

Acceleration Enveloping – Higher Sensitivity, Earlier Detection

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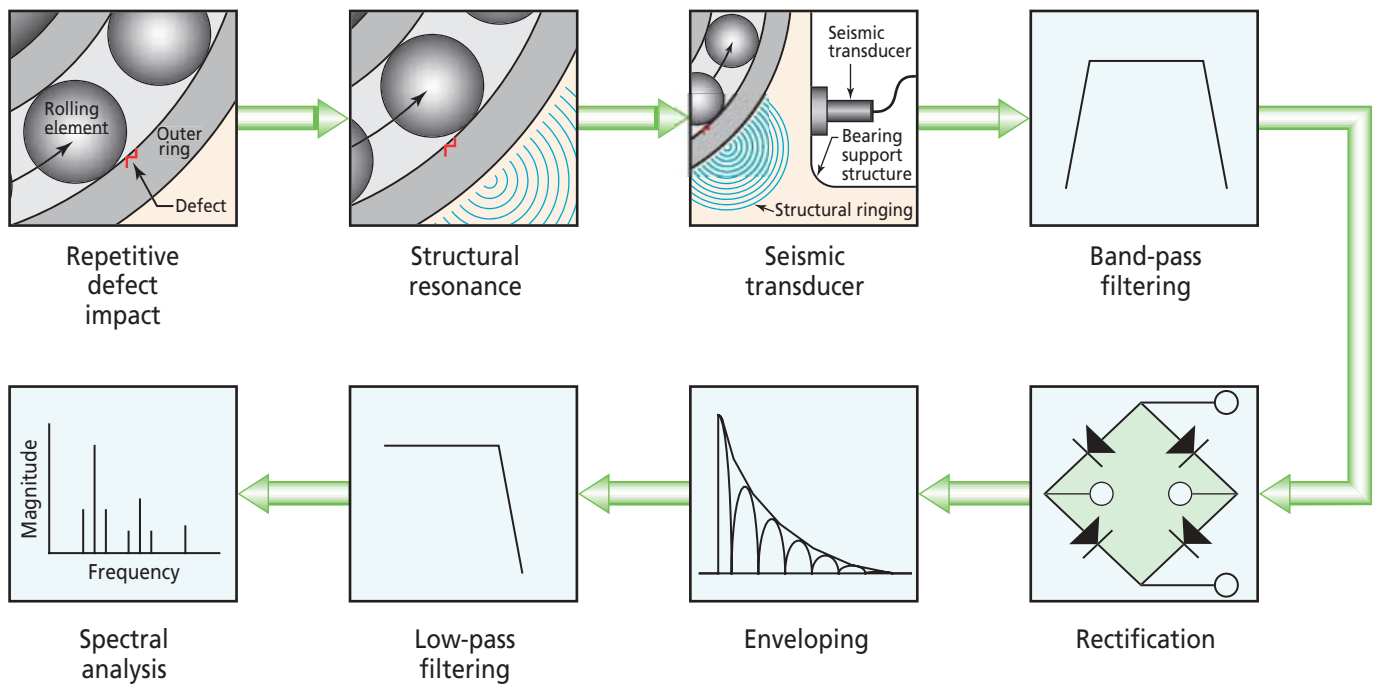
Enveloping is a tool that can give more information about the life and health of important plant assets. It is primarily used for early detection of faults in rolling element bearings and gearboxes. Enveloped acceleration is an especially valuable parameter to trend, as the progression of machine condition can be evaluated. Armed with good information and assisted by Bently Nevada service experts, plant engineers can be confident in the proper operation and management of the important assets under their care.

Enveloping can reveal faults in their earliest stages of development, before they are detectable by other machinery vibration measurements. Without an early fault detection technique like enveloping, personnel must wait until the latter stages of failure, when overall vibration increases, lubricants become contaminated, and temperatures rise. By this time,

the remaining usable life of the failing machine elements could be very short and the damage more extensive than if the fault had been detected earlier.

