Enveloping for Bearing Analysis

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The use of enveloping or demodulation techniques in machinery analysis instrumentation allows a user to detect fault signals in rotating element bearings during their operating history. This article describes the technique and provides many examples which compare the results of various measurements on the same bearings.

In the continuing effort to improve methods of gathering data to determine the condition of rotating equipment, another signal processing technique has been incorporated into some portable data collectors. Known by either the term "enveloping" or "demodulation," the technique allows the user to detect fault signals much earlier than previous techniques permitted.

The short answer to how this is done is that the signal processing mathematically adds up all the harmonics of the fundamental frequency that are located inside a given filter range and presents the information in the FFT frequency range that the user has selected. That is the short answer, now here is the how as explained by a mechanical engineer.

Most machinery vibration generates harmonics. If the dynamic range of the data collector is large enough, these signals can be seen for several orders of the fundamental. If the dynamic range is small, the signals are buried in the noise floor sometimes referred to as "being down in the mud." Even with a large dynamic range display, the harmonics still disappear within a short span and cannot be seen.

The trick is to capture the harmonics without including the fundamental frequency. To do this most efficiently, SKF has incorporated into their data collector four permanently set digital filters and two methods of measurement, selected by the user depending on the frequency and vibration units of interest. The frequency ranges of these filters are: 1) 5 to 100 Hz; 2) 50 to 1000 Hz; 3) 500 to 10,000 Hz; and 4) 5,000 to 40,000 Hz. The question then is which filter to use for which application. The two methods of measurement are "Enveloped Acceleration" and Enveloped Velocity." Please note that to use enveloped velocity with the SKF data collector you must use a velocity sensor. There is no integration function and if an accelerometer is used in conjunction with the "Enveloped Velocity" setup, the data collected will be completely erroneous.

The filter setup is best explained by using several actual examples. If the area of interest is the bearing on a slow rotating kiln for example, then the Ball Pass Frequency Outer Race (BPFO) and the Ball Pass Frequency Inner Race (BPFI) are determined. Let's assume the BPFO is 2.53 Hz and the BPFI is 4.32 Hz. The important thing to remember is that the selection of the filter is determined by the fundamental frequency of interest and that this frequency *must* be below the low frequency cut-off of the filter. In this case, since the first filter starts at 5 Hz and both of our fundamental frequencies of interest are below 5 Hz, the first filter would be selected. For another example, assume we have an 1800 RPM motor with a bearing that has a BPFO of 107.6 Hz. The filter selected would be the third since the first filter would never see the harmonics because they are above the filter range and the second filter would include the 107.6 Hz fundamental signal. The fourth filter may also capture and display the information if the fault is generating strong harmonics. However, for analysis, the filter selected should be the first available above the fundamental frequency of interest.

What the filters do is to capture a time block of the signal, the block size being the specific filter range. This block of data is then processed by high pass filtering, rectification, low pass filtering and then processing into a frequency spectrum. The result of this "black magic" is that the repetitive signals are enhanced and the nonrepetitive signals are degraded.

This procedure can be followed by using our example of a damaged bearing with a BPFO of 107.6 Hz and the third filter. The fundamental of 107.6 Hz plus the second (215.2 Hz), third (322.8 Hz) and fourth (430.4 Hz) harmonics are removed by the filter that starts at 500 Hz. So, beginning with the fifth harmonic to the one just below 10,000 Hz, the energy in these harmonics is added together. If the bearing is on a pump that has cavitation, a random nonrepetitive noise, then the cavitation signals are degraded and depressed. This allows the enhanced bearing fault signal to be seen above this mathematically depressed noise floor. Assuming that the FFT is set for a F_{max} of 400 Hz, then the display would show the enhanced fundamental at 107.6 and the second and third harmonics. It is very important to remember that these are enhanced signals and the amplitudes shown are a summation of the energy in the filter band. Because of the summation, the amplitudes are false and do not compare with any normal acceleration signal. However, the signals are trendable. Since the same filter band is used each time, any increase in damage to the equipment will increase the signal strength in that band. As the signal increased over time, it will show up as an increasing overall amplitude trend or the specific frequency of interest may be trended, i.e. 107.6 Hz.

Although this analysis technique works very well for bearings, it also provides early warning of other faults such as in gear boxes, misalignment, and looseness. Any type of machinery vibration that generates harmonics can be examined.

