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Research on variational mode decomposition in rolling bearings fault diagnosis of the multistage centrifugal pump

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ABSTRACT

Rolling bearing faults are among the primary causes of breakdown in multistage centrifugal pump. A novel method of rolling bearings fault diagnosis based on variational mode decomposition is presented in this contribution. The rolling bearing fault signal calculating model of different location defect is established by failure mechanism analysis, and the simulation vibration signal of the proposed fault model is investigated by FFT and envelope analysis. A comparison has gone to evaluate the performance of bearing defect characteristic extraction for rolling bearings simulation signal by using VMD and EMD. The result of comparison verifies the VMD can accurately extract the principal mode of bearing fault signal, and it better than EMD in bearing defect characteristic extraction. The VMD is then applied to detect different location fault features for rolling bearings fault diagnosis via modeling simulation vibration signal and practical vibration signal. The analysis result of simulation and experiment proves that the proposed method can successfully diagnosis rolling bearings fault.

1. Introduction

Multistage centrifugal pump is the key equipment of the process industry. Since its high efficiency, wide performance and stable operation, it is widely used in refineries, power plants, chemical plants, etc. [1]. Rolling bearings are frequency encountered in multistage centrifugal pump due to their carrying capacity and low-friction characteristics. As the connection between the rotor and the support, the safety and stability of rolling bearings are the key to ensure the safety and stability of the multistage centrifugal pump. Therefore, it is very important to diagnosis the rolling bearing fault at its incipient stage in order to prevent long-term breakdowns or in some cases possibly catastrophic failures.

Various diagnosis techniques are used to prevent machinery failures caused by the rolling bearings and new methods are being developed. Sugumaran et al. [2] have comprehensively studied of fault diagnostics of rolling bearings using continuous wavelet transform. Ali et al. [3] realize automatic rolling bearings fault diagnosis by using the method of empirical mode decomposition and artificial neural network. Xue et al. [4] have proposed adaptively fast ensemble empirical mode decomposition method and applied to rolling bearings fault diagnosis. Safizadeh and Latifi [5] presents a new method for rolling bearings fault diagnosis by using the fusion of an accelerometer sensor and a load cell sensor. Zhao et al. [6] via discriminative subspace learning algorithm effectively recognize different rolling bearings fault.

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Variational mode decomposition is an adaptive signal decomposition method recently proposed by Dragomiretskiy and Zosso [7], which is an entirely non-recursive signal decomposition method. VMD can extract the principal mode of the signal and their respective center frequencies. VMD has been applied in many fields for signal extraction and has achieved a certain effect. For example, Zhao et al. [8] denoise the power transformer partial discharge by using VMD and achieve a better result of signal de-noising. Wang et al. [9] make use of VMD to extract features of rub-impact fault in the rotor system. The result of comparison VMD, EWT, EEMD, EMD shows that the rub-impact features can be better extracted with the VMD. Viswanath et al. [10] detect spike of disturbed power signal by using VMD and found that the proposed methodology gives good results in case of single tone signals. Upadhyay and Pachori [11] use VMD to detect instantaneous voiced/non-voiced of speech signals. The experimental results at different signal to noise ratios indicate the effectiveness of the proposed method. At the same time, VMD was compared with some other signal decomposition method such as EMD, EWT, EEMD et al., and it shows superior performance in signal decomposition and feature extraction [12–14].

In this paper, VMD is used to detect the different location defect signal of multistage centrifugal pump rolling bearings. The rolling bearings fault of outer race, inner race and rolling element can be diagnosis by the extracted mode signal. In order to analyze the validity of the proposed method, we studied the failure mechanism of rolling bearings, established the different location defect signal model of rolling bearing, and simulated the fault signal of outer race defect, inner race defect, and rolling element defect in Section 2. Then, we analyze and diagnosis the simulation vibration signal of different fault bearing by using VMD and EMD in Section 3. The fault vibration signal is given to VMD and it is observed that the defect information of the original signal is available in one of its modes, which can be obtained by energy ratio calculation on all modes. The mode with defective signal has higher energy ratio than other modes and this is observed in the discussion for the simulation and experimental signal. The fault of rolling bearings is simulated by using multistage centrifugal pump test rig, and the proposed method is verified in Section 4.

2. Simulation and analysis of vibration signal of rolling bearings with different location defect

The vibration signal of rolling bearings is complex either under normal or with defect, resulting from its structure, tolerance, and surface deterioration. Many researchers predict the vibration response of rolling bearings by modeling analysis. McFadden and Smith [15,16] developed a mathematical modeling to predict the vibration produced by a single defect on the inner race of a rolling bearing under constant radial load. Tandon [17,18] proposed an analytical model for predicting the vibration frequencies of rolling bearings and the amplitudes of significant frequency components due to a localized defect on the outer race, inner race or on one of the rolling elements under radial and axial load. Kiral and Karagülle [19,20] presented a model for defect detection in rolling bearings with single or multiple defects under the action of an unbalanced force based on the finite element vibration analysis. Cong et al. [21] derived the defect signal calculating the equation of the outer race and inter race by dynamic and kinematic analysis. The derivation takes into consideration of the gravity of the rotor-bearing system, the imbalance of the rotor, and the location of the defect on the surface. In these models, the vibration signal of different location defect is established by a series of impulses. When a defect on one surface strikes its matching surface, the impulse will be produced which can excite resonances of bearing and housing structures. As the bearing rotates in constant speed, these impulses are generated periodically and the frequency of impulses can be determined by the position of the defect.

In this section, the single point defect impulse signal model of out race defect and inner race defect was set up based on Ref. [21], and then the signal model of rolling element defect was derived. Various location defect simulation signal will realize by using the proposed model and the vibration characteristic frequency. Simulation signal of outer race defect, inner race defect, and rolling element defect will be discussed and analyzed by using envelope analysis method and fast Fourier transform (FFT).

2.1. Rolling bearings fault signal modeling

The simulated signal of rolling bearings defect calculating model can be expressed as [21]:

$$x(t) = \sum_{i=1}^{N} A_i \cdot s(t - iT_0 - \tau_i) \tag{1}$$

where T_0 is the period of impulses. τ_i is the minor random fluctuation around the average period T_0. N is the number of the simulated impulses and i is the sequence number of the impulse. A_i is the amplitude modulator, whose periodical feature can be determined by the following equation:

$$A(t) = \rho \cdot (M(t) + T(t)) \tag{2}$$

where $M(t)$ represents the gravity load(G) and $T(t)$ represents the imbalance force load(Fe) indicated in Fig. 1. ρ is the factor between amplitude and load.

$s(t)$ in Eq. (2) is an impulse exponential decay oscillation [22], and can be expressed as:

$$s(t) = e^{-Bt} \cos(2\pi f_n t) \tag{3}$$