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Bearing Fault Detection Based on Multi-scale Laplace Wavelet Transform Spectrum

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Abstract. Laplace wavelet transform is self-adaptive to non-stationary and non-linear signal, which can detect the singularity characteristic of a signal precisely under strong background noise condition. A new method of bearing fault diagnosis based on multi-scale Laplace wavelet transform spectrum is proposed. The multi scale Laplace wavelet transform spectrum technique combines the advantages of Laplace wavelet transform, envelope spectrum and three dimensions color map into one integrated technique. The bearing fault vibration signal is firstly decomposed using Laplace wavelet transform. In the end, the multi scale Laplace wavelet transform spectrum is obtained and the characteristics of the bearing fault can be recognized according to the multi-scale Laplace wavelet transform spectrum. The proposed method has been verified by vibration signals obtained from rolling bearing with inner race fault.

Introduction

The roller element bearing is an important component for gearbox drive train. Monitoring the condition of the bearing component provides advantages in the safety, operation and maintenance areas. Therefore, the predictive maintenance philosophy of using vibration information to lower operating costs and increase machinery availability has been the subject of intensive research throughout industry. Since most of the machinery in a predictive maintenance program contain rolling element bearings, it is imperative to establish a suitable condition monitoring procedure to prevent malfunction and breakage during operation.

The wavelet transform provides powerful multi-resolution analysis in both time and frequency domain and thereby becomes a favored tool to extract the transitory features of non-stationary vibration signals produced by the faulty bearing [1]. The wavelet analysis results in a series of wavelet coefficients, which indicate how close the signal is to the particular wavelet. In order to extract the fault feature of signals more effectively, an appropriate wavelet base function should be selected. Morlet wavelet is mostly applied to extract the rolling element bearing fault feature because of the large similarity with the impulse generated by the faulty bearing [2]. An application of Hermitian continuous wavelet transform for the detection of cracks in geared system is presented in [3,4].

The Laplace wavelet is a complex, single-sided damped exponential formulated as an impulse response of a single mode system to be similar to data feature commonly encountered in health monitoring tasks [5]. It is also applied to diagnose the bearing fault of gearbox [6]. In this paper, an alternative approach for detecting localized faults in the outer and inner races of a roller element bearing using the envelope spectrum of the Laplace wavelet transform (LWT) is investigated. The shape parameters of Laplace wavelet ensure a large similarity between the wavelet function and the generated fault impulse. The methodology developed in this paper decomposes the original times series data in intrinsic oscillation modes, using the Laplace wavelet transform. Then multi-scale Laplace wavelet transform spectrum is applied to the vibration signal of bearing faults. The techniques are demonstrated by the experiments on a gearbox with a rolling element bearing under simulated crack on the inner race or the outer race. The characteristic frequency related to the bearing fault can be effectively extracted. The experimental results show that this method based on multi-scale Laplace wavelet envelope spectrum can effectively diagnose the fault of rolling element bearing.

Laplace wavelet transform

The Laplace wavelet is a complex, analytical, and single sided damped exponential and it is given by [5]

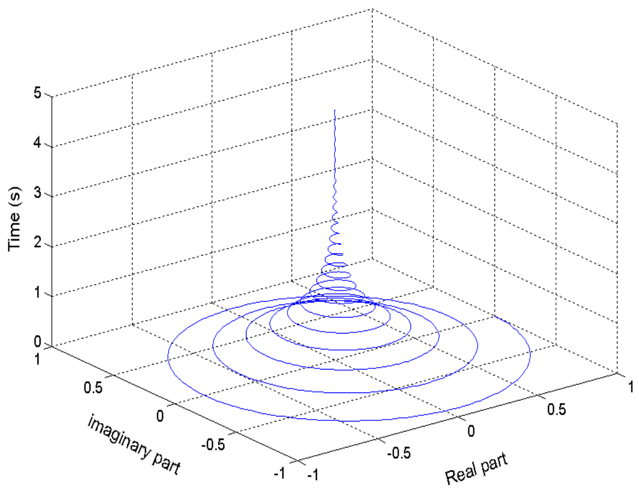
$$\psi(t) = \begin{cases} Ae^{-\frac{\xi}{\sqrt{1-\xi^2}}\omega_c t} e^{-j\omega_c t}, & t \geq 0 \\ 0, & t < 0 \end{cases} \tag{1}$$

