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Vibration signal correction of unbalanced rotor due to angular speed fluctuation

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ABSTRACT

The rotating speed of a rotor is hardly constant in practice due to angular speed fluctuation, which affects the balancing accuracy of the rotor. In this paper, the effect of angular speed fluctuation on vibration responses of the unbalanced rotor is analyzed quantitatively. Then, a vibration signal correction method based on zoom synchrosqueezing transform (ZST) and tacholess order tracking is proposed. The instantaneous angular speed (IAS) of the rotor is extracted by the ZST firstly and then used to calculate the instantaneous phase. The vibration signal is further resampled in angular domain to reduce the effect of angular speed fluctuation. The signal obtained in angular domain is transformed into order domain using discrete Fourier transform (DFT) to estimate the amplitude and phase of the vibration signal. Simulated and experimental results show that the proposed method can successfully correct the amplitude and phase of the vibration signal due to angular speed fluctuation.

1. Introduction

Vibration caused by unbalanced mass and eccentric moments is a common problem in rotating machinery, and thus rotor balancing is necessary to ensure the stable operation of the machines. The influence coefficient balancing method is widely used in workshop [1], and accurate measurement and estimation of unbalance mass from vibration signals is an essential issue during balancing process. The basic assumption of the influence coefficient balancing method is that the rotating speed is constant. However, the rotating speed of the rotor is hardly constant in practice, since there are slight periodic or quasi periodic speed fluctuations around the nominal speed caused by inherent design constraints of electrical motors, torsional vibration, assembled fault or time-varying torques [2]. Therefore, the effects of angular speed fluctuation on the unbalance vibration need to be studied, either with dynamic modelling [3] or signal processing method, and it is necessary to eliminate the effect of the angular speed fluctuation on the amplitude and phase of vibration signal in rotor balancing process.

In order to eliminate the effect of the angular speed fluctuation, the instantaneous angular speed (IAS) need to be calculated or estimated firstly. Order tracking is an effective method to map a time signal to the angular domain, conserving a consistent periodicity in angular domain. The angular period becomes unchanged along the cycles. Thus, the order spectrum generated from angular domain becomes sharper than original spectrum. The critical issue of order tracking technique is to determine a map of phase (rotation angle) vs. time, and then the equal phase spacing can be determined to resample the signal. The order tracking methods consists of tachometer-based [4–6] and tacholess order tracking methods [7–10].

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Tachometer-based order tracking methods construct phase-time relationship directly based on pulse signal for reference, and then resample the vibration signal using polynomial interpolation according to the time instant obtained from the map. However, the accuracy of these methods is restricted by the tachometer resolution, i.e. the number of pulses per revolution. For example, for once-per-revolution keyphasor signal, it only contains effectively one phase point per rotation, so the reference signal can only represents speed variations up to half the tacho fundamental order [9]. In addition, the tachometer or encoder is not always accessible because of structural design problems or operating conditions, which limits the applicability of the methods. Tacholess order tracking methods attracted more attentions, which require less hardware and cost, as it constructs the phase-time relationship from the vibration signal itself. In 2005 Bonnardot et al. [8] proposed a novel method for order-tracking using phase demodulation to extract the nearly continuous phase–time relationship directly. Different from constructing the phase–time map in time domain from the tacho signal, their demodulation based method is inherently more accurate than tacho-based methods in time domain, as phase-demodulation effectively calculates accurate phase values at each sampling time of the signal. In addition to the phase-demodulation method, time-frequency analysis (TFA) based tacholess order tracking is also a promising method, which is robust to noise and can provide more reliable IAS estimation results [11]. For signals whose harmonics overlap in the frequency domain so that phase demodulation based methods are not applicable, proper TFA can distinguish instantaneous frequencies (IFs) of each order in the time-frequency plane, as long as the parameters are selected correctly. Zimroz et al. [12] presented a method to measure IAS from vibration signal by short time Fourier transform (STFT). In [13], discrete IF was estimated by peak search on the linear time-frequency plane called spectrogram, and then polynomial fitting was employed to obtain a more smooth IF curve. The IF was further integrated to obtain the phase-time map aforementioned for resampling. Urbanek et al. [14] combined the advantages of phase demodulation methods and joint TFA to overcome the obstacles of harmonics overlapping phenomenon. However, the accuracy of IAS estimation in these methods is restricted by resolution limitations of STFT due to Heisenberg uncertainty principle.

Daubechies et al. [15] proposed a novel TFA method known as synchrosqueezing wavelet transform (SWT) which has higher time-frequency resolution than traditional linear TFA methods. What is more, it allows reconstruction to time domain and is robust to bounded perturbations noise [16]. In our previous study, the SWT has been applied in machining chatter detection [17] and its modified version called frequency-shift synchrosqueezing transform has been successfully applied in IAS estimation of rotating machinery [18]. For signals whose IFs have highly fluctuating frequency but small fluctuating amplitude, a novel version of SWT called zoom synchrosqueezing transform (ZST) was proposed and used in rub-impact fault diagnosis [19] and evaluating the quality of the workpiece surface [20]. Since the IAS of the unbalanced rotor is located in a specific frequency region, the TFA method with good time-frequency resolution is required. As the improved SWT, ZST can achieve high time resolution through frequency shift and high frequency resolution through partial zoom. In this paper, ZST is used to estimate the IAS of the unbalanced rotor, and then a correction method of the amplitude and phase of vibration signal based on ZST and tacholess order tracking is proposed.

The rest of the paper is organized as follows. The theoretical basis including SWT, ZST and tacholess order tracking are introduced briefly in Section 2. The effect of angular speed fluctuation on unbalance response is analyzed quantitatively in Section 3. In Section 4, a correction method of the amplitude and phase of vibration signal is proposed, followed by simulation and experimental verification in Section 5. Finally, the main results are discussed and conclusions are given in Section 6.

2. Theoretical basis

As a refined version of SWT, ZST squeezes the energy in a partial frequency region, which can provide both excellent time and frequency resolution for signals with weakly fluctuating IFs. In this section, the brief principle of SWT is reviewed first so as to better introduce the advantages and effectiveness of ZST for IF estimation. After that, the theory of the tacholess order tracking is also introduced, as the bridge between time domain signal and angular domain signal.

2.1. Synchrosqueezing wavelet transform (SWT)

SWT can be regarded as a post-processing method of the continuous wavelet transform (CWT). SWT reallocates the time-scale representation obtained from the CWT in scale direction for a concentrated time-frequency representation (TFR), from which instantaneous frequency lines can be extracted → from which IF curves can be extracted [15].

$$W_s(a,b) = \int s(t)a^{-1/2}\overline{\psi\left(\frac{t-b}{a}\right)}\mathrm{d}t \tag{1}$$

where a is the scale parameter, b is the time parameter, $\psi(t)$ is an appropriately chosen wavelet basis and $\overline{[\bullet]}$ denotes the complex conjugate. For a purely harmonic signal $s(t) = A\cos(\omega t)$, its CWT can be described by Plancherel's theorem as

$$\begin{aligned} W_s(a,b) &= \frac{1}{2\pi}\int \hat{s}(\xi)a^{1/2}\overline{\hat{\psi}(a\xi)}e^{jb\xi}\mathrm{d}\xi \\ &= \frac{A}{4\pi}a^{1/2}\overline{\hat{\psi}(a\omega)}e^{jb\omega} \end{aligned} \tag{2}$$