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Application Note

Technique description – Envelope analysis for effective rolling-element bearing fault detection. Fact or fiction?

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ABSTRACT

Envelope analysis has been used for many years for diagnosing rolling-element bearing defects, but there is still considerable confusion on how it works and how effective it is. This Application Note intends to clear up this misunderstanding.

Introduction

Envelope detection, also sometimes referred to as “amplitude demodulation”, is a well-known signal processing technique used within the field of electronics and telecommunications.

During the 1980s, machine monitoring systems began using this technique primarily for rolling-element bearing (REB) fault detection and diagnostics. As digital technology evolved and made it easier to implement such techniques in low-cost, easy-to-use field instruments, envelope analysis became a very popular tool amongst maintenance personnel.

Envelope detection for REB faults utilises the frictional forces produced by fault-free, rolling-element bearings. These forces are influenced by surface and lubrication quality and they generate broadband random stationary vibration. When a fault develops, the vibration becomes amplitude-modulated due to periodic changes in the forces. This can originate from changes in friction, changes in pressure on the bearing surfaces, or from repetitive impact forces due to local surface defects. That means:

1. Amplitude modulation of the random friction forces, mostly due to mounting errors like radial tension or bearing misalignment.

2. Amplitude modulation of structural resonance excited by repetitive periodic impacts. This occurs when there are localised defects on the races or rolling-elements, e.g. in the case of indentations or cracks.

3. Amplitude modulation of deterministic frequencies (pure tone), i.e. characteristic frequencies of other machine elements (gear-mesh frequency, slot harmonics, blade-pass frequency, etc.), by bearing frequencies.

Both amplitude modulation due to modulating forces (geometric faults) and an increase in random stationary forces caused by frictional changes (lubrication problem) will show up in the envelope spectrum. (Note that they appear also in the original spectrum but are more difficult to extract and identify.)
When applied to REB diagnostics, the process of envelope analysis can be described as:

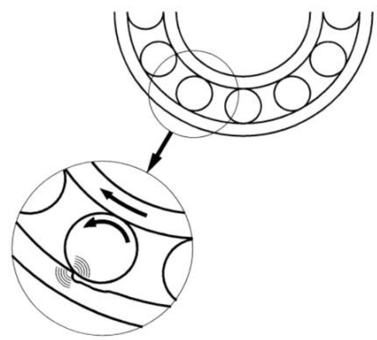

Figure 1.A defect in the outer race Causes a shock impulse to spread through the bearing components and machine structure.

- Selecting a frequency range in the vibration spectrum where the amplitude modulation occurs and removing all the components outside of the band. This is under the

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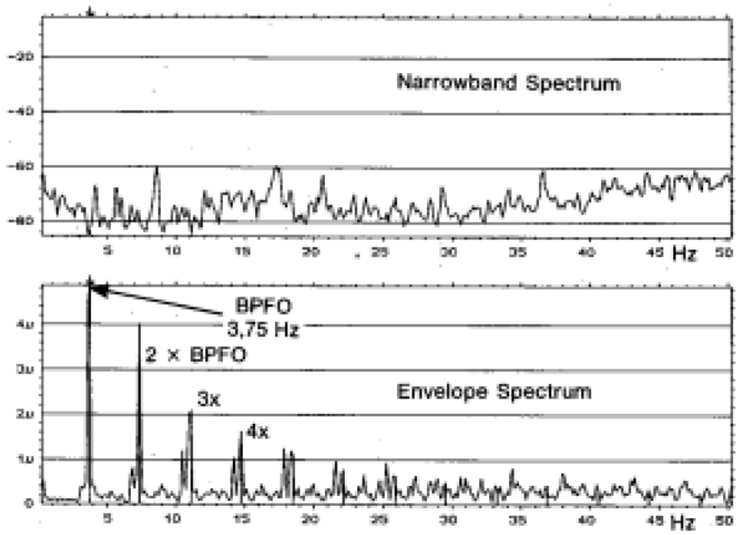

Figure 2. Comparison between narrow-band and envelope techniques. The narrow-band spectrum (upper) ,taken from a bearing which has a fault in the outer race, shows no sign of the fault. The lower display shows an envelope signal of the same signal.

assumption that the frequency components extracted are only related to bearing faults and not to other machine faults.

