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Frequency Estimation in the Fault Detection of Rolling Element Bearing

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Abstract

Faulty rolling element bearings under very low shaft speed and light load exhibit vibrations which possess periodic envelope-autocorrelations. The main frequencies of this envelope-autocorrelation are the fault characteristic frequency and its harmonics. In this paper, one of the improved Notch Filtering Techniques with a designed filter is used to estimate the fault characteristic frequency and its harmonics. The designed filter is used to remove the estimated frequency. With this technique, the fault characteristic frequency and its harmonics can be accurately estimated.

1 Introduction

The condition monitoring of rotating machinery can reduce operational and maintenance costs, provide a significant improvement in plant economy, especially for the condition monitoring of rolling element bearings which are the most commonly wearing parts in rotating machinery.

A variety of bearing fault detection techniques have been proposed. The non dimensional amplitude parameters [1, 6], such as Crest factors(Cf), Kurtosis value(Kv), and so on, are reliable only in the presence of significant impulsiveness.

Spectral analysis of bearing vibration in which the fault signals are not submerged in background noise frequencies and other structural resonance frequencies is the useful diagnostic and fault detection technique. The cepstrum [1, 2], while it is seldom used on its own, is an invaluable complementary technique to spectral analysis. It is also limited

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to use when strong background noise and other structural signals do not swamp the fault vibration signal.

Envelope power spectrum [4] is very useful in the presence of a high background noise level, but in complex structures it also contains many other frequencies and side frequencies.

A moving window technique in the fault detection of a ball bearing has been investigated in [5], the signal to noise ratio of measured vibration signature of a ball bearing is improved using this technique. The algorithm is quite powerful in the early detection of flaws in a ball bearing system.

Raw spectra or the demodulated ones of a signal from defect bearings have an EFSD pattern ("equal frequency spacing distribution") [7], the spacing of the main peak is the defect frequency, and the features of multiple defects are the superposition of these of each defect.

An impulse index based on the Haar transform, and the phase-shift effect on both Haar transformed data and the impulse index have been investigated in [8].

Most of these techniques are only available to the normal shaft speed. They are useful in laboratory condition, but will not be so effective in the harsh environment of factory plants, especially when the speed is less than 100 RPM. Some of them may be useful for the outer race fault, but not for the inner race fault and roller fault. The outer race fault is easily detected in comparison with the inner race fault and the roller fault [1, 4], because the outer race is usually closer to the transducer.

AR spectral estimation in low speed has been investigated [9], it is very effective for vibration signal without high resonance frequencies and noise frequencies, but in practical condition, the vibration signal from accelerometer usually contains some large peak high resonance frequencies and noise frequencies, the low fault characteristic frequency signal may be weak, because the accelerometer is much more sensitive to the middle and high frequencies.

In this paper, a frequency estimation technique based on notch filtering proposed by Quinn and Fernandes is used to estimate the fault characteristic frequency and its harmonics of the envelope-autocorrelation from the fault rolling element bearing under the very low shaft speed and the light load. The designed filter is used to remove the estimated frequency.

2 Frequency Estimation Method

2.1 Frequency Estimation for Envelope-Autocorrelation

For periodical envelope-autocorrelation $R_{zz}(t)$ from the fault rolling element bearing under the very low shaft speed and the light load [14] can be expressed

$$R_{zz}(t) = \mu + \sum_{j=1}^{N_R} A_{RR}^j \cos(j\omega_0 t + \phi_{RR}^j) + n(t), \quad (1)$$

where μ is the mean value, ω_0 is the fault characteristic frequency of the rolling element bearing. A_{RR}^j and ϕ_{RR}^j are the amplitude and the initial phase of j-th harmonic, and N_R is the number of harmonics. $n(t)$ is some zero-mean random noise sequence with variance σ^2. This is a multi-harmonic frequency estimation problem.

The maximum likelihood frequency estimation [12] for the envelope-autocorrelation is

$$\hat{\omega}_p = \max_{\omega} I_R(\omega), \tag{2}$$

where

$$I_R(\omega) = |\sum_{t=1}^{T-1} R_{zz}(t)e^{-i\omega t}|^2. \tag{3}$$

The maximization of I_R is computationally intensive, particularly if T is large.

