ICSV14
Cairns • Australia
9-12 July, 2007
14th International Congress on Sound & Vibration

SEPARATING GEAR AND BEARING SIGNALS FOR BEARING FAULT DETECTION

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Abstract

This paper presents a technique for separating vibration signals generated by gears and rolling element bearings in rotating machinery for the detection of bearing faults. One of the most commonly used methods for detection of rolling element bearing fault is envelope analysis of the vibration signal, which often relies on the identification of structural resonances. However, envelope analysis can often be difficult when the measured vibration signal is dominated by gear mesh harmonics. The technique proposed in this paper uses a resampling process synchronised with respect to the shaft rotation and a multi-band filtering process that removes all shaft synchronous vibration components. The resulting non-synchronous signal is expected to be dominated by bearing vibration, to which an envelope analysis across the whole bandwidth should be sufficient for the extraction of bearing fault characteristic information. An application of this technique to test data shows that it is effective in detecting a small seeded raceway fault. In comparison to the commonly used envelope technique, the proposed method does not rely on the identification of prominent resonance peaks that are only excited by the faulty bearing vibration. The proposed technique should be particularly useful in cases where bearing excited resonances are not easily identifiable or they are corrupted by stronger gear mesh harmonics. It should be straightforward to implement the technique into any existing fault detection system that has a shaft speed signal.

1. INTRODUCTION

The envelope spectral technique [1][2], also referred to as high frequency resonance analysis, is widely accepted as a powerful tool in diagnosing faults in rolling element bearings. The envelope spectrum reveals outer race faults most effectively provided noise contamination is low. With the detection of inner race and rolling element faults, the intertwinement between the harmonics of fault frequency and their accompanying sidebands can make this technique difficult to use, especially in the presence of other vibration sources. The autocorrelation analysis of envelope signals [3] can resolve the above mentioned intertwinement problem. The envelope autocorrelation function exhibits a series of lag impulses corresponding to various integer-multiples of the characteristic fault periods. The envelope autocorrelation function presents a superior detectability to the envelope spectral analysis for the diagnosis of inner race and roller/ball faults. This superiority is particularly obvious if the signal is subject to large noise disturbance. However, the use of this technique may be limited by the threshold effect [4][5] of the envelope detection if a non-linear rectification (full-wave or square-law) process is employed.

Both envelope spectral and envelope autocorrelation techniques rely heavily on the identification of high frequency structural resonances which modulate the impulses generated by bearing elements striking the faults. It is often difficult to carry out such analyses when structural resonances are not readily identifiable or they are located within the bandwidth of gear mesh harmonics which are larger in amplitude than the bearing signals. A typical example is bearing fault detection of helicopter gearboxes, where the gear mesh vibration extends into the high frequency range and interacts with bearing fault related vibrations. In simple cases where gear and bearing signals are purely additive, it is probably not very difficult to separate them. But the gear bearing interactions are most likely to be multiplicative because gear mesh vibration has to pass through bearings to vibration sensors.

Antoni and Randall have developed several techniques [6][7][8][9] in separating gear and bearing signals. The spectral kurtosis (SK) technique [6][7] employs the kurtosis in time-frequency plane to search for an optimal demodulation band for envelope analysis. The 4^{th} order statistic, kurtosis, is used to detect transient vibration, which differs from the 2^{nd} order statistic used in short time Fourier transform or spectrograms. The self-adaptive noise cancellation (SANC) principle [8] can be used in separating additive gear and bearing signals. The technique presented in [9] is based on recognizing gear signals as being purely periodic, whereas bearing signals being random with approximately 2^{nd} order cyclostationarity (i.e., a periodic bivariate autocorrelation function).

