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Research on variational mode decomposition and its application in detecting rub-impact fault of the rotor system

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ABSTRACT

Multi-component extraction is an available method for vibration signal analysis of rotary machinery, so a novel method of rubbing fault diagnosis based on variational mode decomposition (VMD) is proposed. VMD is a newly developed technique for adaptive signal decomposition, which can non-recursively decompose a multi-component signal into a number of quasi-orthogonal intrinsic mode functions. The equivalent filtering characteristics of VMD are investigated, and the behavior of wavelet packet-like expansion is first found based on fractional Gaussian noise via numerical simulations. VMD is then applied to detect multiple rubbing-caused signatures for rotor–stator fault diagnosis via numerical simulated response signal and practical vibration signal. A comparison has also been conducted to evaluate the effectiveness of identifying the rubbing-caused signatures by using VMD, empirical wavelet transform (EWT), EEMD and EMD. The analysis results of the rubbing signals show that the multiple features can be better extracted with the VMD, simultaneously.

1. Introduction

Rub occurs in a rotating machine with radial clearance between rotor and stator, such as bearing internal clearance, seal/packing or blade/case. Radial clearance between rotor and stator in high-speed rotating machines, such as generator sets, aeroengines, turbines and compressor, is of great importance. If the radial clearance between the rotating rotor and the stator is smaller, the efficiency of these kinds of machines greatly improves. Nevertheless, the smaller the clearance of the modern rotating machinery is, the more the possibility of rub occurs. When the rub severely induces the rotor dynamic instability, it will finally lead to the catastrophic failures.

Complicated nonlinear behavior is generally associated with a vibrating system of a faulty rotor, for example, chaotic motions often accompanied by the periodic motions. High synchronous vibrations of the rotor may exceed available clearances and result in rubbing and impacts between rotor and stator. Thus, some signatures, including synchronous vibration, sub-synchronous and super-synchronous vibrations, will exist in the measured vibration signal, when rub occurs in a rotating machine. Many researchers by now have comprehensively investigated the mechanism and dynamic characteristics of rub in rotors using analytic method or

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numerical simulations. For example, Muszynska [1] wrote a detailed literature review work on rotor rub related phenomena and the vibration response. Beatty [2] proposed a wildly used mathematical model for rubbing forces and a detailed response format of diagnostic data in actual cases. Ehrich [3] applied a modified Jeffcott model to address the sub-harmonic vibration via numerical simulations under various conditions, such as the subject of higher sub-harmonic response for a high-speed rotor in the case of bearing clearance. Goldman used an analytical approach associated with the numerical calculation to study the phenomenon with supercritical sub-harmonic in a rotor system with clearance, where the results showed regular periodic vibrations of synchronous and sub-harmonic order, as well as chaotic vibration patterns all accompanied by a higher harmonic motion [4].

Moreover, the contact and separation process often generated impacts between the rotor and the stator. This is another common defective signature, besides the sub- and super-harmonics caused by the rubbings. Several methods have been proposed to detect all these signatures from the rotor response of signals. Peng et al. applied the reassigned scalogram to detect the rubbing-caused impacts in [5]. A demodulation method based on the local mean decomposition (LMD) was proposed for rub-impact fault diagnosis [6], which can extract the transient fluctuations of the instantaneous frequency of the fundamental harmonic component. Hu et al. [7] proposed a stochastic resonance method for early detecting rub-impact fault of rotor systems. A local rub-impact fault diagnosis method of rotor system based on empirical mode decomposition (EMD) was proposed in [8], where it showed intrinsic mode functions of the vibration signal of a rotor system with local rub-impact fault obviously own the amplitude-modulated characteristics. Lei et al. [9] proposed a method to diagnose rotating machinery with the ensemble empirical mode decomposition (EEMD) to overcome the problem of mode mixing existing in EMD. In view of the dynamics of rotors in retainer bearings is very similar to other problems of rotor-to-stator contact, Markert investigated transient vibrations of elastic rotors in retainer bearings in [10], and he also mentioned the transients from no contact to continuous contact were usually accompanied by more or less intense impacts.

The main contribution of this work is outlined as follows: (1) a novel recently proposed technique – variational mode decomposition (VMD) – for adaptive signal decomposition is first applied to detect multiple signatures caused by rotor-to-stator rubbing; (2) the equivalent filtering property of the VMD is also first investigated in this work, which results in its advantages in detecting multiple signatures, simultaneously; (3) the comparisons are thoroughly conducted using a numerical simulated signal and a practical vibration signal, in order to investigate the effectiveness of the proposed method with some of the methods mentioned above, such as EEMD [11] and the traditional EMD [12] as well as another newly developed empirical wavelet transform (EWT) [13]. The remainder of the paper is organized as follows. VMD algorithm and its equivalent filtering characteristics are investigated in Section 2. In Section 3, VMD is then first applied to detect multiple rubbing-caused signatures of a simulated rotor response signal and a practical vibration signal, while its effectiveness for fault diagnosis of the rotor system is evaluated in comparison with other methods. Conclusion is presented in Section 4.

2. Variational mode decomposition and its equivalent filter property

2.1. VMD algorithm

VMD is a newly developed methodology for adaptive and quasi-orthogonal signal decomposition [14], which can non-recursively decompose a multi-component signal into a number of band-limited intrinsic mode functions (BLIMFs). VMD can decompose a real valued signal f into a discrete number of sub-signals u_k with the specific sparsity properties of its bandwidth in the spectral domain. Each mode is compact around a center pulsation ω_k and its bandwidth is estimated using H^1 Gaussian smoothness of the shifted signal. The VMD is written as a constrained variational problem [14]:

$$\min_{\{u_k\},\{\omega_k\}} \left\{ \sum_{k=1}^{K} \| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) \times u_k(t) \right] e^{-j\omega_k t} \|_2^2 \right\}$$

$$\text{subject to} \quad \sum_{k=1}^{K} u_k = f \tag{1}$$

Eq. (1) can be addressed by introducing a quadratic penalty and Lagrangian multipliers. The augmented Lagrangian is given as follows:

$$L(\{u_k\},\{\omega_k\},\lambda) = \alpha \sum_{k=1}^{K} \| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) \times u_k(t) \right] e^{-j\omega_k t} \|_2^2 + \| f(t) - \sum_{k=1}^{K} u_k(t) \|_2^2 + \left\langle \lambda(t), f(t) - \sum_{k=1}^{K} u_k(t) \right\rangle \tag{2}$$

in which α denotes the balancing parameter of the data-fidelity constraint. Eq. (2) is then solved with the alternate direction method of multipliers (ADMM) [15]. All the modes gained from solutions in spectral domain are written as

$$\hat{u}_k(\omega) = \frac{\hat{f}(\omega) - \sum_{i \neq k} \hat{u}_i(\omega) + \left(\hat{\lambda}(\omega)/2 \right)}{1 + 2\alpha(\omega - \omega_k)^2} \tag{3}$$