Bearing Fault Stages

The past problem with a "one time look" at a suspected bearing fault was that one never knew for sure in what stage of damage the bearing was operating. By the time you were positive the bearing was in trouble, you were also in trouble because you hadn't told anyone soon enough to get it fixed in an orderly manner. Using enveloping in conjunction with SEE technology, it is possible to now divide the life of a bearing into four stages. And the enveloped FFT clearly defines these stages for you. The following examples will show each stage.

Stage one is a good bearing. If the bearing is heavily loaded the BPFO frequency may be seen. This is generated by the rolling elements going into and out of the load zone. At one instant in time there are three elements in the zone and in the next instant there are four followed in the next instant with three again. This changing support in the load zone causes the outer race of the bearing to flex microscopically, generating energy at the BPFO. The difference in a heavily loaded bearing and a damaged bearing is the lack of harmonics. As the bearing degrades, harmonics of the damage frequency will begin to show in the FFT. For this reason, when doing troubleshooting, it is important to set the F_{max} so that two or three harmonics of the bearing frequencies can be captured. In like manner, if examining a gear box, the F_{max} should be set to capture two or three harmonics of the gear mesh frequency.

Stage two is a bearing with some wear as noted by the harmonics. There is no reason to change the bearing at this point. In fact, I have seen bearings pulled at this stage and the only damage apparent is pinpoint spalling in the races. However, as the harmonics increase in amplitude it may be prudent to increase the frequency of data collection. Bearing degradation is usually linear for a period of time and can be trended, but as the lifetime ends it will become nonlinear.

In stage three the damage in the bearing is becoming terminal. In the FFT the fundamental frequency and the harmonics

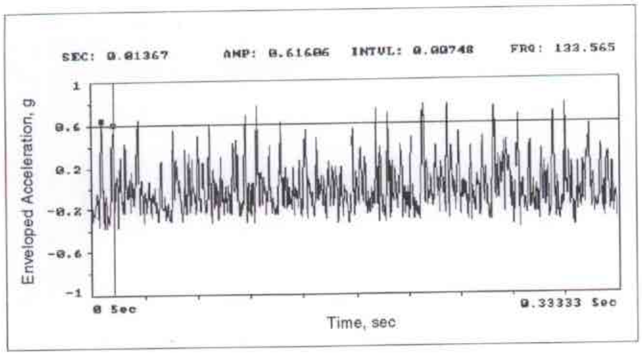


Figure 1. Vibration time history of a flawed bearing.

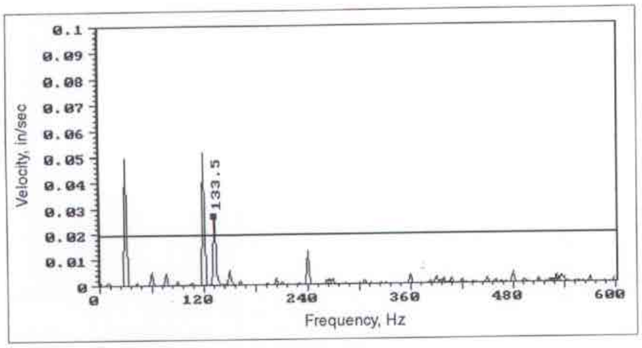


Figure 2. Velocity spectrum of a flawed bearing.

will begin to show sidebands of bearing shaft rotating speed. For example, using our BPFO of 107.6 Hz on a shaft turning 1800 RPM or 30 Hz, the sidebands will be at 77.6 Hz and 137.6 Hz (107.6 plus and minus 30) and the second harmonic will have sidebands at 185.2 Hz and 245.2 Hz (215.2 plus and minus 30). Further progression of the damage will generate additional sidebands at 2× running speed (47.6 and 167.6). Now you have overlapping frequencies and it becomes a mess to figure out. But beware, the bearing is in the last days of its life and should be changed as soon as possible.

In addition to the spectrum information, the overall magnitudes will give you a clue to the condition of the bearing. Using the third filter, stage one will be from 0.1 to 0.4 g and stage two from 0.4 to 4 g. Stage three is from 4 to 10 g and stage four is a measurement of over 10 g. If it is a very slow speed bearing using the first or second filter, these magnitude limits are greatly reduced since the slower speeds do not generate as much energy with the same size flaw. A general rule of thumb would be to reduce the magnitudes for the first filter by a factor of 100 and the second filter by a factor of 10. In the same manner a high speed bearing using the fourth filter would have the magnitudes increased by a factor of 4. These ranges are subject to modification as more empirical data are collected and correlated with what we see when the bearing is taken apart. Never make a bad bearing call using overall magnitude only. Check the frequency spectrum for the energy content and where it is being generated.