In this paper, we propose a technique of separating vibration signals generated by gears and rolling element bearings for bearing fault detection. The technique uses a resampling process in the angle domain and removes all shaft synchronous components (SSC) including gear mesh harmonics in the order (i.e., normalised frequency) domain. The residual signal is then expected to expose the non-synchronous bearing vibration, which is usually much smaller than gear mesh vibration. When the mixture between SSC and bearing signal is additive, an envelope spectrum of the residual signal across the whole bandwidth should be sufficient to extract bearing fault characteristic information. If the interaction between SSC and bearing signal is multiplicative, the SSC’s will still show up in the residual envelope spectrum as modulation sidebands to bearing components. In this case, the SSC’s may need to be removed from the residual envelope spectrum to further expose the bearing fault frequency and its harmonics. An application of this technique to test data shows that it is effective in detecting a small seeded outer race fault. In comparison to conventional envelope techniques, the proposed method does not rely on the identification of prominent resonance peaks that are excited by the faulty bearing vibration. The proposed technique should be particularly useful in cases where bearing excited resonances are not easily identifiable or they are corrupted by stronger gear mesh harmonics. It should be straightforward to implement the technique into any existing fault detection system that has a shaft speed signal.

2. MIXTURE OF BEARING AND GEAR SIGNALS

The vibration signal generated by a bearing fault can be described by combining Braun's [10] and McFadden’s [11] models. The vibration induced by shaft rotation & gear mesh is denoted by $s(t)$, and the vibration by a bearing fault is $b(t)$,

$$s(t) = \sum_j A_j \cos(j\omega_s t + \phi_j)\,, \tag{1}$$

$$b(t) = \sum_k B_k \left(e^{-(t-kT)/\alpha} \cdot \cos[\omega_n (t-kT)] \cdot U(t-kT)\right), \tag{2}$$

where j is the shaft order number, A_j and ϕ_j are amplitude and phase, respectively, at j^{th} order and ω_s is the shaft rotation frequency (in *rad/sec*). In the bearing signal shown in Eq. 2, T is the characteristic fault period (i.e., the reciprocal of the fault frequency $2\pi/\omega$), and ω_n the structure resonant frequency exited by bearing fault. α denotes the time constant for the exponential decay of the resonant oscillations, which is determined by system damping, and $U(t)$ is a unit step function. B_k represents the peak amplitude of k^{th} impulse produced by the bearing fault. When the bearing fault is small, the amplitude of $b(t)$ can be much less (about 100 times smaller in the example shown later in the paper) than that of $s(t)$. The shaft synchronous signal $s(t)$ and bearing fault induced signal $b(t)$ can be mixed together in both additive and multiplicative (by a factor of σ = 0~1) forms, resulting a signal

$$x(t) = s(t) + b(t) + \sigma \cdot s(t)b(t) = s(t) + [1 + \sigma s(t)] \cdot b(t) \tag{3}$$

In practice, the actual measured signal will be the convolution of signal $x(t)$ with the system's transmission path function $h(t)$ plus measurement noise. Hence, the measured vibration signal is usually expressed by

$$y(t) = x(t) \otimes h(t) + n(t)\,, \tag{4}$$

where $\otimes$ denotes the convolution operation, and $n(t)$ is the measurement noise which is assumed random. For bearing fault detection we need to extract $b(t)$ from $y(t)$, or from $x(t)$ if system and noise effects are neglected for mathematical simplicity. The conventional, and usually very effective, approach is envelope analysis, where resonance frequency ω_n is readily identifiable and it is outside, and normally much higher than (which is why it is often referred to as high frequency resonance analysis) the signal bandwidth associated with $s(t)$ so that $b(t)$ and $s(t)$ shown in Eq. (3) are separated by their bandwidths.

