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Application of the horizontal slice of cyclic bispectrum in rolling element bearings diagnosis

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ABSTRACT

The vibration signals of rolling element bearings are random cyclostationary when they have faults. However, because the background noise is very heavy when the early fault occurs, it is difficult to disclose the latent periodic components successfully even using the second order cyclostationary analysis. To overcome this difficulty, the cyclic bispectrum (CBS), an alternative approach based on bispectrum and cyclostationarity analysis, is discussed in this paper. Furthermore, the slice spectrum analysis of the CBS is proposed. The CBS is a third-order cyclic statistical parameter, in the frequency domain. The CBS gives full play to the advantage, which is provided from the higher order cyclic statistical methods. It can restrain noise and provide more information than classical methods such as amplitude spectrum analysis and envelope analysis when the fault is at an early stage. However, the CBS is four-dimensional. So, the Slices Spectrum Analysis of the CBS is introduced to fault diagnosis. Firstly, the slice of the CBS, which is 3D structure, is sliced along the cyclic frequency axis. The CBS corresponding to one cyclic frequency is called the once slice of the CBS. However the information in the once slice is redundant and indirect for fault diagnosis. So the twice slice of the CBS, which is sliced along one frequency axis is studied. By analysis, the horizontal slice of the once slice of the CBS (HSCBS), which is at a special given cyclic frequency is proposed to resolve the contradiction. Simulation and experiment of the rolling element bearing fault diagnosis are performed, and the results indicate the feasibility and validity of the HSCBS analysis in rolling element bearing early fault diagnosis.

1. Introduction

Rolling element bearings are one of the common elements in rotating machinery, as a consequence, many efforts were employed to clarify the process of bearing failures. In a long period, vibration signals from point defects in rolling element bearings are modeled as a series of repeated decaying oscillation waveforms with possible amplitude modulation [1]. The model gives a satisfactory explanation of the fault process.

In recent few years, some scholars realize that bearing fault signals are not strictly phase-locked because of variable slip between the bearing components. Then they brought the inevitable minor and random slip between rolling elements and races into the successful model, and rolling element bearing point defect signals are verified to be cyclostationary [2–4]. When the early fault occurs, the bearing characteristic frequencies contain very little energy and the background noise is very heavy so that the characteristic frequencies are usually overwhelmed by noise and higher levels of macro-structural vibrations, so it is difficult to disclose the latent periodic components successfully.

For the high-order statistics (HOS) features of noise component equal to zero, the features based on the HOS has a natural tolerance to the stationary and non-stationary Gaussian noise that may be corrupting the signal of interest [5–7]. The bispectrum,

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Nomenclature

t	time variable
τ	time lag variable
f	(spectral) frequency variable
$B_{3x}(f_1, f_2)$	the bispectrum of the signal $x(t)$
$C_{3x}(\tau_1, \tau_2)$	the third-order statistics (cumulant) of the signal $x(t)$
$X(f)$	Discrete Fourier transform
$P_{2x}(f)$	power spectrum
$M_{kx}^{\alpha}(\tau)$	signal cyclic moment
$C_{kx}^{\alpha}(\tau)$	signal cyclic cumulant
α	cyclic frequency
$S_{3x}^{\alpha}(f_1,f_2)$	cyclic bispectrum
C_{3x}^{α}	the third-order cyclostationarity statistics (cumulant) of $x(t)$
$S_h^{\alpha}(f)=S_{3x}^{\alpha}(f_1,f_2)\|_{f_1=f,f_2=f_0}$	the horizontal slice of the α slice of the CBS
A_i	the amplitude modulator
T	the period of impulses
$\omega(t)$	the oscillating waveform
$n(t)$	the stationary noise
$1/Q$	the shaft speed for inner faults and the cage speed for rolling element faults
τ_i	the minor and random fluctuation around the average period T
B	an appropriate value, which can fitly simulate the attenuation of oscillation waveforms
C_A	an arbitrary constant
ϕ_A	the original phase
f_{bc}	the cage frequency
f_c	the central frequency
f_r	the shaft frequency
f_n	the resonance frequency
f_{op}	the outer race passing frequency
f_s	the sampling frequency
$S_{3x}^{f_c}(f_1,f_2)$	the central frequency slice of the CBS
$E\{\cdot\}$	ensemble average

a third-order statistic powerful technique has the advantage of less computing than the other HOS analysis, but it gives fully play of the advantages of the HOS analysis. For the rolling element bearing vibration signals is a typical cyclostationarity [8,9], the cyclic bispectrum (CBS), which combined bispectrum with the cyclostationarity is intensively studied here.

Some literatures about the CBS have been published. The estimation of cyclic polyspectra is introduced in [10]. The applications of the CBS are proposed in [4,11–15], they are specially for mechanical fault diagnosis and condition monitoring. Raad described the estimation of CBS in detail in [16] and used the CBS in gear fault diagnosis. Zhu et al. [13] starts from the definition of the CBS, then he tried to compute the sum of the third order cyclic cumulant in frequency set $\alpha \in \{(\alpha_j)\}$ firstly and secondly computed the two-dimensional Fourier transform of the sum of the third order cyclic cumulant. The CBS, which based on this method is three-dimensional and is effective in representing the gearbox condition, however it is lack of resolution. The algorithm of CBS by Yiakopoulos and Antoniadis [11] is based on the computation of the bispectrum with a simple modification to introduce the notion of the cyclic frequency [17]. The calculating amount is reduced, and a special frequency pattern for fault diagnosis is given for fault diagnosis.

Actually, CBS is four-dimensional. So, the Slices Spectrum Analysis of the CBS is introduced to fault diagnosis. According to the algorithm by Yiakopoulos and Antoniadis, the actual CBS analysis is a set of specific values for cyclic frequency α. Thus, contour plots are practically generated, similar to those of the traditional bispectrum analysis. And, each of them corresponds to a specific cyclic frequency α. We called each of them to the once slice of the CBS. That is, the once slice of the CBS, which is 3D structure, is sliced along the cyclic frequency axis firstly. However the information in the once slice is redundant and indirect for fault diagnosis. So the twice slice of the CBS, as the horizontal slice of the once slice (HSCBS), the vertical slice of the once slice (VSCBS) and the diagonal slice of the once slice (DSCBS), is studied. By analysis, the horizontal slice of the once slice of the CBS (HSCBS), which is at a special given cyclic frequency is proposed to resolve the contradiction. Additionally, the less computation of HSCBS is also appealing.

The outline of this paper is arranged as follows. In the next section, the estimation technique for the HSCBS based on the bispectrum and the cyclostationarity theory is introduced. Then the effectiveness of the HSCBS is demonstrated in Section 3. Section 4 presents a rolling element bearing signals model. The model of Section 4 is further used in Section 5 to generate an outer race defect signal without noise and with different degrees noise, and the signal is further analyzed, using amplitude spectrum, envelope spectrum, CBS and the HSCBS analysis methods. By comparing the results of the signal with different degrees noise, the validity of the proposed method-HSCBS is proved. Finally, Section 6 verifies the results from two experimental outer race fault signals.

2. Estimation technique for HSCBS

2.1. Bispectrum

From a theoretical point of view, a bispectrum can be considered as a two-dimensional Fourier transform of the third-order statistics (cumulant) of the signal $x(t)$.

$$B_{3x}(f_1,f_2) = \sum_{\tau_1=-\infty}^{\infty}\sum_{\tau_2=-\infty}^{\infty} C_{3x}(\tau_1,\tau_2)e^{-j(f_1\tau_1+f_2\tau_2)} \tag{1}$$