Bi-spectrum Analysis Based Bearing Fault Diagnosis

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Abstract—A novel method for detection and diagnosis the bearing inner and outer race fault according to bi-spectrum analysis technique is presented. The bi-spectrum analysis is widely recognized as an effective technique for machinery fault diagnosis using vibration signals since it can be used to eliminate the effect of strong noise. This advantage makes it very suitable for extracting useful features from the noisy mechanical vibration signals in gearbox transmission system. The experimental results show that the bi-spectrum analysis technique can effectively extract the transients from strong noise signals and diagnose the fault of bearing.

Keywords—fault diagnosis; bearing; vibration; bi-spectrum; signal processing

I. INTRODUCTION

Bearings are an important element in a variety of industrial applications such as machine tool and gearbox. An unexpected failure of the bearing may cause significant economic losses. For that reason, fault detection of bearing has been the subject of intensive research. Vibration signal analysis has been widely used in the fault detection of rotation machinery. Many methods based on vibration signal analysis have been developed. The spectral contents of emitted vibration signals are analyzed to ascertain the current condition of the monitored process. Vibration signal analysis has been widely used in the fault detection of rotation machinery. Many methods based on vibration signal analysis have been developed [1]. These methods include power spectrum estimation, envelope spectrum analysis, cepstrum analysis [1], wavelet transform [2-14], Hilbert-Huang transform [15,16], Teager-Huang Transform [17] and Wigner-Ville distribution (WVD) [18,19], which have been proved to be effective in bearing fault detection. However, the vibration signals are almost always interfered by random noises from near mechanical components. These noises reduce the signal-to-noise ratio (SNR) and affect the fault diagnosis result. Therefore, it is very important to eliminate the random noise and extract useful features from the mechanical vibration signals. Higher order statistics can effectively suppress additive Gaussian noise of unknown power spectrum and extract the fault feature [20,21].

In this work, we introduce the approach for extraction useful features from the noise-contaminated mechanical signals. An application of bi-spectrum technique to bearing fault diagnosis is presented. This paper is organized as follows. Section II, presents the principle and procedure of bi-spectrum. Section III, gives a brief description of experimental set-up. Section IV, gives the applications of the method based on bi-spectrum to bearing fault diagnosis. Finally, our conclusions are provided in section V.

II. INTRODUCTION OF BI-SPECTRUM

Higher order spectra are defined as multi-dimensional Fourier transform of higher order moments or cumulant. In practice, most widely used higher order spectra are the third order spectrum (i.e. bi-spectrum). Bi-spectrum is defined as 2-dimensional Fourier transform of the third order cumulant.

Let \{x(n)\} be a real, discrete, zero-mean stationary process with third-order cumulant \( R_{xx}(\tau_1, \tau_2) \) defined as

\[
R_{xx}(\tau_1, \tau_2) = E[x(n)x(n + \tau_1)x(n + \tau_2)]
\]  

(1)

Then the bi-spectrum of \{x(n)\} is given by the expression

\[
B_{xx}(\omega_1, \omega_2) = \sum_{\tau_1=-\infty}^{\infty} \sum_{\tau_2=-\infty}^{\infty} R_{xx}(\tau_1, \tau_2)e^{-j(\omega_1 \tau_1 + \omega_2 \tau_2)}.
\]  

(2)

where \( |\omega_1| \leq \pi \), \( |\omega_2| \leq \pi \), \( |\omega_1 + \omega_2| \leq \pi \).

From Eq (2), we can know that the bi-spectrum is complex valued, contains phase information, and is a function of two independent frequencies, \( \omega_1 \) and \( \omega_2 \).

Therefore, in the same way that the power spectrum decomposes the power of a signal, the bi-spectrum decomposes the third-order cumulant. The bi-spectrum is a function of two frequency variables, \( \omega_1 \) and \( \omega_2 \), and whilst the power spectrum includes the contribution of each individual frequency component independently, the bi-spectrum analyses the frequency interaction between the frequency components at \( \omega_1 \), \( \omega_2 \) and \( \omega_1 + \omega_2 \). Therefore, the power spectrum is of limited value in analyzing vibrations where non-linearities are involved; whereas the bi-spectrum provides supplementary information.