where ξ is the damping factor that controls the decay rate of the exponential envelope in the time domain and hence regulates the resolution of the wavelet, and it simultaneously corresponds to the frequency bandwidth of the wavelet in the frequency domain. The frequency ω_c determines the number of significant oscillations of the wavelet in the time domain and corresponds to the wavelet center frequency in frequency domain, and A is an arbitrary scaling factor. This function is called a Laplace wavelet to emphasize its derivation is related to the Laplace transform. In particular, the Laplace wavelet has a strong similarity to the inverse Laplace transform of the transfer function for an un-damped second order system. Figure1 shows the Laplace wavelet, its real part, imaginary part, and its spectrum.

It should be noted that Laplace wavelet is generated by considering features anticipated in mechanical system responses. Figure1 also shows the projections of Laplace wavelet $\psi(t)$ onto the real and imaginary planes. These projections graphically demonstrate the relationship between the wavelet and an impulse response of a single mode system. The Laplace wavelet has real and imaginary parts which are 90° out of phase. In a manner similar to the Fourier transform, a complex wavelet is required to properly handle phase differences between the wavelet and the signal. A wavelet could be derived with only a real part to match physical data that is typically real. However, using both parts ensures a smoothness and continuity of the wavelet transform.

The continuous wavelet transform (CWT) $W_x(t,a)$ of the signal $x(t)$ is defined as a convolution integral of $x(t)$ with scaled and dilated versions of Laplace mother wavelet function $\psi(t)$:

$$W_x(t,a) = \frac{1}{a}\int x(\tau)\psi\left(\frac{t-\tau}{a}\right)d\tau = x(t) * \psi_{ab}(t) \tag{2}$$



(a) The Laplace wavelet

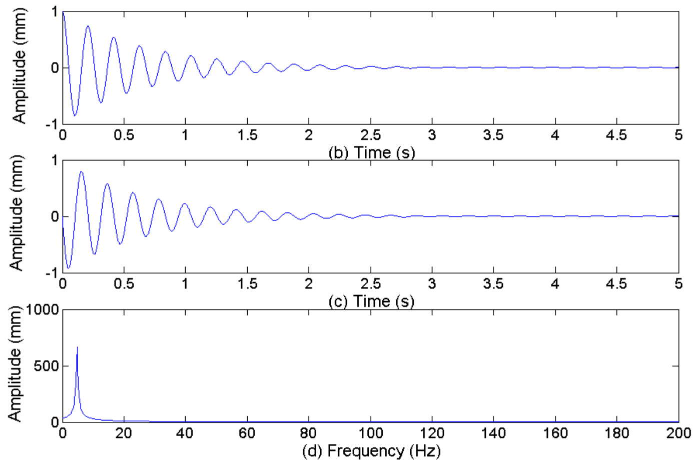


Fig. 1. (a) The Laplace wavelet, (b) the real part,(c)the imaginary part, and (d) its spectrum

When the signal $x(t)$ is periodic, Eq.(2) becomes a circular convolution, and the continuous wavelet transform (CWT) is also better calculated in the frequency domain according to

$$W_x(t,a) = \frac{1}{a} F^{-1}[X(\omega) \bullet aW(a\omega)] \tag{3}$$

where $X(\omega)$ and $aW(a\omega)$ are the Fourier transform of the signal $x(t)$ and dilated wavelet $\psi_{ab}(t)$,respectively. The operator $F^{-1}[\bullet]$ denotes inverse Fourier transform.