The enveloping technique enables the detection and analysis of low-level, repetitive vibrations by extracting them from the overall machinery vibration signal. Enveloping thus facilitates earlier prediction of failure in machines with metal-to-metal contact. While the examples in this article are based on rolling element bearings, the techniques also can be applied to gearboxes and electric motors with commutators.

It is important to note that the successful application and interpretation of enveloping data require experience. Enveloping is just one tool in the analyst's toolbox, and it is best used as one of a number of techniques for complete monitoring of a machine.



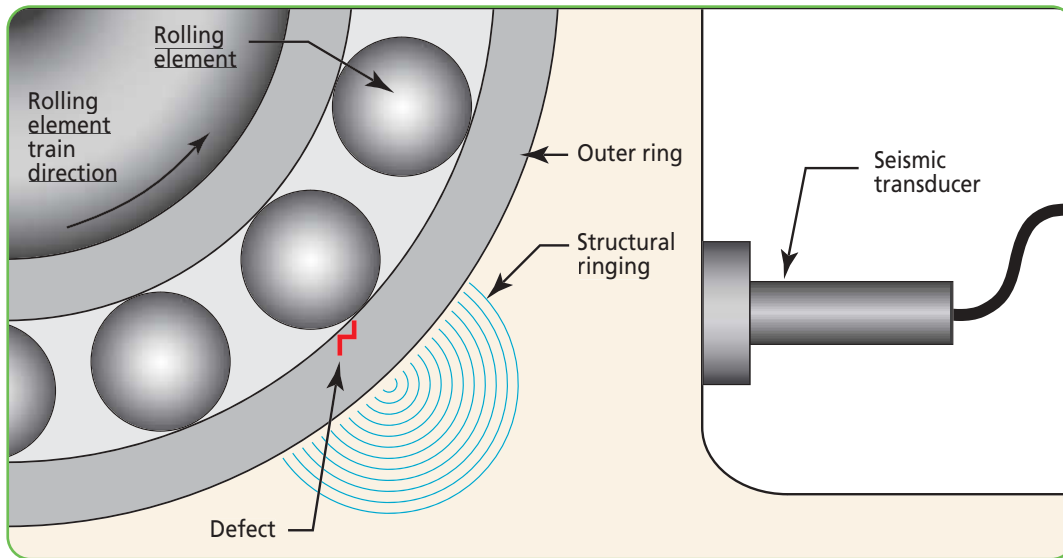
TYPICAL STEPS IN THE IMPLEMENTATION OF ENVELOPING. | FIG. 1

Enveloping Isolates Signals of Interest

Enveloping is a multiple-step process that extracts signals of interest from an overall vibration signal (Figure 1). In a rolling element bearing, the interaction between bearing elements and defects excites a structural resonance in the bearing support structure. A seismic transducer measures the vibration, and this signal is band-pass filtered to keep only signal components around the resonance frequency. The fil-

tered signal is rectified and then enveloped, which removes the structural resonance frequency and preserves the defect impact frequency. A low-pass filter then eliminates some of the extraneous high-frequency components, and a spectrum is generated. Frequency components are correlated with physical bearing parameters, and a trend of the spectra can show progression of defects.

Analysis of the enveloping process begins with the source of the vibration signal. As the elements of