To determine stage four, it is necessary to incorporate another analysis technique into the process. SEE (Spectral Emitted Energy) technology, which is built into the data collector exclusive with SKF, analyzes the bearing condition using enveloped acoustical energy generated by the rolling elements over rolling foreign particles in the lubrication. These particles could be from lubrication contamination or from particles spalled from the races. In any event, if SEE technology is used and a signal is detected, the bearing is probably in stage four which says that failure may occur very soon and the machine should be shut down immediately. If there is no SEE signal because the rolling elements and races or particles are not making contact through the oil film, then the damage analysis reverts to stage three and the bearing should be monitored closely and changed as soon as possible. SEE signals appear in the FFT at the same frequency as any of the bearing fault frequencies or gear mesh frequencies when examining a gear box. In our previous example, if the bearing had damage in the outer race and the rollers and outer race were making metal to metal contact, the SEE FFT would display an energy source at 107.6 Hz.

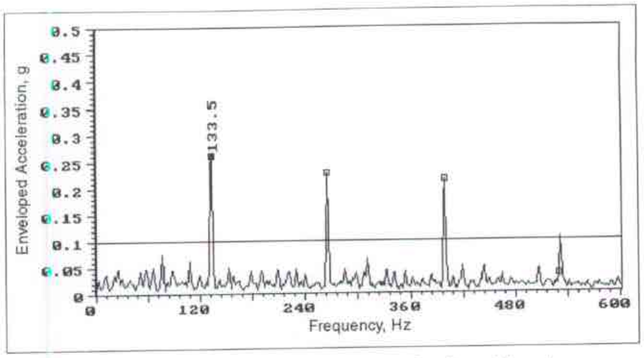


Figure 3. Enveloped acceleration spectrum of a flawed bearing.

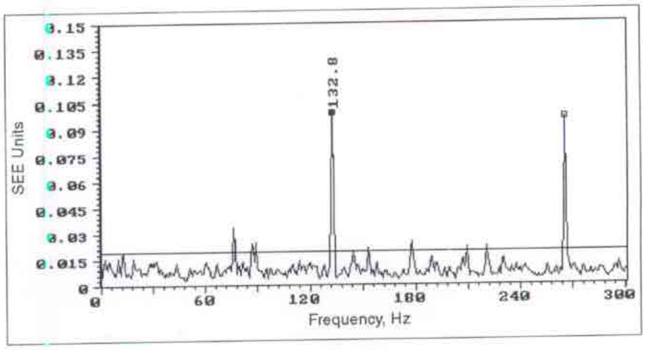


Figure 4. SEE spectrum of a flawed bearing.

One note on the observed frequencies. The bearing frequency calculations are for a perfect bearing. In production, this perfect bearing doesn't exist. So therefore, the variations that occur will cause some variations in the actual frequency observed. In addition, an older bearing will have worn and changed the clearances it had when new.

Bearing Fault Diagnoses

The following spectrums will illustrate bearings in various stages with comparisons to standard velocity spectra. Although we don't usually look in the time domain except when we are testing a gear box, the bearing flaw signals will be there if the flaw is large enough. Usually there is so much data captured in the time domain that it defies interpretation. In Figure 1 the inner race flaw shows up as each roller passes over the flaw. The markers show the interval to be 0.00748 sec which equals the frequency of 133.5 Hz. The bearing was damaged during installation. Figure 2 is vibration signature of the same bearing, an SKF 6201. We do see the BPFO in the velocity spectrum since the damage was extensive, but there are no harmonics and the amplitude is low. Figure 3 is the same data processed using enveloped acceleration. Note the difference from Figure 2. All the nonrepetitive signals are depressed and the BPFO with harmonics is very clear. Finally, in Figure 4 we will look at a SEE spectrum. SEE units are expressed as either SEEs or SEE units. In hindsight we should have set the F_{max} to 600 Hz. This would have displayed the additional harmonics shown in Figure 3.

In looking at these four spectrums one might think that all these measurements aren't necessary. However, when it comes time to make a decision on whether to shut down a machine and work on it, use all the tools you have to help make those decisions. The better our information, the better our decisions.