- Rectifying the remaining signal (carrier) to keep only its envelope (which represents the modulation effect) and re-analysing the latter in a low frequency range to identify the modulating frequency.

These are the basic principles of envelope analysis that are readily defined and accepted. However, when it comes to a discussion on the implementation of envelope analysis for REB fault detection and diagnosis, several different opinions emerge. These can be basically classified into four groups:

- Envelope analysis works, but only selectively on the high-frequency structural resonance.
- Envelope analysis works, but only selectively outside of the structural resonance, where the spectrum is flat.
- Envelope analysis works, *without being selective,* on a broad middle frequency range
- Envelope analysis *does not work*.

Selective envelope detection around high-frequency structural resonance

This approach is based upon the belief that only localised REB faults are of interest, and envelope analysis should therefore be used selectively on the high-frequency structural resonance (see 'Introduction' point 2). By selecting the high-frequency resonance, it makes in easier to avoid interferences from other vibration sources (e.g. gear-mesh, blade-pass, electrical forces, etc.) and their own modulating effects.

A disadvantage of this approach is that the system is made much less sensitive to random, friction-force modulation caused, for example, by uneven radial tension, misalignment or race slip. The argument to counter this is that other sources of friction-force modulation, other than those produced by impacts, are readily visible in the low-frequency part of the original FFT spectrum. Lubrication problems – without modulation effect – are clearly visible as well as a broadband increase in the original FFT spectrum itself.
This approach is the one most commonly used in the field. Regular condition monitoring techniques are used to highlight suspected resonance excitation caused by a local bearing problem and then envelope analysis is used to pinpoint the source of the problem.

Selective envelope detection outside of the structural resonance

In another approach, contrary to the previous one, envelope analysis is performed outside of the resonance area where the spectrum is relatively flat. The argument for this is that any

distortion produced by the structural resonance is avoided, allowing one to get a ‘true’ representation of the forces and their modulation. Consequently, all types of faults can be ‘quantified’ with indicators such as ‘modulation depth’ (difference between an harmonic level and the noise carpet level), and the harmonic content of the envelope spectra.

This is a very attractive approach even if it would seem difficult in such a complex structure as the body of a machine to identify a frequency range without either resonance or anti-resonance components. However, it has been successfully used in Russia where experiments on numerous bearings have yielded methods of distinguishing between different types of faults and their severity.

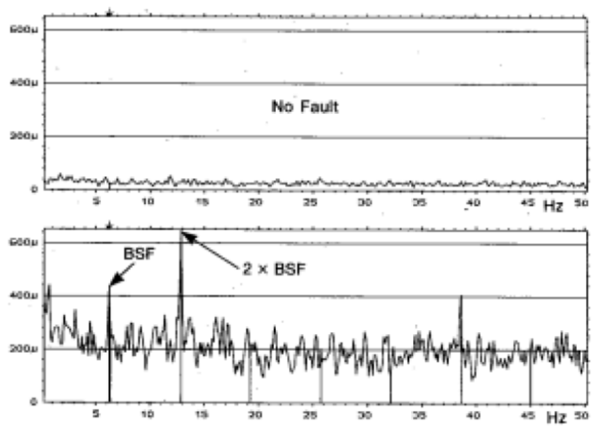

Figure 3. Envelope spectra from a healthy (upper) and a damaged (lower) bearing, showing how the envelope spectrum only displays peaks if a fault is present.

Broadband envelope detection

Whereas the first two methods require measurement data to pinpoint the location of structural resonances, the third approach does not.

A default ‘middle-frequency range’ is selected, typically starting from above 4 to 5 times the highest REB frequency and going up to 5 kHz. In theory this broadband will cover the range corresponding to the natural resonance frequencies of the rolling-element bearings and hence will detect most bearing faults. The selected frequency range is dependent upon the machine speed; This is not because the bearing’s natural frequencies depend upon the machine speed. The size of the bearing does depend upon it and therefore the resonance subsequently depends on the size of bearing.

