Cyclic Modulation Spectrum Based Bearing Defect Recognition

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Abstract. A novel practical technique for bearing defect detection and recognition based on cyclic modulation spectrum (CMS) is presented. Cyclic modulation spectrum stands as a much faster method to detect periodic modulation feature and has a lower complexity. CMS has a very fast calculation speed, but it can provide similar results with spectral correlation density. This advantage enables the cyclic modulation spectrum to extract useful information from the noisy environment in rotating machine. The validity of this technique is exhibited on bearing defect vibration data from an industrial gearbox. The results show the advantage of cyclic modulation spectrum. CMS can correctly pick up the transient features from interference signals and can accurately recognize the rolling element bearing defect.

1. Introduction
Rolling element bearings are major mechanical elements in rotating machinery such as agricultural machinery, coal mining machinery, automobile gearbox and so on. Therefore, the healthy state of the bearing has a significant impact on the normal operation of the machinery. At present, scholars have put forward many methods of bearing fault diagnosis. Among the numerous detection methods, vibration based detection is of great interest and favor. Traditional bearing defect diagnosis methods include Fourier transform, power spectrum analysis, cepstrum analysis, and so on [1]. However, rotating machinery vibration data is more nicely characterized by cyclostationary process. Cyclostationarity is very easily succeeded in handling a diagnostic conundrum in rotating machinery. Cyclostationary analysis technique has been testified to be a significant approach in recognizing the frequency spectrum components of signal for fault detective purposes [2, 3].

Therefore, in recent years, the fault diagnosis technology based on cyclostationary analysis technique has attracted extensive attention and been widely used [4-8]. Some significant advance has been made in spectral correlation density estimation algorithm and specific application in health detection and defect diagnosis of rotation machine. However, the major disadvantages of cyclostationary signal processing method are its slow computing speed and large amount of computer memory.

The paper introduces a new bearing diagnosis method based on the currently put forward cyclic modulation spectrum (CMS) [9], which is nearly optimal solution in detecting cyclostationary information under intensive background noise, while simultaneously being simple and very quickly to calculate. In this work, the fundamental theory of cyclic modulation spectrum is briefly introduced.
CMS is used to detect and recognize bearing fault of rotating machine. Cyclic modulation spectrum (CMS) provides the ability to demodulate and extract the envelope of bearing fault vibration signal.

2. Cyclic modulation spectrum
CMS has a long history of research which was first induced by Antoni in 2009 [9] and fully formulated in 2012 [10], which expresses the puzzle of passive inspection of surface naval vessels from radiative propeller noise in the distance. The cyclic modulation spectrum can be achieved using double-domain fast Fourier transform (FFT).

The first step consists in the calculation of the Short Time Fourier Transform (STFT) of the vibration data. Let \( y(t_n) \) \( (n = 0, 1, 2, \cdots, N - 1) \) denote the signal of interest. The STFT of vibration data \( y(t_n) \) across the time span of \( N_w / f_s \) is given follow

\[
Y(i, f) = \sum_{m=0}^{N-1} y(iR + m)V(m)e^{-j2\pi m \frac{f}{f_s}}
\]

(1)

Where \( f_s \) is named as the sample frequency and \( V(m) \) is a symmetric data cone window with length \( N_w \Delta t \) seconds, with \( \Delta t \) being the sampling periods. The fast Fourier transform of \( w(m) \) plays the role of a spectral window. \( N_w \) is the window length. \( R \) is named as the time shift between two successive window.

Then the CMS is gained using a second fast Fourier transform along the rest time axis of STFT \( Y(i, f) \), denoted here by

\[
CMS(\alpha, f) = \frac{1}{P\|V\|^2} \sum_{i=0}^{P-1} \left| Y(i, f) \right|^2 e^{-j2\pi(iR+N_0)\frac{\alpha}{f_s}}
\]

(2)

Where \( N_0 \) is the center number of the sampling data window \( (N_0 = (N_w + 1)/2 \) in case of \( N_w \) is odd or \( N_0 = N_w / 2 \) in case of \( N_w \) is even). \( P \) is the total number of sampling data segments and \( P = [(L - R) / R] + 1 \). \( \|V\| \) is the data window norm. Frequency \( \alpha \) is commonly named as cyclic frequency and \( f \) is known as spectral frequency of the vibration signal.

Equation (2) demonstrates the efficiency and simplicity for the computing of the quantity which is operated at a calculating the cost controlled by the influence coefficients \( PN_w \log 2^{KN_w} \). The CMS was for the first time and unique trial to utilize this relationship in the evaluation of cyclostationary statistics in view of envelope analysis of the signal.

