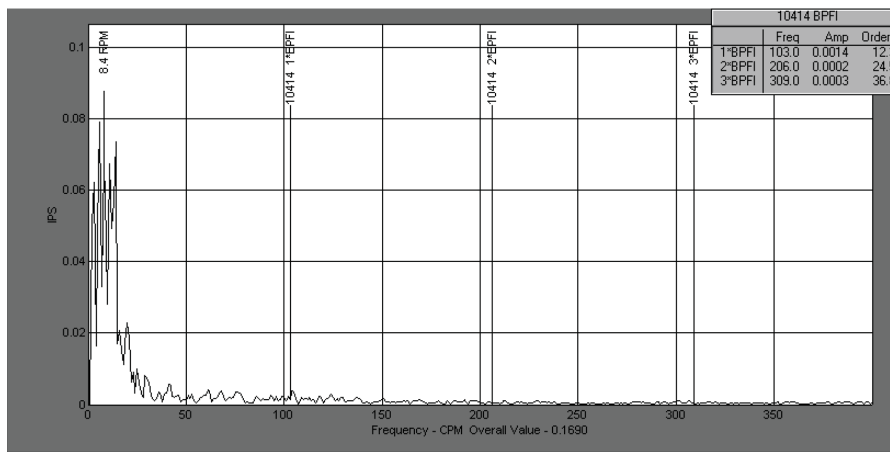

Fig. 15. Velocity spectrum.

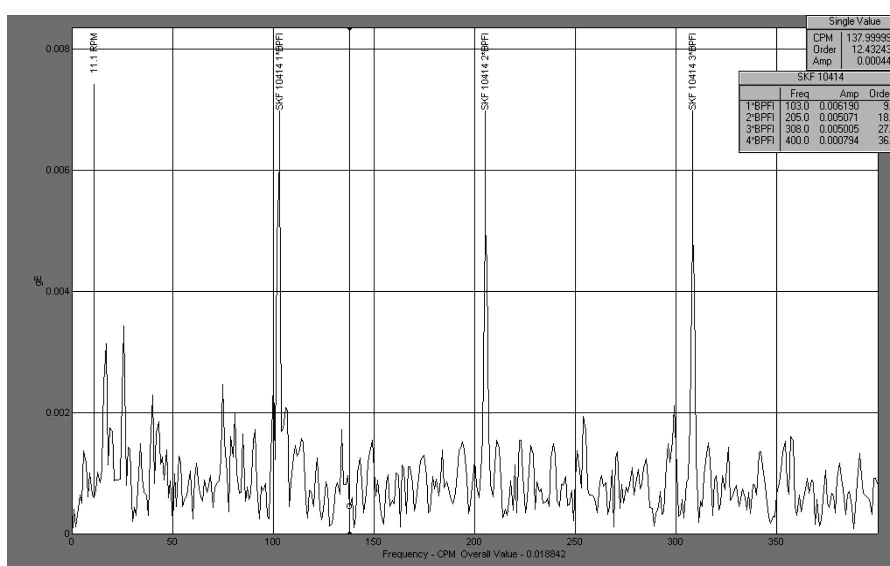

Fig. 16. Enveloped acceleration spectrum.

This large gearbox had other bearings of course and, for comparison purposes, we collected data from another bearing, which based on the harmonic content, appeared to have damage. With the application of the bearing frequency overlay, it appeared there was in fact damage on the outer race (→ **fig. 17**).

A follow up report told us that they had found both bearings to be damaged as detected with the enveloped acceleration spectrums (→ **fig. 18**). In all cases, the two most important items to look for is the harmonic content and the non-integer order of rotation speed. Then if the bearing information is available, use the overlay function, FAM, to confirm your data.

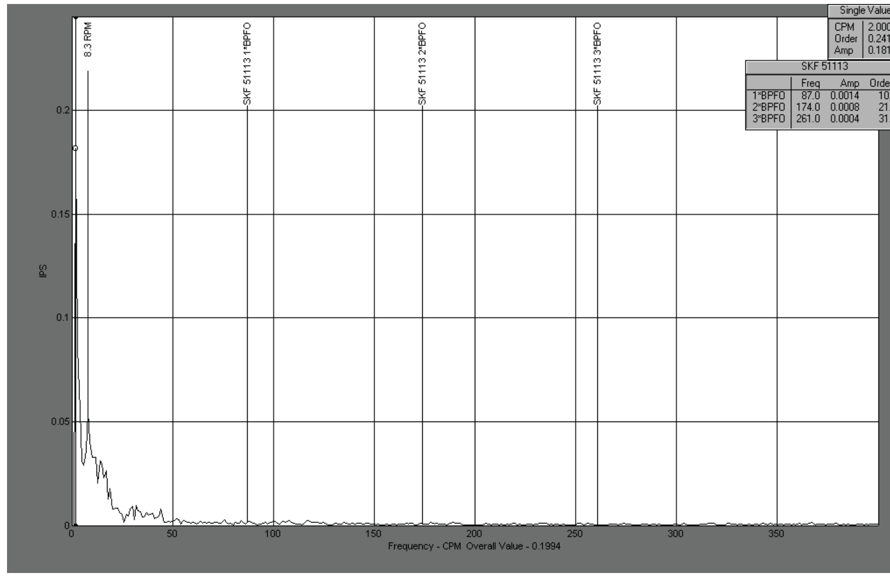

Fig. 17. Velocity spectrum.