Then the Laplace wavelet envelope spectrum of signal $x(t)$ is given as follows,

$$Env_x(a,b) = \sqrt{[\mathrm{Re}(WT_x(a,b))]^2 + [\mathrm{Im}(WT_x(a,b))]^2} \tag{4}$$

The multi-scale Laplace wavelet envelope spectrum is calculated according to,

$$E_{wt}(a,f) = F[Env_x(a,b)] \tag{5}$$

where $F[\bullet]$ denotes Fourier transform.

Bearing fault detection based on multi-scale Laplace wavelet transform spectrum

To demonstrate the performance of the proposed approach, this section presents the application examples for the detection and diagnosis of localized bearing defects. In the example, the Laplace wavelet is as a wavelet mother function.

Bearings are installed in many kinds of machinery. A lot of problem of those machines may be caused by defects of the rolling bearing. Generally, local defects may occur on inner race, outer race or balls of bearing. A local fault may produce periodic impacts, the size and the repetition period, which are determined by the shaft rotation speed, the type of fault and the geometry of the bearing. The successive impacts produce a series of impulse response, which maybe amplitude modulated because of the passage of fault through the load zone. The spectrum of such a signal would consist of a harmonics series of frequency components spaced at the component fault frequency with the highest amplitude around the resonance frequency. These frequency components are flanked by sidebands if there is an amplitude modulation due to the load zone. According to the period of the impulse, we can judge the location of the defect using characteristic frequency formulae. Because inner race defect has more transfer segments when transmitting the impulse to the outer surface of the case, usually the impulse components are rather weak in the vibration signal.

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 monitoring and diagnostic system is composed of four accelerometers, amplifiers, B&K 3560 spectrum analyzer and a computer. The sampling frequency is 32768 Hz.The input motion is produced by an AC motor. The speed of the spindle is 1500r/min, that is, the rotating frequency f_r is 25 Hz. The type of the ball bearing is 208. There are 10 balls in a bearing and the contact angle $\alpha = 0°$, ball diameter d= $55/3$ mm, bearing pitch diameter D=97.5mm. Then the characteristic frequency of the inner race defect and outer race defect can be calculated by the Eq.(6) and Eq.(7) respectively [4-5].

$$f_{inner} = \frac{z}{2}\left(1 + \frac{d}{D}\cos\alpha\right) f_r \tag{6}$$

$$f_{outer} = \frac{z}{2}\left(1 - \frac{d}{D}\cos\alpha\right) f_r \tag{7}$$

Therefore, according to Eq.(6) and Eq.(7), the characteristic frequency of the inner race defect and outer race defect are calculated to be at 148.5Hz and 101.5 Hz, respectively.

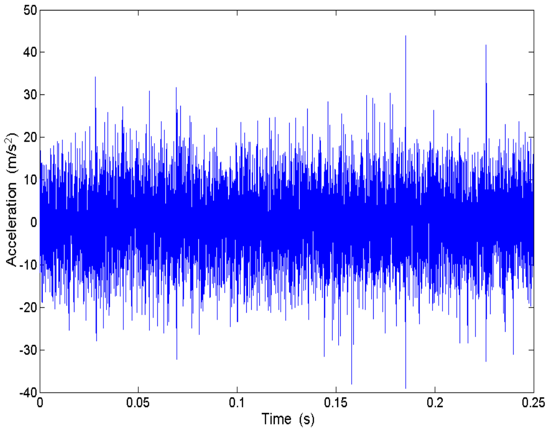


Fig.2 Vibration signal with inner race fault

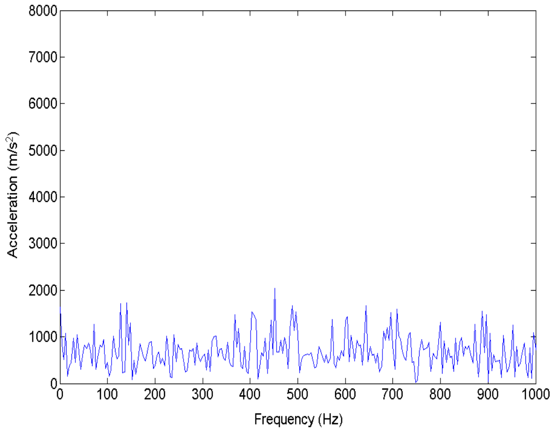


Fig.3 Envelope spectrum of the vibration signal

Fault detection of inner race based on multi-scale Laplace wavelet transform spectrum. The original vibration signal of inner race defect is displayed in Fig.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 Fig.2, we can hardly find the characteristic period of the inner race defect.