The advantage of using the natural frequencies of the bearing elements is that they are equally excited/influenced by random-force modulation and impact-force modulation, as opposed to the high structural resonance frequencies, which are more sensitive to impacts. The main disadvantage however is that this middle-frequency range happens to be where all the other machine components have their characteristic frequencies – e.g. gear-mesh frequency and harmonic, blade-pass frequency, slot-passing frequency – and these are in turn amplitude-modulated by neighbouring elements including the bearing frequencies. However, there are investigations into the use of additional signal processing such as ‘self-adaptive noise cancellation’ to separate such effects.

Envelope detection – Best avoided!

As the popularity of envelope analysis has increased, so has the ambition level of its practitioners. Scalar descriptors have been derived from the envelope spectra, simplifying the trending of the phenomena. Empirical algorithms based upon statistical data have also been developed in an attempt to derive absolute limits. In an attempt to eliminate the need for trending altogether, specific descriptors have been used for a ‘single-shot’ assessment of REB condition.

But these are giant leaps! The nature of the signal transmission path, the differences found amongst machines of the same type and the very nature of the processing technique used make it fundamentally difficult to quantify

the default with a representative absolute value. Even if the nature of the transmission path did not complicate the interpretation, the natures of the faults themselves make maintenance decisions difficult. For example, which is more dangerous: A large indentation or a small transverse crack in the race? The first produces more modulating energy but can run for a long time provided there is adequate lubrication; the second can cause a collapse at any moment!

The consequences of such investigations have been profound. Faulty diagnoses and consequent errors in judgement have seriously undermined envelope analysis and alienated the technique further from the sceptics. This unfortunate situation has been further muddled by the issue of displacement sensors vs. acceleration sensors.

Some of the major arguments for the validity of the demodulation technique are in fact more based upon a preference for shaft displacement measurements than for acceleration sensor-based vibration measurements. However, there is absolutely no foundation for this, since signals from displacement sensors do not show more of the ‘real thing’ than those from acceleration sensors. Both show symptoms of the faults; the changes in the forces acting on the rotating elements alone, and not the resulting vibration, give a true representation of the fault. Unfortunately these forces cannot be directly measured.

Conclusion

Every good tool has its uses and its special place amongst the other tools in your toolbox. As a good tool, envelope analysis is no different. Based upon the evaluation of amplitude modulation of random vibration and structural resonance, there is no doubt that envelope analysis is an efficient way to detect, diagnoses and assess the condition of a rolling-element bearing.
Envelope analysis also has a much broader field of application if one considers that its main benefit is to ‘shift’ the high-frequency modulation effect into the low-frequency range. It therefore removes the need for an extremely high resolution that is often incompatible with the lack of speed stability encountered in rotating machines. Amplitude demodulation of pure-tone components is an indicator of fault identification. Some examples of this are modulation of the slot harmonics in electrical machines by the slip frequency, the gear-meshing frequency by one of the gears, or modulation of the blade-passing frequency by the rotating speed.

In addition, the use of the Hilbert transformation on a time signal zoomed around the carrier frequency, rather than filtering and rectifying as is commonly done for the REB fault diagnosis, provides not only amplitude- demodulation but phase-demodulation and frequency-demodulation as well. Frequency-demodulation opens up the field of new gearbox fault diagnostics and the not very well known problems of torsion.

But why carry around a complete toolbox if you are going to use only one tool? It is always recommended to use envelope analysis as part of an overall maintenance strategy together with other signal processing techniques, especially if a decision to shut down critical machinery is involved. FFT spectrum should be considered because it shows the entire original signal, while Cepstrum analysis, a purely linear transformation, can be used to separate effects due to the transmission path from those due to exciting forces. It is even possible to determine the size of the cavity or a spalling, which is more related to the severity of the fault than the extent of the modulation.

Finally can one conclude what is the correct approach to envelope analysis? In the end, since no article, conference paper or theory can replace years of successful monitoring experience with envelope analysis, there can only be one approach – try it and see the results for yourself!

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