DEFECT IMPACT CAUSES RINGING OF THE MACHINE STRUCTURE AT ITS NATURAL FREQUENCIES. | FIG. 2

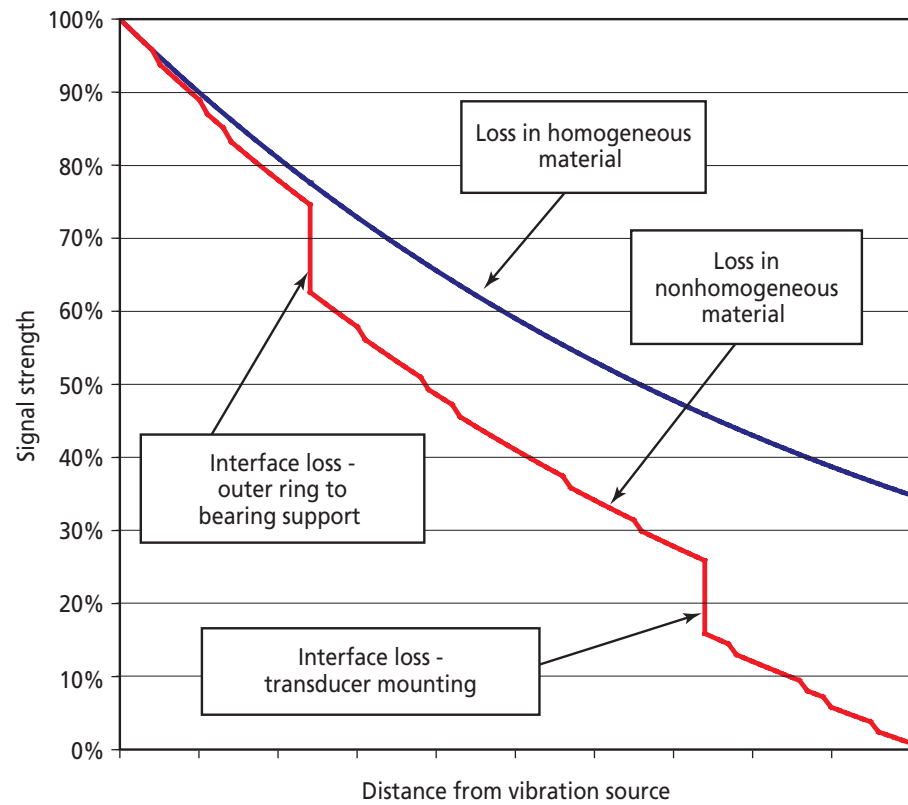
the bearing interact with each other and with defects, forces are coupled to the machine casing, producing vibration. These defect interactions behave as impacts that excite a natural resonance frequency of the machine, causing it to ring (Figure 2). The amplitude of the ringing decays until the next impact, which re-excites the resonance. Thus, the defect amplitude modulates the natural resonance response at the impact frequency. The defect-related signal becomes part of the overall vibration of the machine.

Because of its higher frequency response characteristics, an accelerometer is generally used to measure the vibration signal for enveloping. Thus, enveloping is often called acceleration enveloping or high-frequency acceleration enveloping. High-frequency vibration signals, such as the resonance carrier of the defect signal, do not travel far in a homogeneous machine structure; metal imperfec-

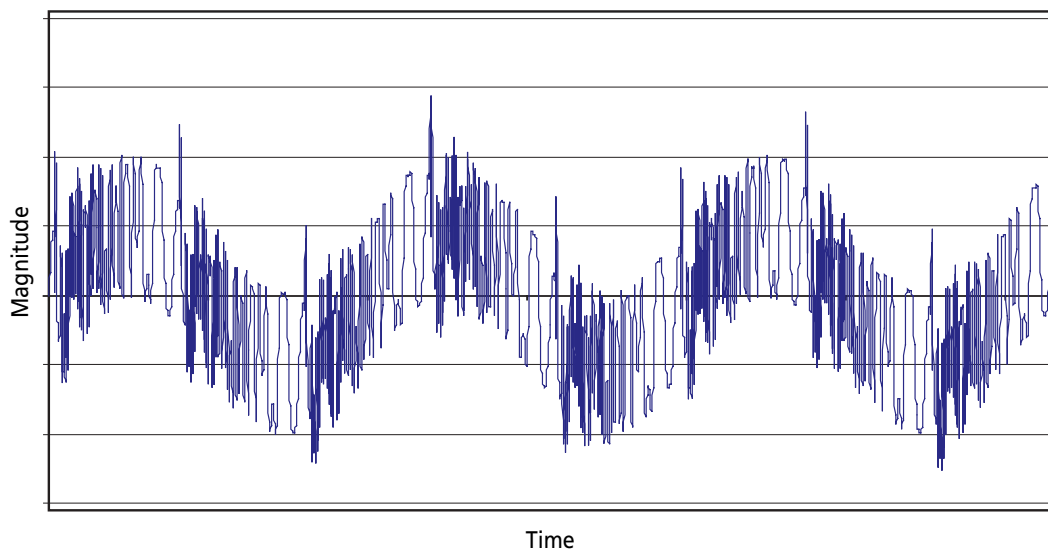
tions, joints, and gaskets cause further significant attenuation (Figure 3). It is critical that this low-level, high-frequency signal be coupled efficiently into the accelerometer; the accelerometer should be mounted as close to the bearing as possible and near the load region of the bearing, where signals are coupled more effectively to the machine case.