In cases where ω_n is not easily identifiable and/or it is within the signal bandwidth of $s(t)$, which is often true for complex machinery such as helicopter gearboxes, the envelope analysis will not be effective because $s(t)$ is usually much bigger than $b(t)$ when they are seen in the bandwidth of $s(t)$. This paper presents a technique where $b(t)$ and $s(t)$ can be separated based on the fact that $s(t)$ is synchronous but $b(t)$ is non-synchronous to shaft rotation, i.e., frequency content of $s(t)$ is on integer shaft orders (1, 2, 3, …) whereas $b(t)$ is on non-integer orders (e.g., 4.89, 9.78, …). Using this technique, $b(t)$ and $s(t)$ may be readily separable if factor σ in Eq. (3) is zero or negligible, i.e., $b(t)$ and $s(t)$ are purely additive. For non-zero σ, $b(t)$ and $s(t)$ become both additive and multiplicative, then the bearing signal $b(t)$ may be extracted in three steps:

- Removing additive $s(t)$ from the spectrum of angle domain resampled $x(t)$;
- Calculating envelope spectrum of the residual signal $[1+ \sigma \cdot s(t)]b(t)$ where bearing signal $b(t)$ can be regarded here as the 'carrier';
- Removing modulation sidebands around DC and harmonics of the fault characteristic

frequency $\omega = 2\pi / T$ in the residual envelope spectrum.

3. TEST DATA

The data were acquired on a bearing test rig with a pair of undamaged gears at 1:1 ratio in the University of New South Wales. An acceleration signal and a tachometer signal were used for the analysis of this paper. The test bearings were of type Koyo 1250 (double row self-aligning ball bearing). The tests were conducted using one good bearing and one faulty bearing with a localized outer race fault. The gear/bearing shaft speed was 10Hz, and the gear torque load was 100Nm. The following table shows other relevant parameters about the rig and the test.

Shaft speed	Gear tooth number	Data sampling rate	Ball diameter d	Pitch circle diameter D	No. of balls per row N	Contact angle ϕ	Outer race fault freq.	Gear mesh freq.
10Hz	32:32	48kHz	7.12mm	38.5mm	12	0º	48.9Hz	320Hz

Note: Koyo 1250 has an outer race diameter of 44.85mm & an inner race diameter of 32.17mm.

4. ENVELOPE ANALYSIS OF TEST DATA

Fig. 1 shows the good bearing raw vibration signal and its spectrum with a FFT length of 4096 samples. We can see that the raw spectrum is dominated by the gear mesh frequency at 320Hz and its harmonics. The spectral power decays by more than 50dB (from the peak at 320Hz) at about 7kHz before a structural resonance at about 7.5kHz. Fig. 2 shows the results of standard envelope analysis using highpass filters from 5kHz and 10kHz. As can be seen, both envelope spectra are showing the pattern of gear mesh harmonics modulated by the shaft frequency, i.e., 320Hz and its harmonics are surrounded by sidebands of 10Hz spacing.

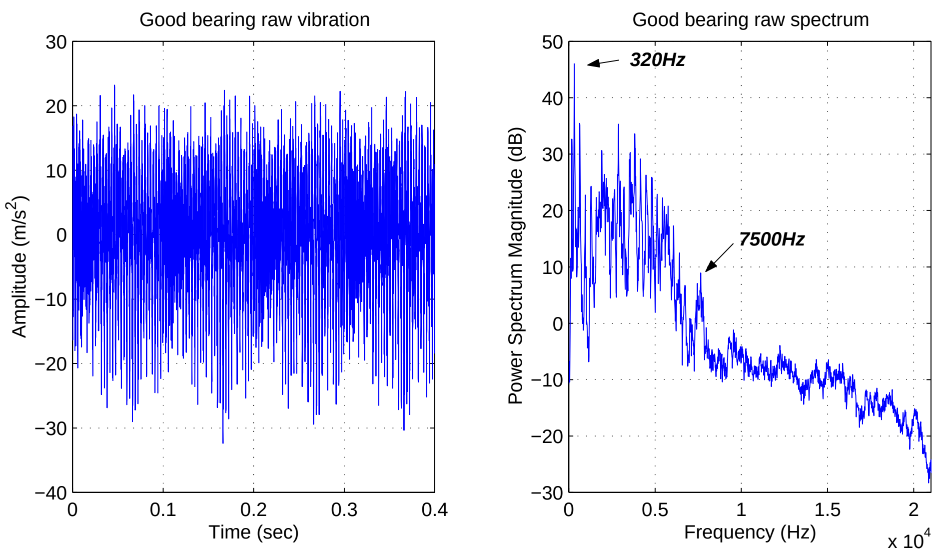

Figure 1. Good bearing raw signal & spectrum (NFFT=4096)