Figure 5 is the spectrum of an MRC bearing that had been poorly stored. It had lain on the shelf for seven years in an acidic environment. The acid had etched the balls and the side of the race. When the bearing was installed, the flaw in the race did not make contact with the balls, but the balls generated the

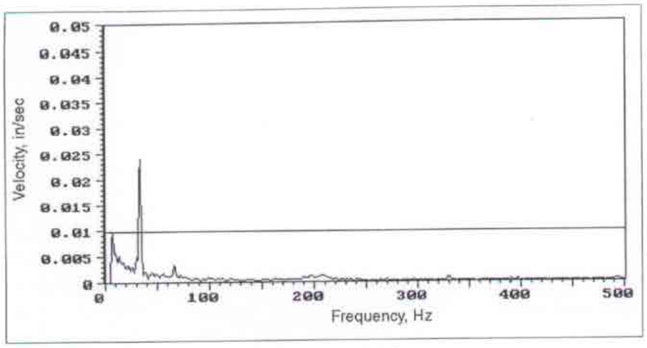


Figure 5. Velocity spectrum of a damaged bearing.

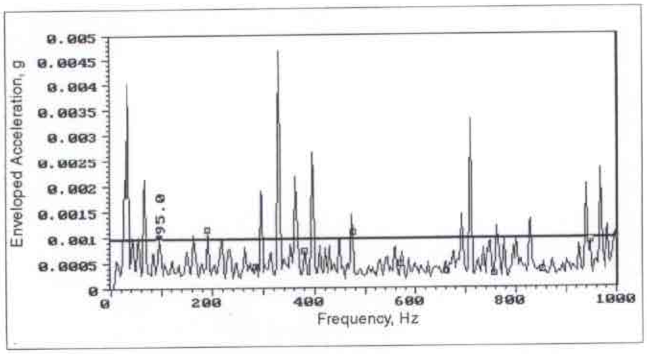


Figure 6. Enveloped acceleration spectrum of the damaged bearing.

BSF (Ball Spin Frequency) at 95.0 Hz as it rotated. There was no defect signal showing in the velocity spectrum. It only appears in the enveloped signal as shown in Figure 6. The amplitudes are very low but we could hear the flawed balls clicking as the machine ran.

Figure 7 is the spectrum of a bearing where the cage was

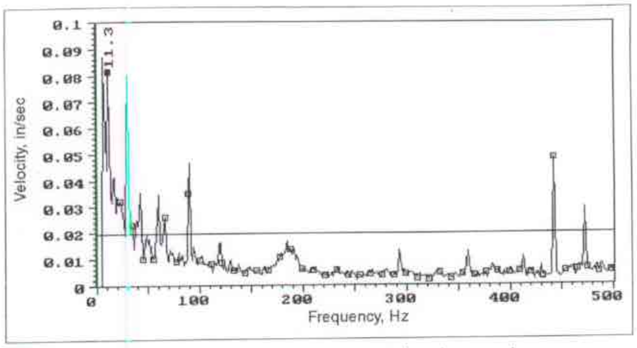


Figure 7. Velocity spectrum of a bearing with a damaged cage.

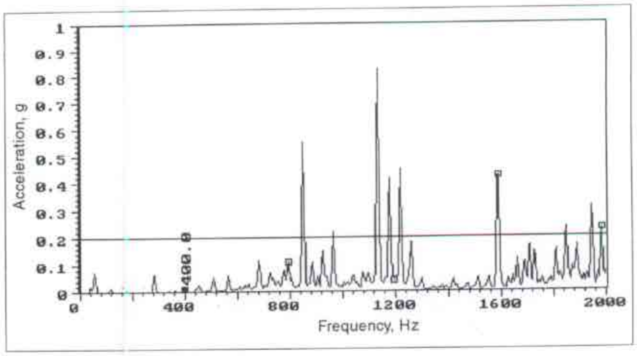
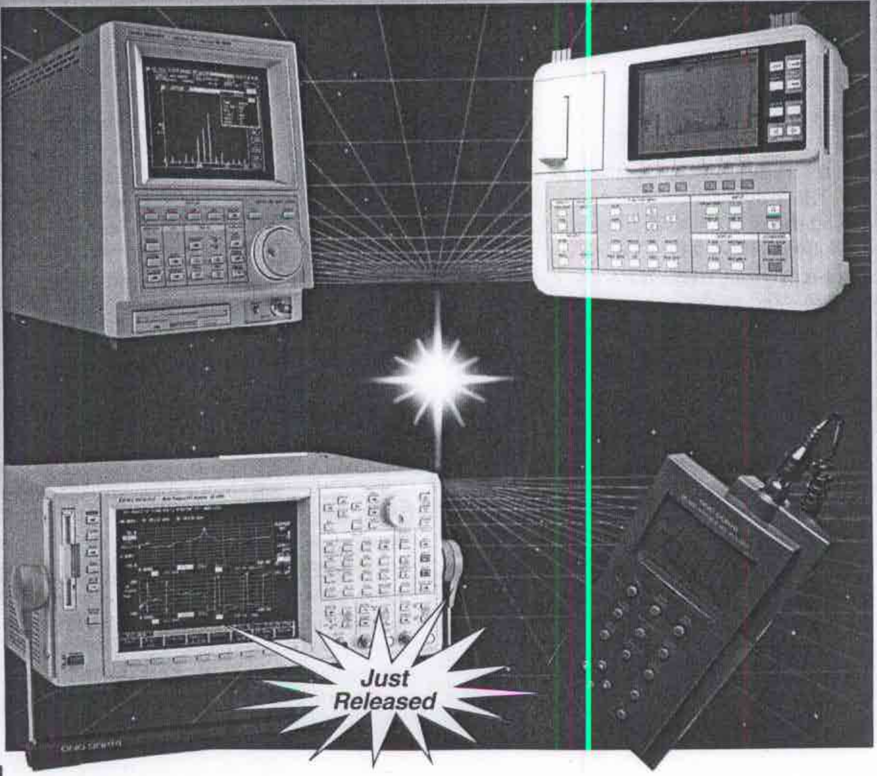


