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Incipient fault information determination for rolling element bearing based on synchronous averaging reassigned wavelet scalogram

Hongkun Li *, Fujian Xu, Hongyi Liu, Xuefeng Zhang

School of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China

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A B S T R A C T

As incipient fault of rotating machinery is weak and interfered by noise, it is difficult for characteristic information determination and incipient classification. In this research, a new method is put forward on rolling element bearing (REB) incipient impact information using synchronous averaging reassigned wavelet scalogram (SARWS) according to time–frequency analysis. Firstly, multi-cycle signal is processed by continuous wavelet transform. Then, time frequency distribution for every working cycle of vibration signal is obtained by wavelet scalogram (WS) based on time domain information. Thirdly, reassigned wavelet scalogram (RWS) for every working cycle of REB can be calculated. In the end, synchronous averaging is applied on RWS, which can effectively reduce noise interference and identify the weak fault information. Both simulated signals and real vibration signals collected from REB of rotating machinery are used to verify this proposed method. Analyzed results show that the proposed method is effective for REB incipient weak fault classification.

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1. Introduction

Condition monitoring and pattern recognition are becoming more and more important for machine safely operation and maintenance [1]. Rolling element bearing (REB) has been widely used on machines such as lathe, grinder machine, wind turbine gearbox, and gas turbine. Vibration signal analysis technique has been broadly used on rotating machines condition monitoring and classification [2]. But acquisition of vibration signals are usually exposed to the interference of noise in practical engineering, especially incipient characteristics of fault signal are more susceptible to noise interference. It is the reason that the incipient fault is not easy to classify. How to identify weak characteristic information from noise interference for fault diagnosis has been investigated by many researchers, such as spectral analysis [3,4], improved spectral analysis [5,6], cyclostationary analysis [7,8], optimal filtering technology [9], and synchronous averaging technology [10].

Wavelet analysis is conductive for the analysis of non-stationary signals. It could carry on multi-scale analysis for the signals by scaling translation and describe the local characteristics of signals in different scales to detect weak fault characteristic effectively [11]. It is verified more conductive to be applied in the mechanical fault diagnosis based on vibration signals analysis [12]. But REB fault diagnosis methods based on practical vibration are often unsatisfactory as noise interference and weak impact information. Time–frequency distribution (TFD) has bee investigated on gearbox pattern recognition [13]. Qingbe He provides a method based on manifold correlation

* Corresponding author. Tel.: +86 411 84706561x8048, +86 130 84158910 (mobile); fax: +86 411 84706571.
E-mail address: lihk@dlut.edu.cn (H. Li).

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matching technology for TFD analysis. It is also investigated on bearing fault diagnosis [14]. Due to the periodic rotation of the machine, its vibration signals always have broad periodicity, and the time-domain synchronous averaging technique could be used to extract periodic waveforms from the signals which are suffering from noise interference. Time domain averaging across all scales can reduce the noise and any other non-synchronous disturbances from the cyclostationary data and detect the existing frequencies [15]. But REB is different from gearbox fault diagnosis. Further investigation should be carried on.

As well, TFD based on wavelet scalogram (WS) is less of concentration, which could lead to error classification result. Reassigned wavelet scalogram (RWS) has better performance for condition classification [16]. It is better to consider the characteristic frequency (CF) information for REB as it is convenient for condition classification. For this reason, a synchronous averaging reassigned wavelet scalogram (SARWS) method is proposed for REB incipient fault condition classification based on impact information determination. The results show that the SARWS method could effectively reduce noise interference and enhance the weak fault characteristics demonstration based on simulated signals and REB monitored vibration signals analysis. It is beneficial for the diagnosis of rotating machinery fault in the incipient stage. This paper is structured as follows: Section 2 introduces the theory of the proposed method in this research. Section 3 presents simulated signal analysis to verify the effectiveness of this method. Section 4 presents incipient REB fault diagnosis from website database based on this investigation. Section 5 gives an experimental vibration signal analysis in the test rig for REB. Concluding remarks are given in Section 6.