2.2 Technique of Quinn and Fernandes in Frequency Estimation

Quinn and Fernandes [11] have suggested a computationally efficient and near statistically efficient method for estimating frequency by estimating the parameters α and β in the following equation:

$$R_{zz}(t) - \beta R_{zz}(t-1) + R_{zz}(t-2) = n(t) - \alpha n(t-1) + n(t-2), \tag{4}$$

subject to $\alpha = \beta$. The estimated frequency is found from

$$\hat{\omega}_0 = \cos^{-1}(\frac{1}{2}\beta).$$

The algorithm proceeds as follows:

1. Set $\alpha = \alpha_1 = 2\cos(\hat{\omega}_i)$ where $\hat{\omega}_i$ is some initial estimate of ω_0 and set $j = 1$.

2. Filter the data to produce $\zeta_{t,j}$

$$\zeta_{t,j} = R_{zz}(t) + \alpha_j \zeta_{t-1,j} - \zeta_{t-2,j}; \qquad t = 0, 1, \cdots, T-1 \tag{5}$$

   where $\zeta_{t,j} = 0$ for $t < 0$.

3. Form β_j by regressing $(\zeta_{t,j} + \zeta_{t-2,j})$ on $\zeta_{t-1,j}$

$$\beta_j = \frac{\sum_{t=0}^{T-1} (\zeta_{t,j} + \zeta_{t-2,j})\zeta_{t-1,j}}{\sum_{t=0}^{T-1} \zeta_{t-1,j}^2} \tag{6}$$

4. If $|\alpha_j - \beta_j|$ is small enough, set $\hat{\omega}_0 = \cos^{-1}(\frac{1}{2}\beta_j)$ and terminate. Otherwise, put $\alpha_{j+1} = \beta_j$, increment j and go to step 2.

The Quinn-Fernandes technique effectively estimates the frequency at which the peak of a smoothed periodogram occurs [13].

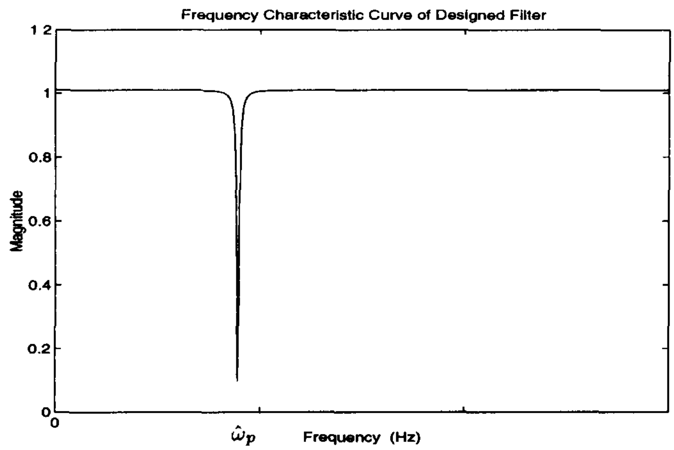

Figure 1: The frequency characteristic curve of the designed filter

2.3 Design of Filter for Removing the Estimated Frequency

Often, once a frequency is estimated accurately, it is desirable to remove this frequency from the signal. Applying the filter

$$H(z) = \frac{1 - 2\cos(\hat{\omega}_p)z^{-1} + z^{-2}}{1 - 2\alpha\cos(\hat{\omega}_p)z^{-1} + \alpha^2 z^{-2}} \tag{7}$$

where $\alpha = 0.99$ to the signal will have the desired effect.

Note that α is chosen to be less than one to ensure that the filtered signal is bounded (i.e. this ensures that the filter is strictly stable).

The frequency characteristic curve of the designed filter is shown in Fig.1. With this filter, the estimated frequency is easily removed from the signal.

3 Frequency Estimation in Fault Detection of Rolling Element Bearing

The in-situ vibration data are from a bearing housing which supports two descaler pinch rolls. The pinch rolls run at a very low shaft speed under the random variation with a small range about the mean. The bearings of interest are of type SKF23226 double row spherical roller bearings.

The acceleration signal in Fig.2a is from a bearing with inner race fault. The mean shaft speed of rolls is 36.06 $RPM(0.601Hz)$. Fig.2b is the envelope-autocorrelation of Fig.2a. Fig.3a is the acceleration signal from a bearing with good condition, and Fig.3b is the envelope-autocorrelation of Fig. 3a. The periodicity of envelope-autocorrelation from the fault bearing is notable (see Fig.2b), but it is not the case for the good condition bearing (see Fig.3b).

