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Identification of multiple faults in rotating machinery based on minimum entropy deconvolution combined with spectral kurtosis

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A B S T R A C T

Due to the complexity of mechanical system, multiple faults may co-exist in a rotating machinery, where vibration is commonly used for diagnosis. The measured vibration signal could be considered as a result of convolution process of malfunction induced periodic impact signal and resonant response of the mechanical component, and deconvolution is an effective way to restore impulses. The minimum entropy deconvolution (MED) has been shown to be an effective deconvolution method and has been employed in rotating machinery fault diagnosis. Nevertheless, the simulation in this paper shows that the MED is unable to identify multi-faults of rotating machinery fully when different faults excite different resonance frequencies. To overcome this shortcoming, a new multi-faults detection method based on Spectral kurtosis (SK) and MED is proposed. The effectiveness of the proposed method is validated by simulation data and field signals from a vacuum pump.

1. Introduction

In rotating machinery, rolling element bearing is one of the most critical mechanical components. Different kinds of bearing failure may lead to the fatal breakdown, it is significant to accurately detect the existence and severity of the faults occurred at bearings. Due to the complexity of mechanical system, multiple faults may co-exist in a rotating machinery. Multi-faults diagnosis has mostly been concentrated on rotor systems such as rub and crack [1,2]. Thus far, little works have been reported on the detection of multiple faults. Simultaneous detection of multiple faults is still a big challenge in monitoring and diagnosis of rotating machinery conditions [1,3].

Vibration signals carry rich information about mechanical equipment health state, the vibration-based signal processing technique have been widely used during the past decade [4,5]. In general, a defect occurs at a bearing, periodic or quasi-periodic impulses will appear in the waveform of the vibration signals [6]. In this case, the detection of faults in rolling element bearings is mainly achieved by identifying the frequency of the impulses from the measured signals. As the measured vibration signal is a result of convolution process of periodic impact signal and resonant response of the

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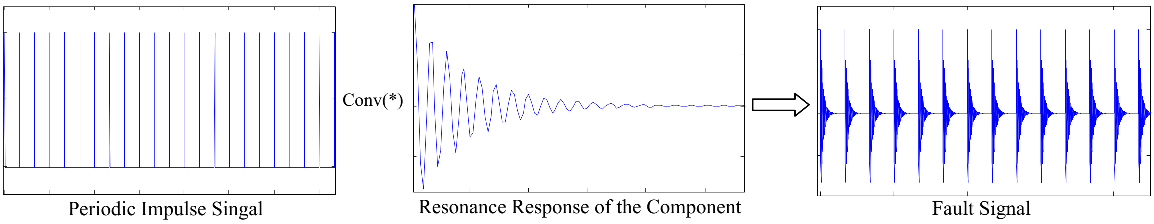

Fig. 1. Produce process of a simplified fault signal.

component. In order to restore the periodic impulses, a successful diagnostic procedure should be applied to deconvolve the effect of the defect-induced impulse responses. The minimum entropy deconvolution method is developed to reduce the spread of the impulse response frequencies by Wiggins [7], it can obtain the signals which is closer to the original impulses that give rise to them. In [8], the MED method is applied to enhance the impulse of autoregressive filter residual signal to detect the fillet crack and spalls of the gear tooth. Sawalhi et al. [9] take the advantage of MED method with SK to further enhance the fault detection and diagnosis ability in the rolling bearing. Ruilong Jiang et al. [10] detected the weak impact of rolling element bearing using MED method with envelop analysis. As shown above, the MED method has demonstrated its power in rotating machinery fault diagnosis, but has not been put in use of multi-faults identification of rotating machinery. It has been reported that different impulsive faults most likely will excite different resonant frequencies under multi-faults co-existed condition [3]. Therefore, it is possible to detect the faults from different bearings in close vicinity or even from a single bearing by demodulating the resonances induced by these defects [3]. When we put the MED into multi-faults identification, the results show that it will cause some resonance frequency bands to be suppressed or filtered in multi-faults, which make some impulsive faults which convolve with the suppressed resonance frequency bands that cannot be detected. As we know, it is the first time that such the MED method's limitation is presented, and it will be further discussed in this paper. To solve this problem, a pre-processing procedure may be needed for multi-faults diagnosis. Spectral kurtosis has been proposed by Antoni and Randall to indicate the presence of series of transients and their locations in the frequency domain [11], with which the vibration signal can be divided into multiple resonance frequency bands. The theoretical background of SK can be found in [11], where a large number of references are given to the previous works in this field. Applying of SK with envelope spectrum to the diagnostics of bearings and gear can be found in [12], but the envelope spectrum based on SK will lose effect in the presence of a high level noise [13]. To this end, we propose a novel hybrid method based on SK pre-processing and MED method for multiple faults diagnosis, which is different from the method proposed by Sawalhi et al. in [9].

The rest of this paper is organized as follows: Section 2 establishes a model to describe the vibration induced by the multiple localized defects of bearings. In Section 3, spectral kurtosis and MED method are reviewed. In Section 4, the performance of MED method will be estimated by theoretical analysis and simulation analysis. A hybrid diagnosis method is proposed in Section 5. The effectiveness of the proposed method will be validated with simulations and experiments in Sections 6 and 7. The Section 8 concludes this paper.

2. A vibration model induced by the multiple localized defective bearings

When a defect on the surface of a bearing strikes another surface, an impact will be generated and excite structure resonance of some elements. As a result, the rotation of either inner race or outer race will produce a series of successive impulses governed by the operating speed and geometry of the bearing, and decay in the vibration transmission path due to the system damping factor [14,15].

To better understand above content, the produce process of a simplified fault signal can be described as in Fig. 1. Fig. 1 shows the convolution process of periodic impact signals and resonant response of the component in a rolling element bearing with single defect. Bearing fault signals can be described by the following mathematical model [16,17]:

$$\begin{cases} x(t) = \sum_{i=1}^{M} A_i \cdot s\,(t - iT - \tau_i) + n(t) \\ A_i = A_0 \cdot \cos(2\pi f_r t + \varphi_A) + C_A \\ s(t) = e^{-\xi t} \cdot \cos(2\pi f_n t + \varphi_w) \end{cases} \tag{1}$$

in which A_i is the possible amplitude modulator, which is periodic in period $1/f_r$, f_r denotes a shaft speed for the inner faults and the cage speed for the rolling element faults. $s(t)$ represents an attenuated damping oscillation caused by the fault impact of cyclical (T), τ_i is a minor and random fluctuation, and $n(t)$ is a stationary noise. We use C_A to denote an arbitrary constant, A_0 to denote a amplitude of modulating signal, ζ is a resonance damping coefficient depending on excited structure, and f_n is the natural frequency of excited structure.

As mentioned above, different kinds of bearing defects may excite different (or common) structural resonance frequency

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