III. EXPERIMENTAL SET-UP

The bearing vibration test apparatus used in this study is...
shown in Figure 1 [15,16]. The vibration signals of the bearing fault are sampled on a single-stage gearbox. The monitoring and diagnostic system is composed of four accelerometers, amplifiers, B&K 3560 spectrum analyzer and a computer. The sampling frequency is 32768 Hz and the sampling point is 8192. The tested bearing was used to study only one kind of surface failure: the bearing was damaged on the inner race or outer race. The rolling bearing tested has a groove on inner race or outer race. Localized defect was seed on the inner race or outer race by an electric-discharge machine to keep their size and depth under control. The size of the artificial defect was 1mm in depth and the width of the groove was 1.5mm. The input motion is produced by an AC motor. The speed of the spindle is 1500r/min, that is, the rotating frequency $f_o$ is 25 Hz. The type of the ball bearing is 208. There are 10 balls in a bearing and the contact angle $\alpha = 0^\circ$, ball diameter $d = 55/3$ mm, bearing pitch diameter $D = 97.5$mm. Then the characteristic frequency of the inner race defect and outer race defect can be calculated by the Eq.(3) and Eq.(4) respectively.

$$f_{inner} = \frac{z}{2} \left(1 + \frac{d}{D} \cos \alpha \right) f_o, \quad (3)$$

$$f_{outer} = \frac{z}{2} \left(1 - \frac{d}{D} \cos \alpha \right) f_o, \quad (4)$$

Therefore, according to Eq.(3) and Eq.(4), the characteristic frequency of the inner race defect and outer race defect are calculated to be at 148.5Hz and 101.5 Hz respectively.

IV. BEARING FAULT DIAGNOSIS BASED ON BI-SPECTRUM ANALYSIS

In this section, the bi-spectrum analysis will be applied to vibration signal measured from a gearbox for bearing fault diagnosis. We analyze bearing vibration signals using bi-spectrum. Also, comparison results with that of power spectrum and envelope spectrum, bi-spectrum and angle slice bi-spectrum are given.

A. Bearing inner race fault diagnosis based on bi-spectrum

The original vibration signal of inner race defect is displayed in Figure 2. It is clear that there are periodic impacts in the vibration signal. There are significant fluctuations in the peak amplitude of the signal, and there are also considerable variations of frequency content. From Figure 2, we can hardly find the characteristic period of the inner race defect.

$$\text{Figure 2. Original vibration signal with inner fault}$$

Figure 3 shows the power spectrum of the vibration signal with bearing inner race fault. There is no fault characteristic frequency component around 148.5Hz. Therefore, the conventional power spectrum was not capable of revealing the characteristic frequency of inner race fault, which was corrupted by the modulation and noise.

$$\text{Figure 3. Power spectrum of the vibration signal with inner fault}$$

Figure 4 shows the envelope spectrum of the vibration signal with bearing inner race fault. 148.5Hz frequency component, which is the first harmonic of the bearing fault characteristic frequency, can be clearly seen in Figure 4. But there are no higher harmonics of the bearing fault characteristic frequency. It can be seen from Figure 4, that envelope spectrum represents the complicated quantities. This complexity of envelope spectrum spectrum follows from the noise effects. Therefore, classical envelope spectrum analysis has some limitation such as unable to process non-stationary or strong noise signals.

$$\text{Figure 4. Envelope spectrum of the vibration signal with inner fault}$$
Figure 4. Envelope spectrum of the vibration signal with inner fault