Fig.4 is the frequency estimation of envelope-autocorrelation (shown in Fig.2b). Fig.4a is the power spectrum of envelope-autocorrelation, and the inner race fault characteristic frequency $\hat{\omega}_0 = 6.513Hz$ is estimated. Fig.4b is the power spectrum after the removal of the inner race fault characteristic frequency $\hat{\omega}_0 = 6.513Hz$, and the 2-*nd* harmonic $\hat{\omega}_1 =$

13.042Hz is estimated. Fig.4c is the power spectrum after the removal of $\hat{\omega}_0 = 6.513Hz$ and $\hat{\omega}_1 = 13.042Hz$, and the 3-*rd* harmonic $\hat{\omega}_2 = 19.572Hz$ is estimated, and so on.

4 Conclusions

In this paper, the technique of Quinn and Fernandes is used in frequency estimation of envelope-autocorrelation from the fault rolling element bearing under very low shaft speed and light load. Using this estimated frequency, a simple notch filter removes the frequency component so that further detail in the vibration signal may be analysed. In this instance, the fault characteristic frequency and its harmonics are estimated (see Fig.4) and subsequently removed with this technique.

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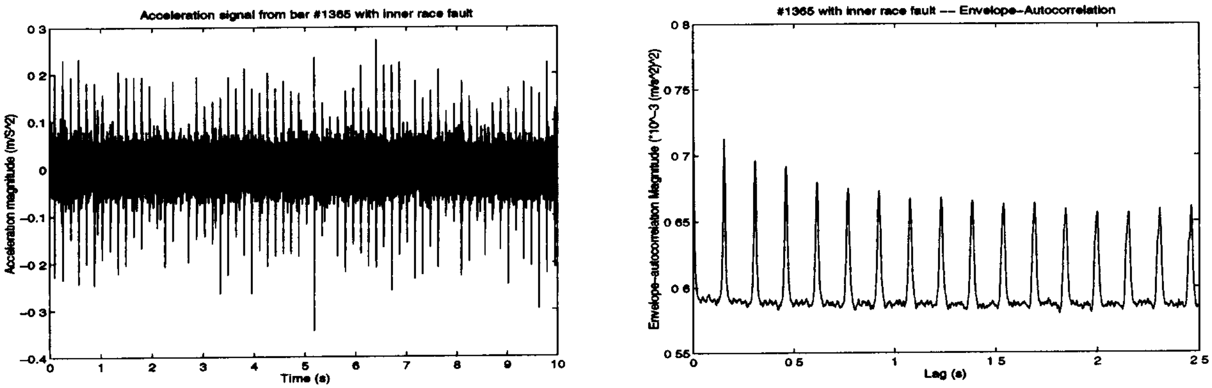
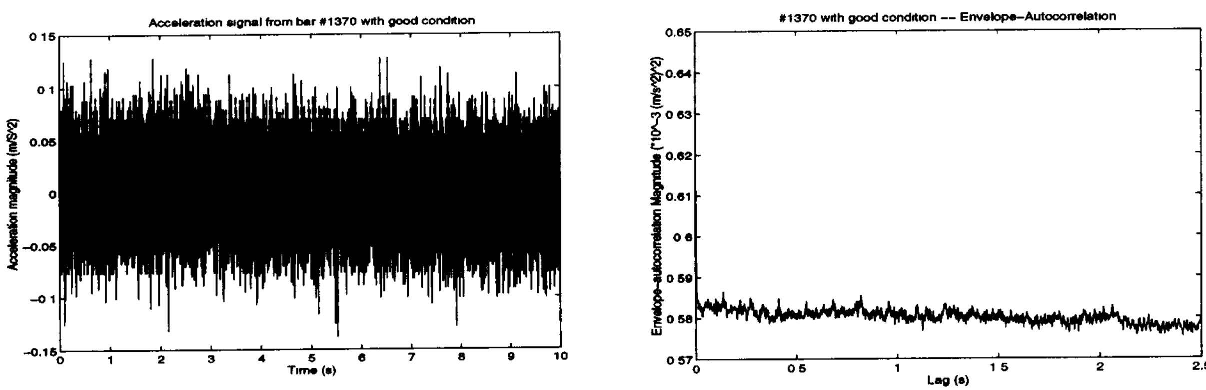