Slow speed analysis using time domain

With very slow rotating equipment, such as in paper and steel mills, large slew bearings and cement kilns, there may not be enough energy generated to produce a signal in the frequency domain. In these cases it is possible to detect bearing flaws in the time domain.

What is necessary is to collect a spectrum of long enough duration so that the rolling elements pass over the flaw five or six times. Sometimes the mechanics of the machine will not allow a full 360 degree rotation, such as a radar azimuth bearing, and in those cases, it may not be possible to collect enough data for a frequency or time analysis. In those cases, it is necessary to use amplitude trending. The Fmax is set so that the time span in the time domain is large enough so that data is collected while the unit is moving and ends prior to the machine stopping.

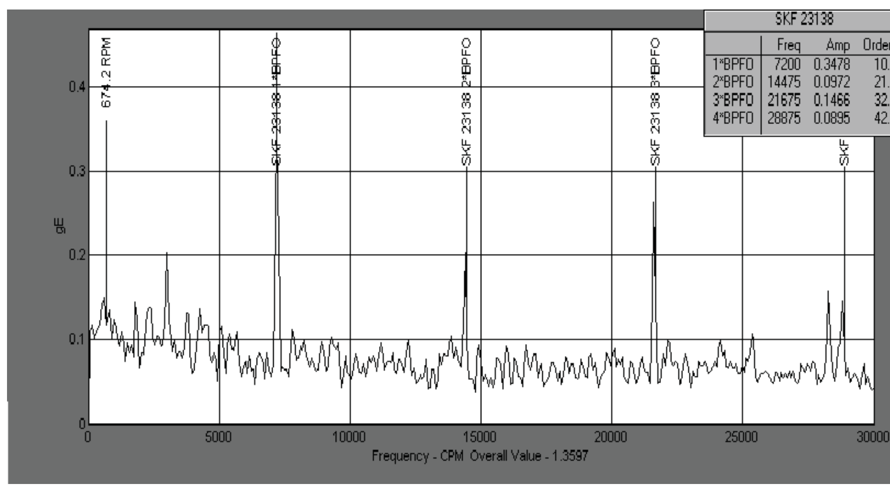

Fig. 18. Enveloped acceleration spectrum.

In a small steel mill, trending of the overall amplitude in acceleration had resulted in a steady increase in the slope of the curve, but there was no indication of specific damage. The bearing frequency for the outer race was calculated to be 6,9 CPM at the 0,5 r/min rotation speed. Using enveloped acceleration, the following time domain was collected (→ **fig. 19**). What we are interested in are the bursts of energy that appear in the spectrum. By using the harmonic markers and placing each one approximately in the middle of a burst of energy, the time interval between bursts is measured, and since frequency is a reciprocal of time, it also provides a frequency. In this case, the frequency is determined to be 6,8 CPM, close enough to the calculated frequency to call it as the flaw and source of the detected energy. What is occurring is that as a rolling element passes over a flaw, the burst of energy is created and the time between bursts gives us the frequency.

The question may arise concerning the lack of signal for the first 12 seconds or so. When the bearing was removed, it was found to be distorted because the expansion assembly had locked and the heat expansion had to go somewhere. It distorted the bearing so that the rollers did not always make contact with the race.

When they did, we got the burst of energy; when they didn't, no signal. We checked the signal using all three filters and this data was collected using the third filter.

The same signal in the frequency domain produced this spectrum (→ **fig. 20**).

The alternative to doing this of course is to set the Fmax to about 100 CPM, but this would have required four minutes of data collection and we could not rotate the vessel for that long.

For comparison, the final two spectrums are from a similar vessel with new bearings (→ **figs. 21** and **22**).

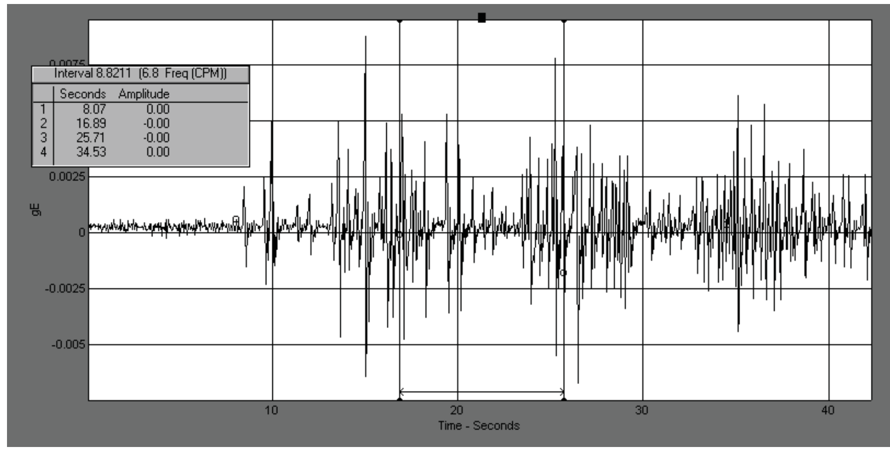

Fig. 19. Time domain of damaged ladle bearing vessel #1.