The output of the accelerometer (Figure 4) contains three important frequencies: a relatively low-frequency, high-amplitude rotor-related vibration; the modulated structural resonance frequency; and other high-frequency vibration components, including harmonics of the structural resonance frequency. Though the signal is complex, application of the enveloping technique allows us to determine an impact frequency associated with the defect, which provides valuable information about machine condition.

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VIBRATION SIGNAL TRANSMISSION LOSS IN HOMOGENEOUS AND NONHOMOGENEOUS MATERIALS. | FIG. 3



ACCELEROMETER VIBRATION WAVEFORM OUTPUT WITH EMBEDDED DEFECT SIGNAL. | FIG. 4

Implementing an Enveloping Program: What Are the Issues?

A SIDEBAR ARTICLE

While the methodology for generating an enveloping spectrum may seem straightforward, valid results depend on careful application. Consider the following eight issues before applying enveloping techniques to machinery monitoring:

EARLY DETECTION: Enveloping provides early detection of faults that would otherwise be obscured by larger components of the machine's vibration signature. However, when a fault is identified in an enveloping spectrum, failure is not necessarily imminent, but monitoring of that machinery component should be increased to trend progression of the fault. Defects will not be detectable until they have progressed to the point that their interaction with other components is repetitive, not random. Check against other data using other measurement techniques, as available.

ELIGIBLE MACHINES: Enveloping techniques can be used to detect faults in machine components with repetitive metal-to-metal interaction. However, because enveloping is not a "direct" measurement, many extraneous factors can add to or diminish the enveloped signal. Several machine components or characteristics can prevent successful enveloping implementation. Joints, interfaces, gaskets, and fluid-film or squeeze-film dampers prevent high-frequency signal transmission critical for enveloping. High-frequency operational noise may overshadow signals of interest in reciprocating machines, variable frequency drive motors, and others. Electromagnetic interference may also introduce itself into the cabling between the transducer and the signal processing device and compromise signal integrity.

TRANSDUCER SELECTION: The frequency response of the transducer must include the expected range of machine resonance frequencies (ranging from 1 kHz to more than 40 kHz). The resonance frequency of the mounted transducer must be sufficiently far away from the machine frequencies of interest to avoid interactions. The transducer should be extremely reliable to ensure trending consistency.


TRANSDUCER MOUNTING: Enveloping measurements are highly dependent on transducer mounting method and location. Even a slight change in mounting location can yield quite different results, so a solid, repeatable mounting is essential to help ensure that changes observed in data are due to changes in machine condition – not just variations introduced by the person collecting the data. A flat, clean (bare metal) surface for mounting the transducer is critical. Handheld transducer applications can be especially susceptible to variation based on changes in applied pressure, mounting angle, and other variables introduced by the person taking the reading. For this reason, use extra care when handheld transducers are used for enveloping measurements. When practical, consider affixing the transducer in a way that reduces variability such as by screwing it onto the measurement surface using a mounting stud, or – if using a handheld "stinger" assembly – develop a routine of holding it in the same manner, applying the same pressure, and orienting it at the same angle (perpendicular to the measurement surface) for every data collection location. Since the high frequency signal on which enveloping depends does not usually travel very far within a machine, the transducer mounting should have a short transmission path from the machinery component of interest, with as little damping of the high fre-