Fig. 3 is the raw vibration signal and its spectrum for the faulty bearing with a localized outer race fault (ORF). Because the ORF was very small and the dominance of gear signal, it is normal for the bearing fault characteristic frequency to be undetectable in the raw spectrum. However, it should be detectable in the envelope spectrum provided the demodulation band is appropriately selected. When comparing the raw spectra of the good bearing case with that of the faulty bearing case, we find that a resonant hump at 5.6kHz stands up in the faulty bearing spectrum and we also find some differences at the frequency band above 8kHz between the two spectra. Consequently, we conducted envelope analyses on the faulty bearing signal using 5kHz and 10kHz highpass filtering before demodulation. The results are shown in Fig. 4.

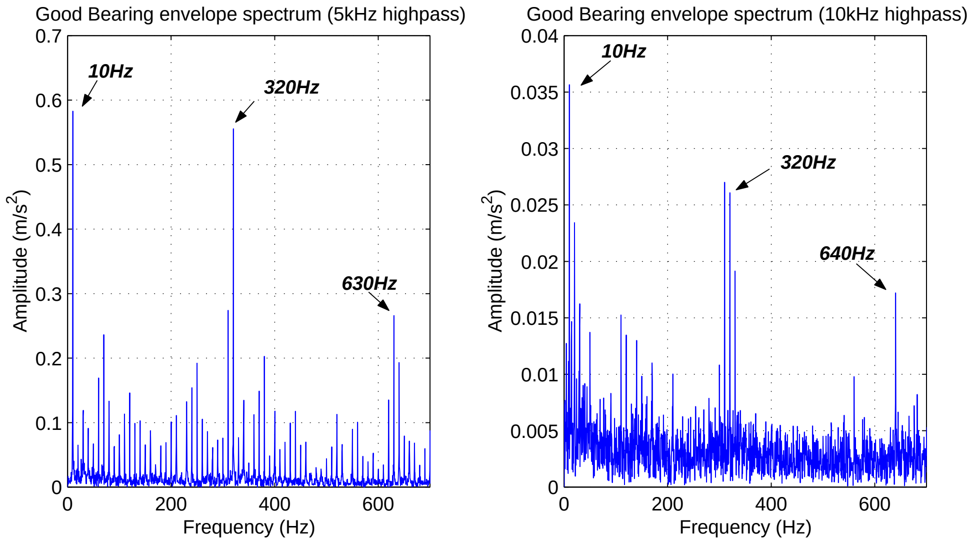

Figure 2. Good bearing envelope spectra (5kHz & 10kHz highpass)