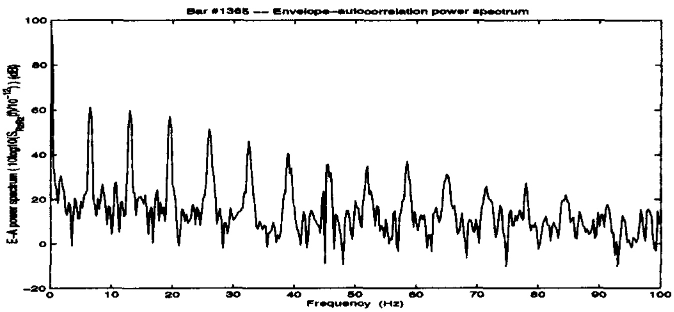
(a) (b)

Figure 2: In-situ data from the bearing with inner race fault ($f_{samp} = 5000Hz$): (a) – acceleration signal from bar #1365, (b) – envelope-autocorrelation of (a)

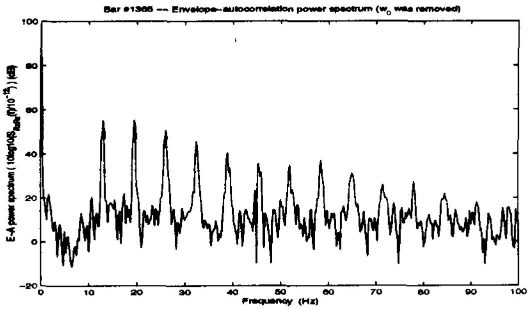


(a) (b)

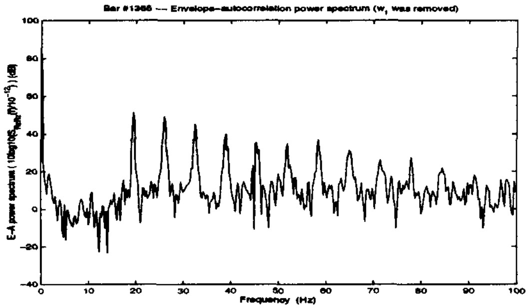
Figure 3: In-situ data from the bearing with good condition ($f_{samp} = 5000Hz$): (a) – acceleration signal from bar #1370, (b) – envelope-autocorrelation of (a)



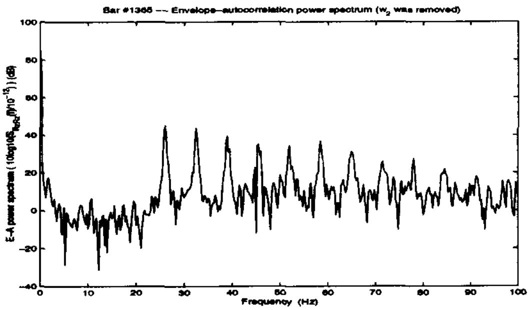
(a) The inner race fault characteristic frequency $\hat{\omega}_0 = 6.513Hz$ was estimated



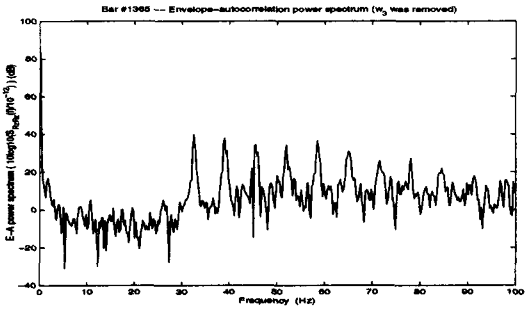
(b) $\hat{\omega}_0 = 6.513Hz$ was removed and the 2-nd harmonic $\hat{\omega}_1 = 13.042Hz$ was estimated



(c) $\hat{\omega}_1 = 13.042Hz$ was removed and the 3-rd harmonic $\hat{\omega}_2 = 19.572Hz$ was estimated



(d) $\hat{\omega}_2 = 19.572Hz$ was removed and the 4-th harmonic $\hat{\omega}_3 = 26.110Hz$ was estimated



(e) $\hat{\omega}_3 = 26.110Hz$ was removed

Figure 4: Frequency estimation and removal of estimated frequency