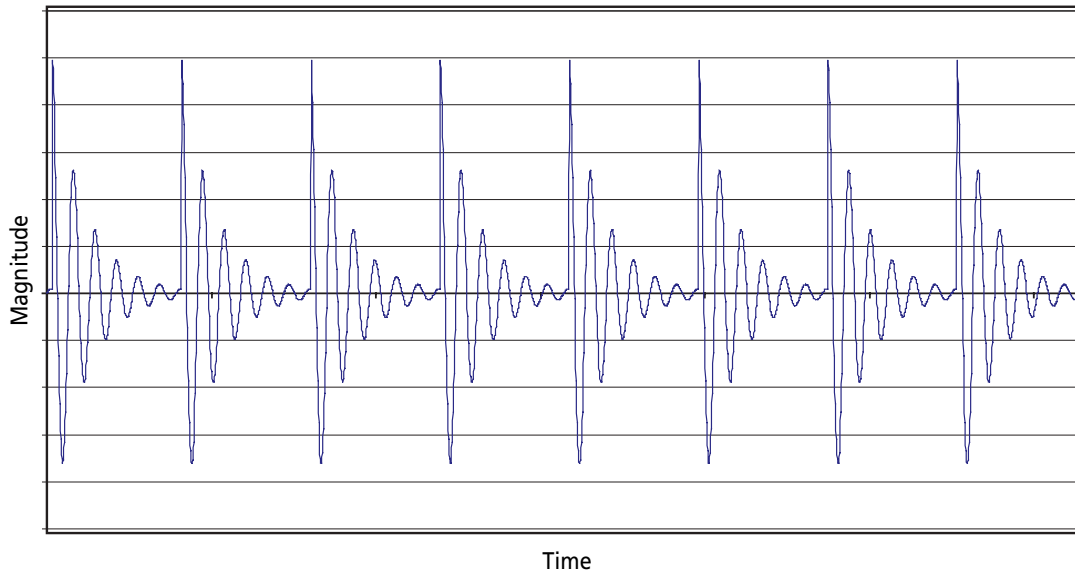
quency energy as possible. Any metal interface or discontinuity in the machine causes significant signal attenuation, and fluid films at any interface can completely stop transmission of a signal. Consequently, faults which are detected with enveloping can be expected to be located near the measurement transducer.

FAULT IDENTIFICATION: Because of the correlation between fundamental spectrum frequencies and fault sources, flawed components can often be identified before the bearing is removed and physically examined, allowing spare parts to be ordered in advance and work procedures to be written with the knowledge of precisely what needs to be changed. Frequencies associated with the machine's components and its natural resonances must both be considered when configuring the enveloping technique to ensure valid data. Since improper lubrication, caused by inadequate, excessive, or contaminated lubricants, can cause frequency components to appear in the enveloping spectrum, lubrication should be checked first when faults appear. Progression of faults is often indicated by the presence of more bearing frequency components and an overall increase in the noise floor of the enveloping spectrum. Overall, the fundamental fault frequencies in the spectrum are the most important for correlation with physical defects.

SEVERITY PREDICTION: Enveloping provides valuable information for machinery management. However, enveloping by itself does not give all the information necessary for reliable and accurate prediction of the condition of a machine component, such as a bearing or gear. In the enveloping spectrum, frequency can be correlated to a specific machine component, but increasing magnitude is not necessarily correlated to the progression of the fault. In fact, a well-known phenomenon is that the acceleration enveloping amplitude may actually decrease as bearing failure becomes more imminent. As a bearing continues to wear, its small, vibration-inducing flaws begin to smooth out, and the characteristic "ringing" caused by the flaws (and detected by enveloping) decreases. When enveloping data is used with other measurements, such as direct machine vibration, acoustical noise levels, and temperature, machinery condition can be more accurately determined.