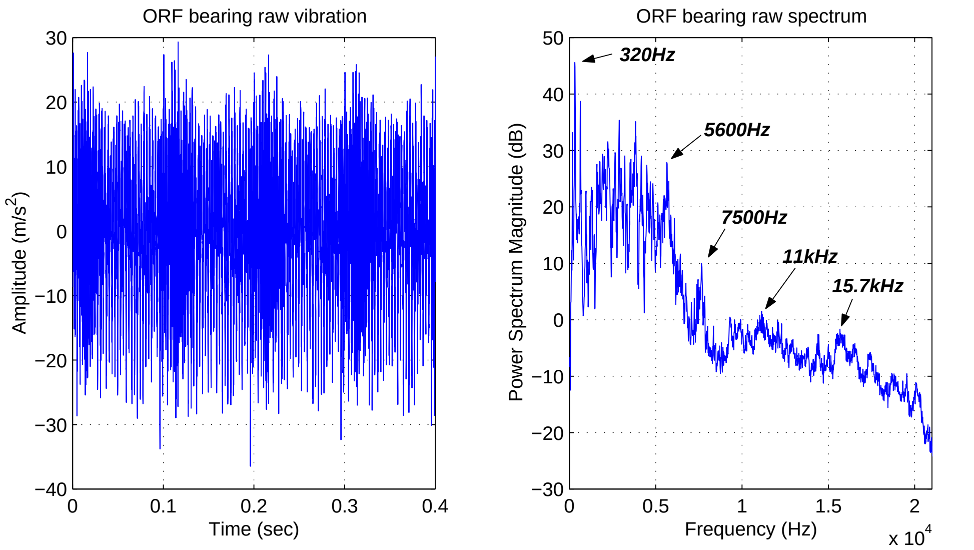

Figure 3. ORF raw signal & spectrum (NFFT=4096)

In Fig.4, we find that the 5kHz highpass envelope spectrum is still dominated by the harmonics of shaft frequency (10Hz), which prevents the ORF frequencies (48.9Hz and its harmonics) from being detectable. Referring back to Eq. (3), this basically means that $s(t)$ is still much bigger than $b(t)$ in the frequency range of 5kHz and above. In contrast, the 10kHz highpassed spectrum brings up the ORF harmonics perfectly, which allows detection of the ORF. This demonstrates that it is crucial to select the right demodulation band for envelope analysis. In the following section, we will employ the 10kHz lowpassed signal, where $s(t)$ is much bigger than $b(t)$, to demonstrate the capability of the proposed technique.

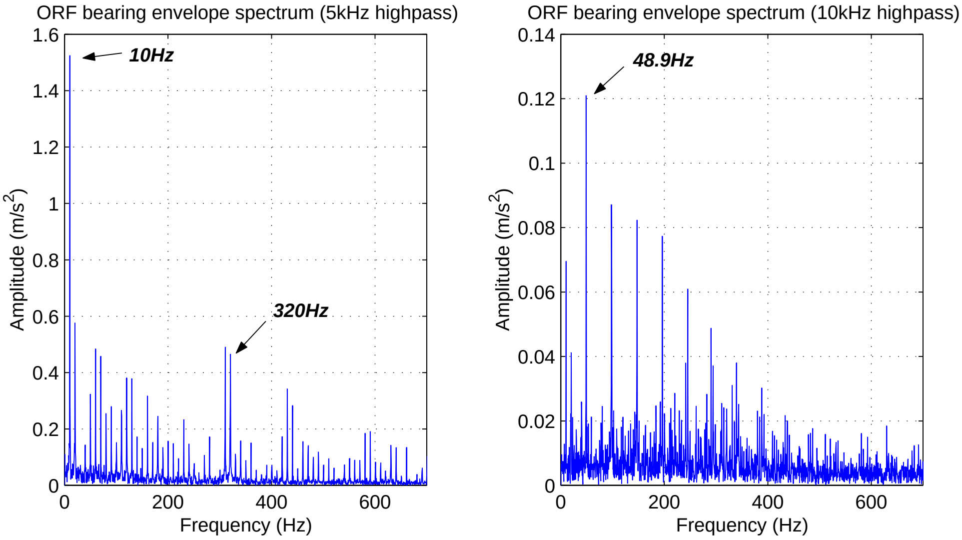

Figure 4. ORF envelope spectra (5kHz & 10kHz highpass) with f_o=48.9Hz revealed

5. ANGLE DOMAIN RESAMPLING AND SIGNAL SEPARATION

As mentioned in previous sections, the fundamental difference between gear and bearing vibration signals is that gear signal is synchronous to the rotation of gear/bearing shaft but the bearing signal is not. Therefore, it is possible to separate gear and bearing signals through an angle domain resampling of the raw vibration signal over multiple revolutions of the gear/bearing shaft. A single Fourier transform with large FFT length is then applied to the entire resampled signal. The amplitude spectrum can be plotted in the order (normalised frequency) domain. In the amplitude spectrum, the synchronous components are expected to be located at integer multiples of the shaft order and non-synchronous ones are at non-integer multiples of the shaft order; hence the gear and bearing components can be separated by order domain filtering.