Figure 8. Acceleration spectrum of a flawed bearing.

damaged sometime during its life. The owner expressed displeasure at the high amplitude of vibration and the analysis showed the cage flaw. Further searching by serial number found the bearing to be over 20 years old! One additional problem here was that the eighth harmonic of Fundamental Train Frequency (FTF) overlaid the third harmonic of the rotating



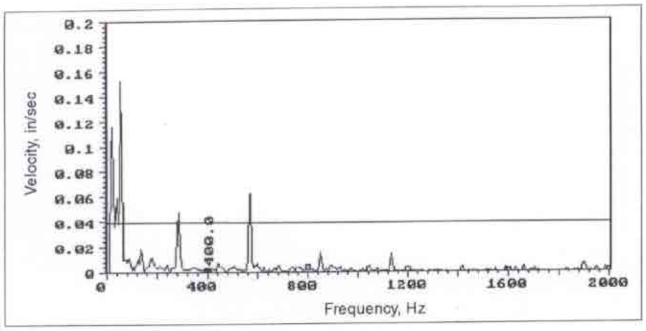


Figure 9. Velocity spectrum of a flawed bearing.

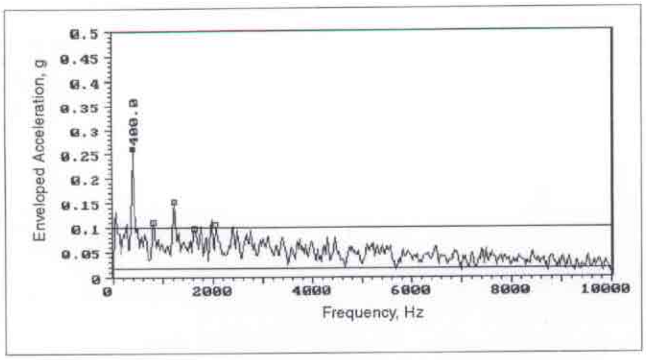


Figure 10. Enveloped acceleration spectrum of a flawed bearing.