TRENDING CONSISTENCY: Data must be collected periodically and consistently to ensure the integrity of the trend. As noted in point #4, this includes using the same transducer in the same location mounted the same way to reduce gross and systematic errors. Then the trend can be evaluated to see the progression of any defects. Permanently mounted transducers are recommended.

FREQUENCY VARIATION: The absolute frequency of enveloping signals is directly dependent on shaft rotation speed. In order for frequencies to be correlated with potential faults, machine speed must be known and relatively constant. Otherwise, the magnitude of frequency components may be affected by frequency-dependent machinery and instrumentation responses rather than changes in defect severity. 



BAND-PASS FILTERED VIBRATION WAVEFORM SHOWING DEFECT MODULATION OF THE MACHINE STRUCTURAL RESONANCE. | FIG. 5

(continued from page 12)

Filtering an Important Part of Enveloping Process

Band-pass filtering is the first signal-processing step in the application of the enveloping technique. Proper filter specifications are critical to the removal of unwanted components of the signal while preventing detrimental attenuation of signal components essential for enveloping analysis. Frequency range selection must take into account machine operating speeds and structural natural frequencies, which depend, at least in part, on bearing design along with machine construction and mounting. In order to get the best (most useful) information from the enveloping technique, some experimentation with available frequency ranges for the filters is often required when enveloping is first applied.

A good starting point is to examine the spectrum plot for a high-frequency, structural resonance “hay-

stack.” The lower corner (high-pass corner) should be set above gear mesh frequencies, but below this structural resonance “haystack.” The lower corner frequency is selected to reject the comparatively high-amplitude, low-frequency components that are associated with the normal machine running speed vibration. This greatly improves the signal-to-noise ratio for the frequencies of interest, since it is these lower frequencies that generally dominate the vibration signal. The upper corner frequency is selected to remove extremely high frequencies which are associated with other machine vibration frequencies and signals amplified by the accelerometer or mounting resonance.

For a machine with rolling element bearings, the lower corner frequency is generally set to be greater than ten times the running speed of the machine (10X) to eliminate the most common harmonics of running speed. However, this frequency

should not exceed one-half of any structural natural frequency associated with the bearing. This natural frequency serves as the carrier frequency excited by the defect impacts, and attenuating this signal of interest is detrimental to the success of enveloping.

The upper corner is generally set to around sixty times the outer-race ball-pass frequency (60X BPFO), or approximately two hundred times running speed (200X). This attenuates high frequency noise and vibration components, some of which have been amplified by accelerometer resonances. These basic rules are relatively simple to apply to a rolling element bearing. However, on a gearbox they become more complicated because of gear-mesh frequencies.

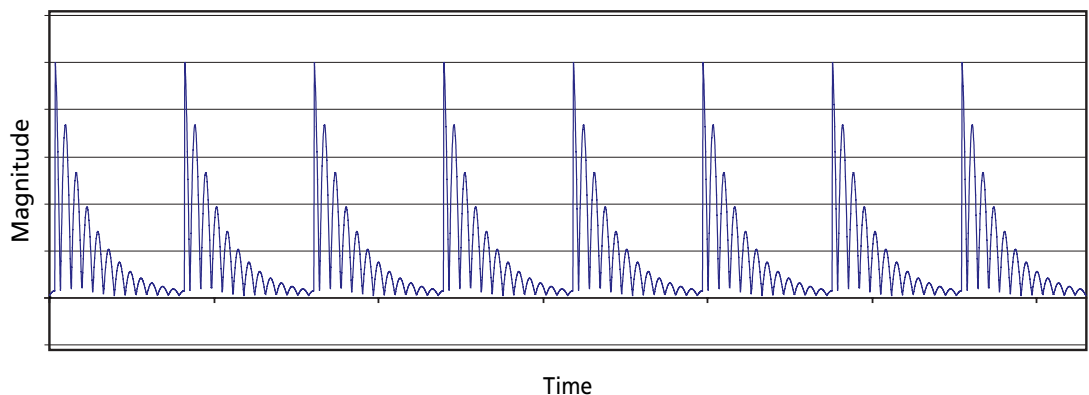
The band-pass filter output (Figure 5) shows the structural resonance frequency, which is the higher frequency in the waveform, modulated by the defect. The impacts associated with the defect excite this carrier frequency, and its