When the bearing fault is small, the amplitude of $b(t)$ can be much less (about -20dB in the example shown here) than that of $s(t)$. For the detection of bearing faults, the synchronous components can be set to zero in the order domain because the angle domain resampled signals are purely periodic. The residual signal should only contain non-synchronous content, such as those produced by localized bearing faults. A demodulation (or enveloping) process across the broad band, if no particular band is known to be associated with bearing fault excitation, should expose the bearing fault characteristic frequencies and their harmonics.

However, in case of multiplicative mixture of bearing and gear signals as shown in Eq. (3) with a non-zero σ, the shaft frequency harmonics can shown up as modulation sidebands at DC and harmonics of bearing fault frequencies in the residual envelope spectrum. This is because the force fluctuation caused by gear mesh, unbalance and misalignment etc. is passed onto bearing load through their common shaft, which in turn causes a modulation of the bearing signal by the SSC. It is important to point out that, in the spectrum of the resampled signal, the modulating SSC's around bearing fault related harmonics are located at non-integer multiples of the shaft order, e.g., $(k\times\omega \pm j\times\omega_s)$ where ω is the bearing fault characteristic frequency and ω_s the shaft frequency and ω/ω_s is non-integer. A demodulation or enveloping process is necessary to turn the modulating SSC's into baseband components around DC (integer multiple of the shaft order) and around bearing fault related harmonics (still non-integer multiple), see Fig. 5(a). The following steps outline the process for the proposed technique:

- Resample raw signal (data length of multiple shaft revolutions to allow sufficient resolution) in angle domain with respect to shaft speed signal;
- Fourier transform of the resampled signal;
- Remove spectral components corresponding to the integer multiples of the shaft order (the normalised frequency) in the order domain;
- Inverse Fourier transform the remaining to get residual signal;
- Demodulate the residual signal;
- Fourier transform again to obtain residual envelope (RE) spectrum;
- Remove shaft harmonics (at integer shaft orders) in RE spectrum to obtain the residual envelope residual (RER) spectrum;
- Remove, if necessary, the sidebands around bearing fault frequency and its harmonics.

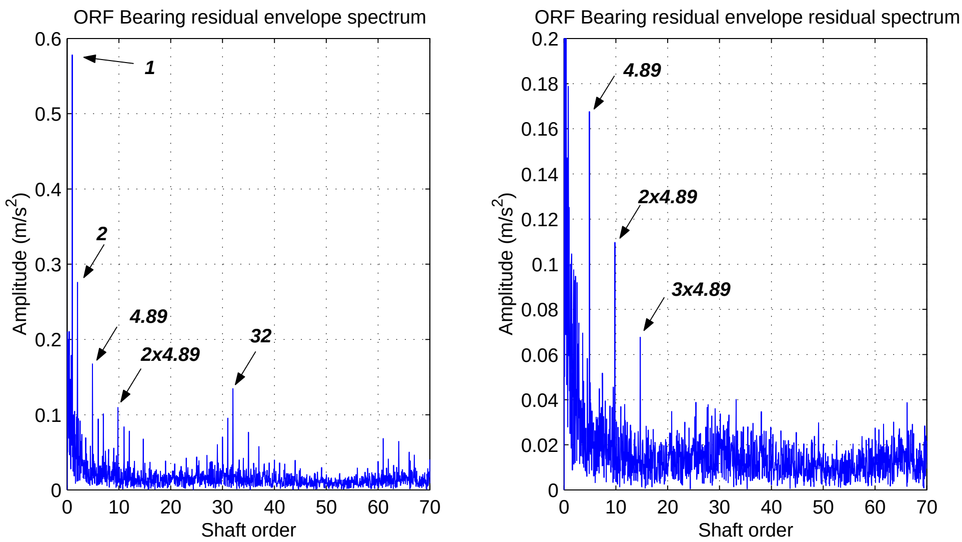

Figure 5. ORF bearing residual envelope (RE) spectrum & residual envelope residual (RER) spectrum with 10kHz lowpass to the original signal