Figure 3 shows the traditional envelope spectrum of the vibration signal with inner race fault. There is no characteristic defect frequencies component around f_{inner} and its harmonics. Therefore, classical has some limitation such as being unable to extract the characteristic defect frequency of inner effectively under strong background noise.

To the data of Fig. 2, the Laplace wavelet transform is applied according to Eq.(5), resulting in multi-scale Laplace wavelet transform spectrum. The multi-scale Laplace wavelet transform spectrum is shown in Fig. 4 and slice plot when scale a=2 is given in Fig.5. In Fig. 4 and Fig.5, we can clearly see the distinctive signature for the vibration signal with bearing inner race fault. From Figure 5, one can see the spectrum lines at the characteristic frequency f_{inner} (148.5Hz) of the roller bearing with inner race fault and its high order harmonic frequencies.

For the defective bearing, transient vibrations caused by the rolling elements-defect interactions are clearly seen through the characteristic defect frequency and its high order harmonic frequencies. Such repetitive cycle reflects degradation of the inner race health condition as the defect propagated through the bearing inner race. Physically, impacts generated by the rolling ball-defect interactions excite intrinsic modes of the bearing system, giving rise to a train of transient vibrations at the mode-related resonant frequencies.

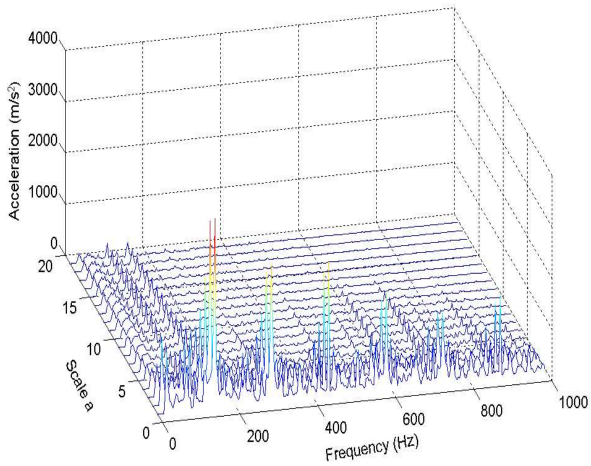


Fig.4 Multi scale spectrum with inner race fault

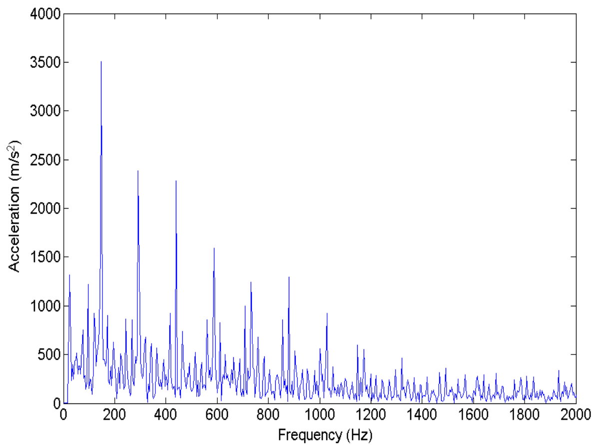


Fig.5 Envelope spectrum (a=2)

Conclusions

In order to extract the defect impulses buried in the vibration signal effectively, the Laplace wavelet transform is constructed. This gives a desirable ability to detect the singularity characteristic of a signal precisely. This research shows that the multi-scale Laplace wavelet transform spectrum is very effective in detection and diagnosis bearing fault. The experimental results have been shown that the multi-scale Laplace wavelet transform spectrum can effectively diagnose the bearing fault.

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