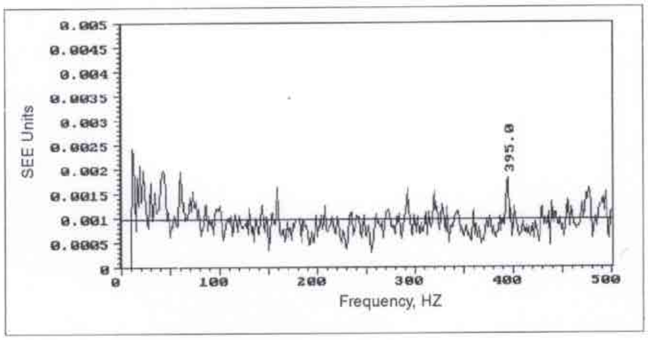


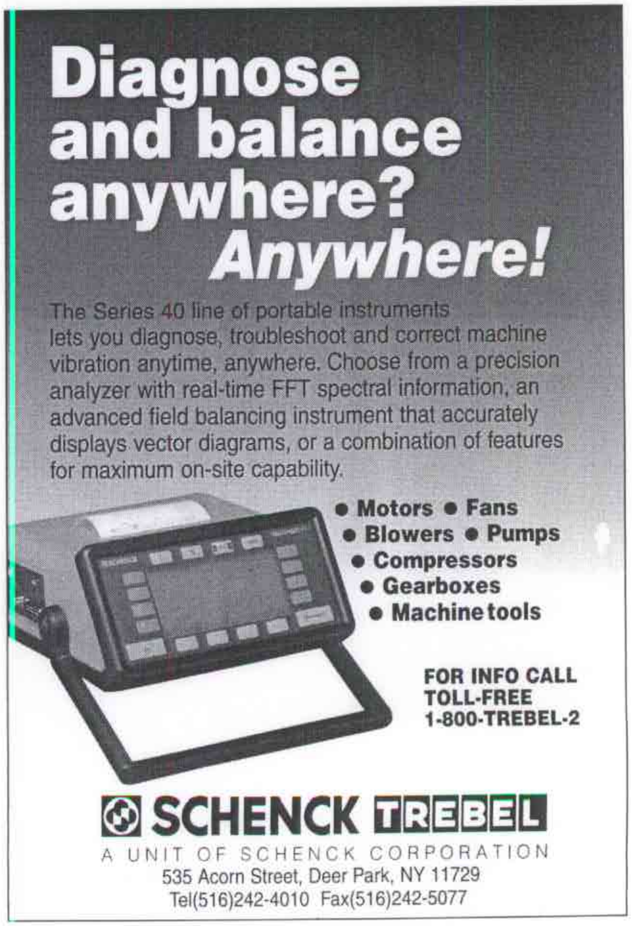
Figure 11. SEE spectrum of a flawed bearing.

speed. Not a good situation and the bearing was changed. Afterwards, the vibration levels were acceptable.

The next set of examples are from tests run with a compressor manufacturer who wanted proof that we could detect bearing flaws. Before we arrived, he had placed flaws in one of the six bearings and asked us to find them. We did. Figure 8 is the acceleration spectrum. The fundamental BPFO doesn't show up but the harmonics do. This would alert you that something was going on, but most people don't take routine bearing measurements in acceleration.

Here is one additional note on bearing troubleshooting. Most bearings will have their BPFO and BPFI at non-integers of rotating speed. In other words, rotating speed is 1× and the BPFO will be at 3.56× or 4.73×. This is a valuable clue when looking at a machine and you have no idea what bearings are installed.

Figure 9 is a velocity spectrum, the method most people use, and there is absolutely nothing here that would cause one to worry. Of the six bearings in the unit, the owner did not tell us which one had the flaw, but because of the different sizes, the bearing flaw frequencies are all different. It turned out the one with a BPFO of 400 Hz was the bad one, so I've gone ahead and marked that frequency. Figure 10 is the same measurement processed using acceleration enveloping. This clearly shows the BPFO that was not visible in the velocity spectrum. And, to show how far out the harmonics are visible, we have set the F_{max} to 10 kHz, not the usual F_{max}! Finally, these data were processed using SEE technology as shown in Figure 11. If the F_{max} was higher, the harmonics would be seen but the important item is that the SEE signal is present which indicates metal to



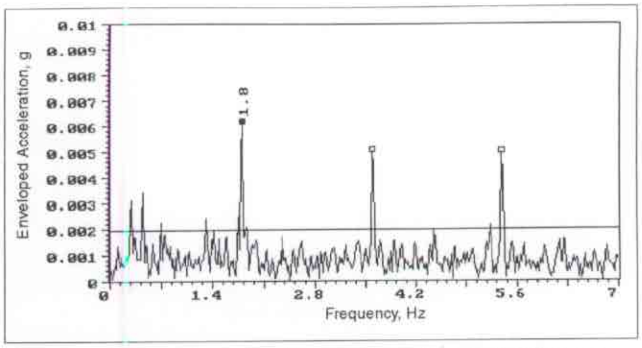


Figure 12. Enveloped acceleration spectrum of a gear box bearing.

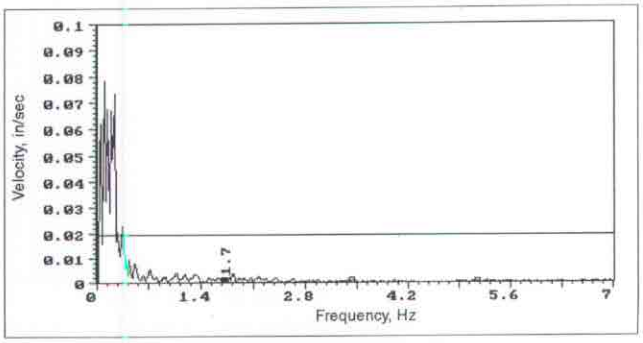


Figure 13. Velocity spectrum of a gear box bearing.