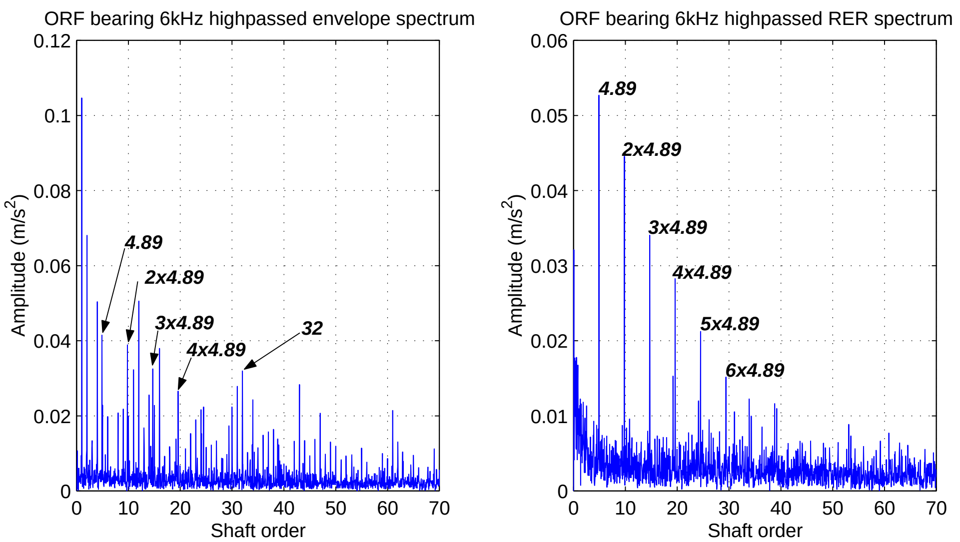

Figure 6. ORF bearing conventional envelope spectrum & residual envelope residual (RER) spectrum with 6kHz highpass demodulation filters

Fig. 5 shows the RE and RER spectra for the test with an ORF bearing. Before conducting angle domain resampling, the raw signal, covering 20 revolutions of the shaft, was lowpass filtered at 10kHz which is the band that conventional envelop analysis is unable to detect the ORF (see Fig. 4a). As seen in Fig. 5(a), the ORF harmonics (48.9Hz …) are revealed in the RE spectrum but they are still dwarfed by the shaft harmonics (10Hz …). By removing the shaft harmonics we make the ORF harmonics clearer in the RER spectrum. Fig. 6 presents the result of a comparison between the conventional envelope spectrum and the RER spectrum in a frequency range (i.e., > 6kHz) where SSC's are still dominating. It is evident that the RER spectrum displays the ORF characteristic frequency and its harmonics much more clearly. For the good bearing signal shown in Fig. 1, the RER spectrum showed no evidence of ORF harmonics.

6. CONCLUSIONS

This paper has presented a technique of separating vibration signals generated by gears and rolling element bearings for bearing fault detection. The technique supplements the commonly used envelope analysis techniques for situations where bearing excited resonances are not easily identifiable in the presence of much stronger gear mesh harmonics. It is very effective for the simple additive and quite applicable for the complex multiplicative interactions between bearing signals and shaft synchronous components (SSC) including gear mesh harmonics. Due to its straightforward process, the proposed technique may be implemented without great difficulty into any existing fault detection system that has a shaft speed reference.

(*The author would like to thank Prof. R.B. Randall of UNSW for providing the test data for this work.*)

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