3. Bearing defect recognition according to cyclic modulation spectrum
The gearbox fault monitoring and diagnosis system is made up of a computer, amplifiers, accelerometers, B&K 3560 analytical spectrometer and a gearbox. The experimental ball bearing is only utilized to research one kind of localized surface defect: bearing inner ring or outer ring flaw. The tested rolling bearing is used discharge device to machine a slot on the inner or outer ring. Then the localized fault is a machine formed on the inner or outer ring. The defect was 1 mm deep and 1.5 mm wide. The gearbox is driven by three-phase alternating current motor. The input spindle speed is 1500 r/min, in other words, \( f_s \) is 25Hz. The bearing model is deep groove ball bearing 6208. The number of balls is 10, the contact angle \( \beta = 0^\circ \). The bearing pitch diameter D is 97.5mm and the ball diameter d is 55/3 mm. The bearing defect feature frequencies of inner ring and outer ring are computed according to Equation (3) and Equation (4), respectively [1].
Therefore, in accordance with Equation (3) and Equation (4), the rolling bearing fault feature frequencies of inner ring and outer ring are 148.5 Hz and 101.5 Hz.

3.1. Rolling bearing inner ring defect recognition based on cyclic modulation spectrum

The sampled bearing inner ring fault vibration data is displayed in Figure 1. Obviously, there is periodic modulation effect in the vibration data. The peak magnitude of the vibration data has obvious variation, and the frequency content has considerable change. However, from Figure 1, it is more difficult to pick up the feature period of bearing inner ring fault.

Figure 2 is the calculated power spectrum of bearing inner ring defect vibration data. Obviously, there is no prominent defect feature frequency peak around 148.5 Hz and its high-frequency harmonics. As a result, the traditional power spectrum can not reveal the bearing inner ring defect feature frequency, that is to say, the feature frequency of inner ring flaw is seriously affected by interference noise and complex vibration modulation.

\[
f_{\text{inner}} = \frac{z}{2} \left(1 + \frac{d}{D} \cos \beta \right) f_r
\]

\[
f_{\text{outer}} = \frac{z}{2} \left(1 - \frac{d}{D} \cos \beta \right) f_r
\]

Figure 1. Sampled data with inner ring defect

Figure 2. Power spectrum
According to the sampled vibration data in Figure 1, the proposed technique is utilized to compute CMS. The CMS is given in Figure 3 (contour map) and Figure 4 (3D map), respectively. In accordance with Figure 3 and Figure 4, one can see that the diagram of frequency magnitude is much simpler than that of the power spectrum diagram displayed in Figure 2. The results show that the feature frequency ($f_{inner}$) of bearing defect and the high-frequency harmonics of inner ring defect are more clearly expressed.

Figure 5 displays the enhanced envelope spectrum (EES) of the rolling element bearing inner ring flaw vibration data in Figure.1. The enhanced envelope spectrum is mainly determined by the feature frequency ($f_{inner}$) of inner ring flaw and the high-frequency harmonics of $f_{inner}$. The enhanced envelope spectrum can also reveal the feature frequency of rolling bearing inner ring flaw under the interference of strong noise and complex vibration modulation.

3.2. Rolling bearing outer ring defect recognition based on cyclic modulation spectrum
Figure 6. Sampled data with outer ring defect

Figure 7. Power spectrum

The sampled bearing outer ring flaw vibration data is exhibited in Figure 6. Obviously, there is obvious periodic effect in the vibration data. However, it is more difficult to pick up the feature period of outer ring flaw in Figure 6. Figure 7 exhibits the conventional power spectrum of the vibration data with bearing outer ring flaw. Obviously, there is also no defect feature frequency about 101.5 Hz.

The CMS is appraised in accordance with the proposed approach. The CMS is shown in Figure 8 (contour map) and Figure 9 (3D map) respectively. In accordance with Figure 8 and Figure 9, it can be seen that the diagram of frequency magnitude is much simpler than that of the power spectrum diagram displayed in Figure 7. The results show that the feature frequency ($f_{outer}$) of bearing defect and the high-frequency harmonics of outer ring defect are distinctly expressed.

Figure 10 shows enhanced envelope spectrum of the sampled vibration data with outer ring defect. The EES is also governed by the bearing outer ring defect feature frequency ($f_{outer}$) and its high frequency harmonics. Therefore, the EES can also reveal the feature frequency of bearing outer ring defect under the interference of strong background noise and complex vibration modulation.
4. Conclusions
This paper introduces the approach of extracting useful defect information features from the sampled vibration data contaminated by strong background noise. The application of cyclic modulation spectrum in bearing fault recognition is introduced. The cyclic modulation spectrum helps to eliminate the modulation and noise effects. On the basis of the cyclic modulation spectrum, the rolling bearing defect feature frequency and its high-frequency harmonics can be easily recognized. The results of the experiment confirm that the amplitude of the cyclic modulation spectrum increases for any defect in the inner or outer ring. This technique is utilized to processing the actual vibration data of bearing defect in an industrial gearbox. The results of the experiment indicate that the cyclic modulation spectrum can be used as the diagnosis symptom characteristics of bearing defect.

5. References
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Figure 10. Enhanced envelope spectrum with outer ring defect
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