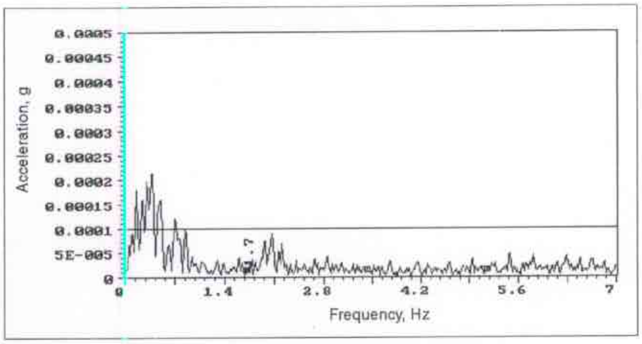


Figure 14. Acceleration spectrum of a gear box bearing.

metal contact. Note that the amplitudes are very low so the contact is very light.

The next four spectrums are from very slow speed bearings. This application is ideal for enveloping. There is no integration and therefore no amplification of the low frequency noise present in all data collectors. The F_{min} can be set at 0 Hz and the spectrum will not have the typical "ski slope" low frequency roll-off.

These spectrums are from a conveyer drive gear box. The bottom bearing has a history of failure and the customer was required to keep three days inventory on hand to maintain his "just in time" shipments if the bearing failed. By being able to know the condition of these bearings, their repair could be scheduled and the expensive products in inventory could be reduced. The rotating speed of the shaft for this unit is 8.3 RPM. The BPFO for the first three spectrums is 1.7-1.8 Hz and for the fourth, a different bearing, it is 1.4 Hz. The BPFO varied because of speed changes while the different readings were being taken. Figure 12 is the bearing processed with enveloped acceleration. With the BPFO at 1.8 Hz, there are two harmonics displayed. But, since there are no sidebands of running speed apparent, the bearings were diagnosed as having some light damage but it wasn't panic time yet. Figure 13 shows a normal velocity spectrum. Notice there is absolutely nothing to indicate bearing damage at the BPFO of 1.7 Hz. Figure 14 shows the same bearing using conventional acceleration processing. No damage was noted even at the extremely low signal level. But Figure 12 clearly shows the BPFO with harmonics. Our advice was to keep running the machine but increase

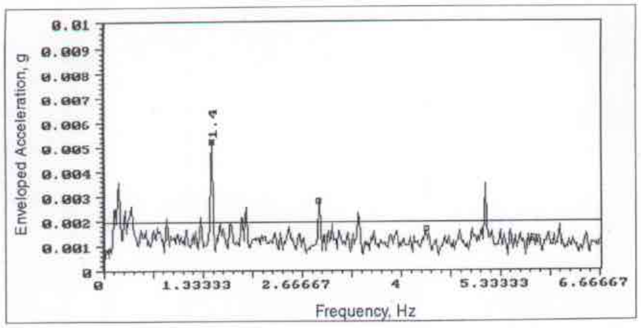


Figure 15. Enveloped acceleration spectrum of another gear box bearing.

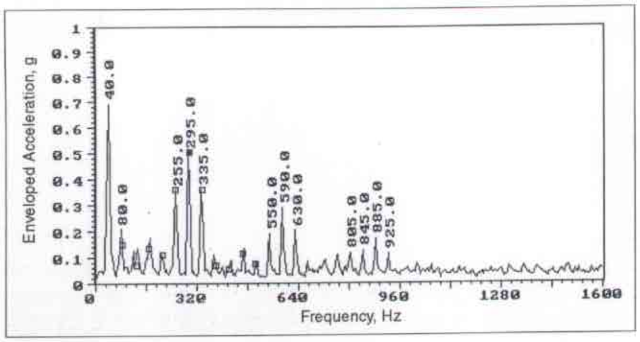


Figure 16. enveloped acceleration spectrum of a damaged laboratory test bearing.