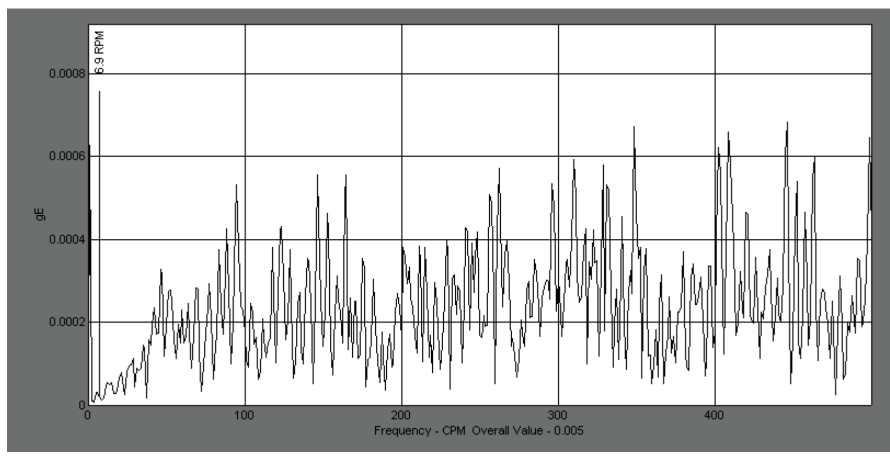

Fig. 20. Frequency domain of damaged ladle bearing vessel #1.

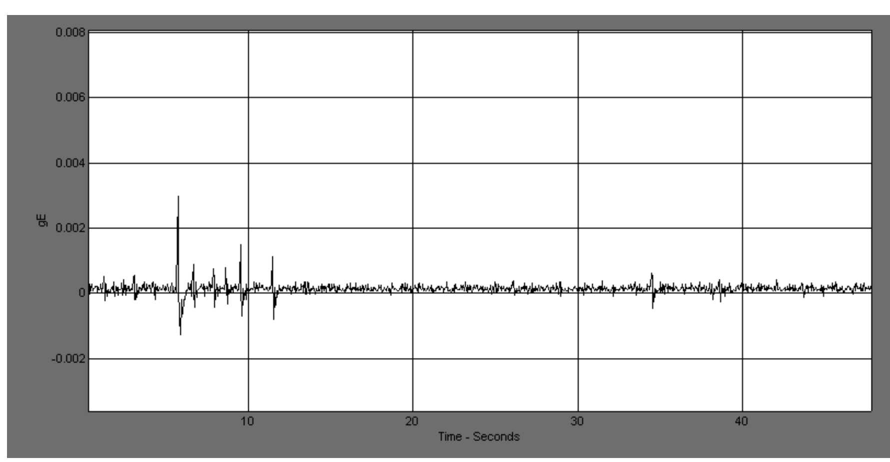

Fig. 21. Time domain of new bearing on vessel #2.

Conclusion

Enveloping of the acceleration signal is the best method available today to analyze bearings. It does require care in the application of the procedures, as with any technique using computer technology (garbage in, garbage out). And the author can speak from experience!

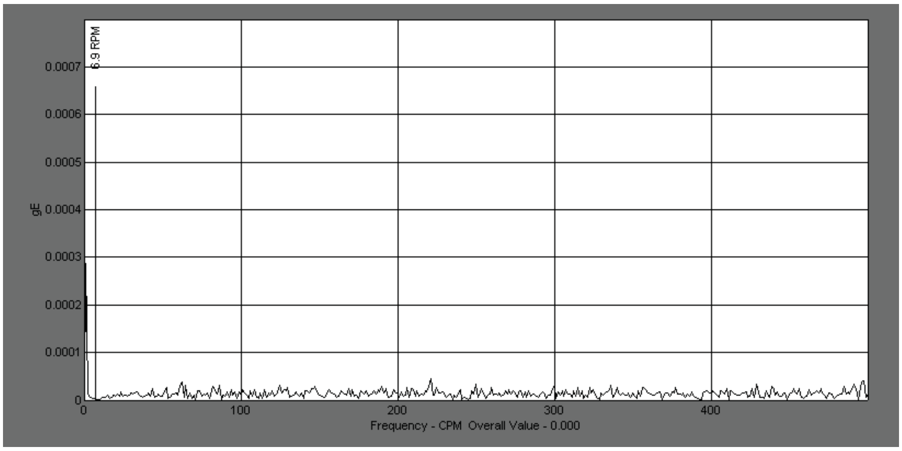

Fig. 22. Frequency domain of new bearing on vessel #2.

Please contact:

SKF USA Inc.
Condition Monitoring Center – San Diego
5271 Viewridge Court · San Diego, California 92123 USA
Tel: +1 858-496-3400 · Fax: +1 858 496-3531

Web: www.skf.com/cm

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