amplitude then decays exponentially. The signal from a defective bearing may have different impact intervals, more frequency components, and differing amplitudes – all potentially influenced by lubrication, the number of defects, the severity of the defects, and the loading of the bearing (among other things). However, enveloping is still effective and even more valuable for these more complicated signals.

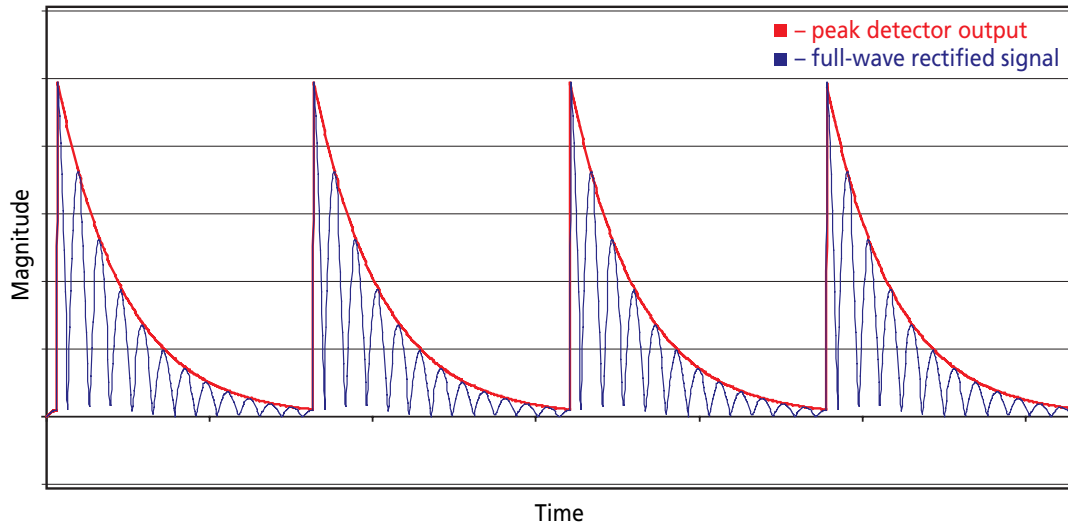
Amplitude Demodulation Eliminates the Resonance Frequency

To envelope (demodulate) the filtered signal, it first is full-wave rectified (Figure 6), which doubles the carrier frequency and further separates the impact frequency and the carrier frequency.

The next step is the actual enveloping itself. Amplitude demodulation of the rectified waveform eliminates the carrier frequency and leaves the repetition



FULL-WAVE RECTIFIED VIBRATION SIGNAL. | FIG. 6



ENVELOPE OF VIBRATION SIGNAL PRODUCED BY A PEAK DETECTOR. | FIG. 7

rate of the defect impact. A number of methods are available to accomplish demodulation, including peak detection (Figure 7), integration, and low-pass filtering.

Generally, enveloping results in a waveform which has spectral components corresponding to the defect impact frequencies and, due to the impact nature of the event, harmonics of the defect frequencies. Frequency components unrelated to the impact will generally be of higher frequency than the components of interest. Some of these can be eliminated by another application of low-pass filtering, leaving the defect impact frequencies and some low-order harmonics. Interpretation of this less-cluttered spectrum is easier, since fewer components need to be considered.