The bi-spectrum is evaluated according to the conventional direct method after the vibration signal has been demodulated by Hilbert transform. The bi-spectrum is depicted in Figure 5 (contour plot). From Figure 5 we can see that the graphs of the frequency quantities are much simple than that of the power spectrum showed in Figure 3 and the envelope spectrum showed in Figure 4. In case of the bi-spectrum, it can be identified that the bearing fault characteristic frequency ($f_{inner}$) of inner race fault and the higher harmonics of $f_{inner}$ are represented clearly. The simplicity of the frequency quantity representation can be put down to the ability of the bi-spectrum analysis technique to eliminate undesirable strong noise and modulation effects. Figure 5 demonstrates the advantage of the frequency quantity application for the analysis vibration signals generated by gearbox. Especially, the bi-spectrum better identifies the frequency components and consequently leads to a better understanding of the transient vibration characteristics than that the power spectrum and envelope spectrum. From Figure 5, one can draw a conclusion that bi-spectrum can identify the characteristic frequency. Therefore, bi-spectrum can be used to detect the fault type of the bearing.

Figure 6 shows the angle slice bi-spectrum of the vibration with inner race fault. The angle slice bi-spectrum is dominated by the bearing fault characteristic frequency ($f_{inner}$) of inner race fault and its higher harmonics of the damaged bearing. The angle slice bi-spectrum is also capable of revealing the characteristic frequency of bearing inner fault that is corrupted by the modulation and noise.

B. Bearing outer race fault diagnosis based on bi-spectrum

The original vibration signal of outer race defect is displayed in Figure 7. It is clear that there are periodic impacts in the vibration signal. There are significant fluctuations in the peak amplitude of the signal, and there are also considerable variations of frequency content. From Figure 7, we can hardly find the characteristic period of the outer race defect.

Figure 8 shows the power spectrum of the vibration signal with bearing outer race fault. There is no fault characteristic frequency component around 101.5Hz. Therefore, The conventional power spectrum was not capable of revealing the characteristic frequency of outer race fault, which was corrupted by the modulation and noise.
The bi-spectrum is evaluated according to the conventional direct method after the vibration signal has been demodulated by Hilbert transform. The bi-spectrum is depicted in Figure 9 (contour plot). From Figure 9, we can see that the graphs of the frequency quantities are much simpler than that of the power spectrum showed in Figure 8. In case of the bi-spectrum, it can be identified that the bearing fault characteristic frequency \( f_{outer} \) of outer race fault and the higher harmonics of \( f_{outer} \) are represented clearly. The simplicity of the frequency quantity representation can be put down to the ability of the bi-spectrum analysis technique to eliminate undesirable strong noise and modulation effects. Figure 9 demonstrates the advantage of the frequency quantity application for the analysis vibration signals generated by gearbox. Especially, the bi-spectrum better identifies the frequency components and consequently leads to a better understanding of the transient vibration characteristics than that the power spectrum and envelope spectrum. From Figure 9, one can draw a conclusion that bi-spectrum can identify the characteristic frequency. Therefore, bi-spectrum can be used to detect the fault type of the bearing.

Figure 10 shows the angle slice bi-spectrum of the vibration with outer race fault. The angle slice bi-spectrum is dominated by the bearing fault characteristic frequency \( f_{outer} \) of outer race fault and its higher harmonics of the outer race damaged bearing. The angle slice bi-spectrum is also capable of revealing the characteristic frequency of bearing outer fault that is corrupted by the modulation and strong noise.

V. CONCLUSIONS
In this paper, a method for fault detection and diagnosis of bearing was presented based on the developed signal processing technique named as bi-spectrum. The definition of the bi-spectrum for analysis of vibration signals generated by rotating machinery was introduced. This method is based on the bi-spectrum estimation technique from the vibration signal. The bi-spectrum method assists in the elimination of noise and modulation effects. Therefore, we can recognize the vibration modes that coexist in the system, and to have a better understanding of the nature of the fault information contained in the vibration signal. The experimental result has been shown that bi-spectrum can be used as a diagnostic feature for damaged bearing.

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