2. Theory and method

2.1. Wavelet scalogram

Wavelet transform can effectively filter noise and preserve signal characteristics. Wavelet analysis is a common tool for analyzing vibration signals to detect local faults in rotating machines [17]. Its definition is shown in Eq. (1) for a set of recursive functions of wavelet packet children bases. Set $\psi(t)$ as a finite energy function, i.e. $\psi(t) \in L^2(R)$, if its Fourier transform $\hat{\psi}(\omega)$ could satisfy the conditions of permissibility.

$$C_\psi = \int \left|\hat{\psi}(\omega)\right|^2 / |\omega| d\omega < \infty \tag{1}$$

$\psi(t)$ is referred to as a mother wavelet. Expand and translate the mother wavelet $\psi(t)$ and let a be its scale factor and b the translation factor. Suppose $\psi_{a,b}(t)$ is the function after stretched and translated.

$$\psi_{a,b}(t) = |a|^{-1/2} \psi\left(\frac{t-b}{a}\right) \tag{2}$$

$\psi_{a,b}(t)$ is called the wavelet function depending on the stretching parameters and translation parameters. The continuous wavelet transform of the continuous time signal $x(t) \in L^2(R)$ is defined as

$$W_x(a,b;\psi) = a^{-1/2} \int x(t) \psi^*\left(\frac{t-b}{a}\right) dt \tag{3}$$

where in $\psi^*(t)$ is the conjugation of $\psi(t)$. The above definition indicates that the wavelet transform, similar to Fourier transform, is also a kind of integral transform and the difference lies in that the wavelet has two parameters, scale a and translation b. The time function is projected onto the two-dimensional time-scale plane after the wavelet transform. The wavelet transform coefficients actually reflect the similarity between the local signal and wavelet function selection, which means that the larger the coefficient is the more similarity is. The continuous wavelet inverse transform is shown as follows.

$$x(t) = \frac{1}{C_\psi} \int \int a^{-2} W_x(a,b;\psi) \psi_{a,b}(t) da db \tag{4}$$

The modulus of the signal's continuous wavelet transform coefficient is defined as $SG(a,b;\psi)$, shown as follows.

$$SG(a,b;\psi) = |W_x(a,b;\psi)|^2 \tag{5}$$

Similar to other time–frequency analysis, such as short time Fourier transform, Wigner–Ville distribution, WS suffers from the limitations defined by the Heisenberg-Gabor inequality [16]. Therefore, interference for the classification based on WS may occur. It could lead to fault classification.

2.2. Reassigned wavelet scalogram

To improve the readability of WS, reassigned method is proposed to better time–frequency representation for the monitored signal [16]. Set the frequency of the center angular as ω_0, and the $SG(a_i, b_j; \psi)$ signifies the mean value of the energy density of a local area above the time–frequency plane with $(\omega_0/\omega_0 a_i a_i, a_i t + b_j)$ as the geometric center. As the energy distribution within this local area does not process the geometric symmetry, it is necessary to assign this mean value to the local energy center $(\omega_0/\hat{a}_i, \hat{a}_i t + \hat{b}_j)$ rather than the geometric center. This objective is achieved by the RWS, and it has better time–frequency aggregation and less interference items. It can be expressed as follows.

$$RSG(\hat{a},\hat{b};\psi) = \iint (\hat{a}/a)^2 SG(a,b;\psi) \times \delta(\hat{b} - b'(a,b)) \delta(\hat{a} - a'(a,b)) da db \tag{6}$$

$$b'(a,b) = b - Re\left\{ a \frac{W_x(a,b;\psi') W_x^*(a,b;\psi)}{|W_x(a,b;\psi)|^2} \right\} \tag{7}$$

$$\frac{\omega_0}{a'(a,b)} = \frac{\omega_0}{a} + Im\left\{ \frac{W_x\left(a,b;\hat{\psi}\right) W_x^*(a,b;\psi)}{2\pi a |W_x(a,b;\psi)|^2} \right\} \tag{8}$$

$$\psi'(t) = t\psi(t), \hat{\psi}(t) = \frac{d\psi}{dt}(t) \tag{9}$$

Based on Eq. (6), the RWS can be determined. RWS can be regarded as a spectrum with constant relative bandwidth, which could reflect the time–frequency information of

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