The next step before analysis is to generate a spectrum of the enveloped signal. The defect impact frequency should show up clearly in relation to all the other spectral

components in the signal. Harmonics of fundamental fault frequencies are generally artifacts of the enveloping process and are not valuable for trending purposes, except that the presence of more harmonics may indicate the progression of a fault. After disregarding harmonics, significant frequencies present in the spectrum may be correlated to physical machine parameters. Note that, especially as defects become more severe, sidebands related to running speed may appear around defect frequencies in the spectrum.

If uncorrelated frequencies are present in the spectrum, the filters may have been configured incorrectly or the transducer measurements were taken improperly. Frequencies may also come from other nearby machinery components, or they may be caused by the machine operation or process. While improper measurement techniques may prevent frequencies from appearing in the spectrum, if defects are absent in the monitored

machinery, then no defect-associated frequency components should be seen in the spectrum.

Interpretation of Information Is Final Step

Interpretation of the information is the very important final step. Trending the magnitude of these frequency components can indicate the progression of bearing faults, but the magnitude is not necessarily related to the severity of the defect. For example, developing faults, such as a spall, may initially cause defect frequencies that have increasingly larger amplitudes. As the spall grows, it may present less of an impact event as the edges of the fault self-peen, or smooth themselves out; the amplitudes now decrease. A measurement trend is therefore valuable to show the phases through which the signal has gone and to allow the user to infer the progression of the fault.

For trending of defect frequencies to be useful, baseline information

is required. It must be taken when the bearing is known to be in good condition and often enough to provide adequate resolution of the progression of the fault. In addition, initial experimentation with filter settings will help validate data. Knowledge of the machine and its bearings is essential to identify the frequencies to monitor. Because successful trending and correlation of data requires repeatable measurements, permanently mounted transducers are recommended.

Proper Installation, Application, and Experience Make Enveloping Work

When properly applied, enveloping can be a valuable tool for early detection of faults in machines with rolling element bearings and gearboxes. It is especially useful when applied in a periodic monitoring schedule and can provide condition information indicating faults in their earliest stages of development. With the help of Bently Nevada solutions and services, including enveloping techniques, machinery availability and reliability are more certain, and personnel can be more confident of the mechanical condition of the assets under their care.

In summary, to use enveloping techniques successfully, care must be taken in a variety of areas. Experience is extremely valuable. Machinery knowledge is critical. Proper configuration of the whole measurement system is essential. Equipment selection and application must be done with all these considerations in mind, and while a good product will make the use of enveloping easier, it is never a mindless exercise. Enveloping must be used with its capabilities and limitations in mind so that, if this is done, it can be a useful tool in the hands of a capable machinery analyst. ☺

Editor's Note: See also our article on page 58 for a case history on enveloping techniques in wind turbines.

Enveloping Now Supported in Selected Bently Nevada Products



The acceleration enveloping capabilities described in this article are now available in the following Bently Nevada products:

- Snapshot™ for Windows® CE portable data collector
- Snapshot™ IS portable data collector
- Trendmaster® Pro – Dynamic Scanning Module and selected Transducer Interface Modules (TIMs)

These hardware devices can be configured to provide acceleration enveloping and other signal processing functions that are particularly useful for managing machinery with rolling element bearings. Each is supported by System 1® software where acceleration enveloping data can be displayed, archived, and trended. In addition, basic level-type alarms can be established on various aspects of the enveloped data. By adding System 1 software's Decision SupportSM capabilities, you can even configure powerful rules that embed your own intelligence and machinery knowledge to automatically analyze enveloping data, spectral data, and other machinery and process measurements (temperature, oil condition, etc.). These rules can then generate customized, Actionable Information® advisories that streamline maintenance activities by providing proactive and intelligent information, enhanced by the early warning capabilities that acceleration enveloping can provide. ☺