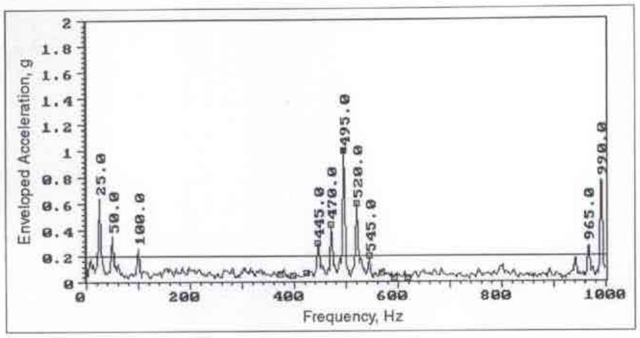


Figure 17. Enveloped acceleration spectrum of a defective gear box bearing.

the observations to once per week rather than once a month. Considering the critical and expensive nature of this operation, this is a bearing that will be changed at the next opportunity. The next example, Figure 15, is the other bearing in the same gearbox. It is heavily loaded and just starting to show some harmonics.

It is difficult to obtain examples of stage three damage. If the observer is paying attention at all, then you can both feel and hear that something is not right. The bearing example in Figure 16 is from a laboratory test where we damaged the bearing in order to get the sidebands. You can see that the frequency gap between the sidebands and the fundamental is equal to the rotating speed of the shaft, 40 Hz. These same sidebands are about the harmonics also. The final example, shown in Figure 17, is a gear box that was in a stage three condition. The owner was a little sly about it. He had asked us for a demo of the enveloping process and how it could be used in a route setup. When we set up the $F_{\max}$ we did not know the gear mesh frequency and the owner didn't know, so we selected an $F_{\max}$ of 1000 Hz. This is fine for routine route data collection. If we had been allowed to go back and take data in a troubleshooting mode, we would have selected a higher $F_{\max}$, probably about 2000 Hz. We barely caught the second harmonic at 990 Hz but the sidebands are very clear at 25 Hz, the shaft rotating speed. When we told the owner he had a serious problem with this gear box, he just smiled and said, "I know, I just wanted to see if your data collector was any good." It is. **SV**

<u>An application</u> : Machinery health monitoring

A machinery can be checked for its health by measuring its vibration and then performing FFT to the data.

Machinery Health Monitoring—an Application of Spectrum Analysis

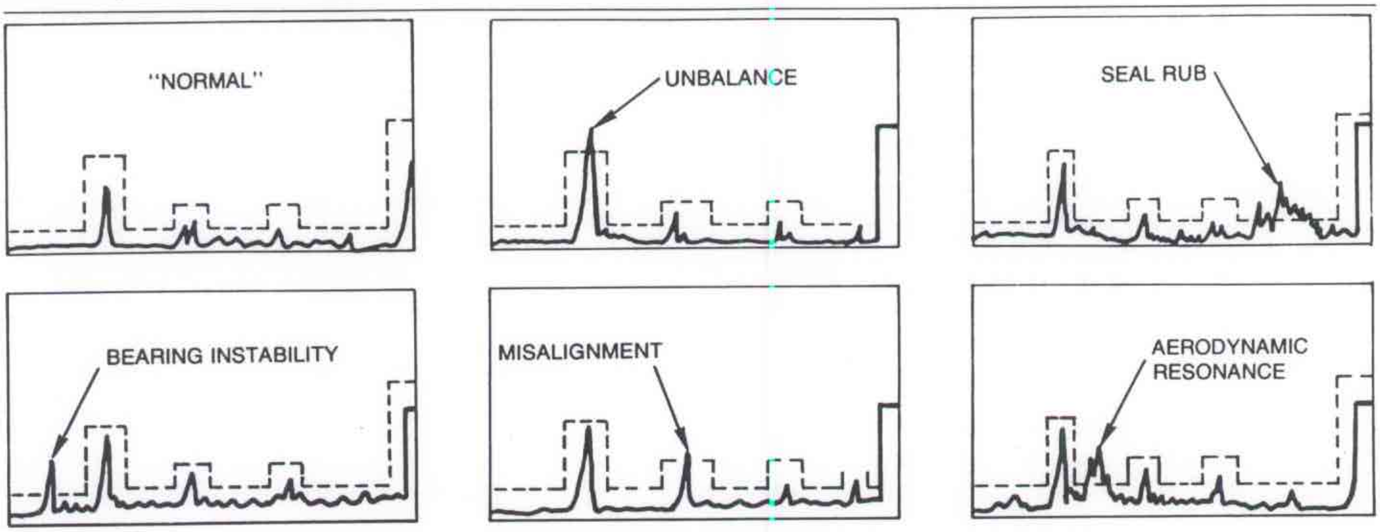


Fig. 8.9 Examples of spectral exceedances above "windowed" spectrum. Courtesy Dymac.