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An underdamped stochastic resonance method with stable-state matching for incipient fault diagnosis of rolling element bearings

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ABSTRACT

Most traditional overdamped monostable, bistable and even tristable stochastic resonance (SR) methods have three shortcomings in weak characteristic extraction: (1) their potential structures characterized by single stable-state type are insufficient to match with the complicated and diverse mechanical vibration signals; (2) they vulnerably suffer the interference from multiscale noise and largely depend on the help of highpass filters whose parameters are selected subjectively, probably resulting in false detection; and (3) their rescaling factors are fixed as constants generally, thereby ignoring the synergistic effect among vibration signals, potential structures and rescaling factors. These three shortcomings have limited the enhancement ability of SR. To explore the SR potential, this paper initially investigates the SR in a multistable system by calculating its output spectral amplification, further analyzes its output frequency response numerically, then examines the effect of both damping and rescaling factors on output responses and finally presents a promising underdamped SR method with stable-state matching for incipient bearing fault diagnosis. This method has three advantages: (1) the diversity of stable-state types in a multistable potential makes it easy to match with various vibration signals; (2) the underdamped multistable SR, equivalent to a moving nonlinear bandpass filter that is dependent on the rescaling factors, is able to suppress the multiscale noise; and (3) the synergistic effect among vibration signals, potential structures and rescaling and damping factors is achieved using quantum genetic algorithms whose fitness functions are new weighted signal-to-noise ratio (WSNR) instead of SNR. Therefore, the proposed method is expected to possess good enhancement ability. Simulated and experimental data of rolling element bearings demonstrate its effectiveness. The comparison results show that the proposed method is able to obtain higher amplitude at target frequency and larger output WSNR, and performs better than traditional SR methods.

1. Introduction

Rolling element bearings play an important role in rotating machinery. They generally work in tough environments and are more prone to malfunction. A bearing failure may result in the breakdown of the entire machine, even a disastrous accident. If the bearing fault is diagnosed in its incipient stage [1], the accident could be avoided by timely maintenance. In such

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cases, incipient failures mean slowly developing failures, which are represented by drift-type changes [2]. They are more important in maintenance activities where it is required that slowly developing problems are detected early enough to avoid more serious consequences. However, incipient fault signatures not only are attenuated by transmission path and are very weak since they are excited by small or slight defects in bearings, but also generally suffer the interference from external and operating environments and thereby are difficult to detect. For this reason, the incipient fault diagnosis of bearings has become an increasingly significant issue [3,4].

To tackle this issue, vibration analysis [5] has been widely applied and shown satisfactory performance to diagnose various bearing failures. Signal processing [6], as a basis of vibration analysis, can be usually categorized into noise cancellation-based methods and noise utilization-based methods. The methods based on noise cancellation attempt to suppress or cancel the noise embedded in vibration signals and further highlight fault signatures, like wavelet transform [7], spectral kurtosis [8], singular value decomposition [9], etc. Although these methods have been extensively applied to the incipient fault diagnosis of rotating machinery, they inevitably endamage incipient fault characteristics more or less in the de-noising process due to their intrinsic properties. Therefore, their performance on weak characteristic extraction is unsatisfactory in the conditions where the incipient fault characteristics are overwhelmed by heavy background noise.

Noise utilization-based methods, however, can utilize noise to amplify the incipient fault characteristics embedded in vibration signals. One of the representative methods is stochastic resonance (SR) [10–12]. SR, as a potential tool for signal processing [13], is an intriguing phenomenon: the added noise to a nonlinear system surprisingly excites the coherent amplification of incipient fault characteristics [14,15]. The physical nature of such a phenomenon is that some energy of the noise in vibration signals is transferred into the incipient fault characteristics. Since SR holds this unique merit, it has attracted considerable attention in various fields, such as physics [16,17], biology [18], medicine [19], optics [20] and communication [21,22].

Most research on SR, however, mainly focuses on overdamped either monostable or bistable SR. For example, Evstigneev et al. [23] explored SR in an overdamped monostable system driven by a harmonic force and an added white noise. Calisto and Clerc [24] studied SR in overdamped monostable oscillators. Lu et al. [25] presented an overdamped monostable SR (OMSR) method with a Woods-Saxon potential to diagnose incipient bearing faults. Above mentioned research concentrates upon the investigations and applications of the OMSR characterized by the intrawell oscillation of Brownian particles, whereas other research pays attention to the overdamped bistable SR (OBSR) characterized by the interwell transition of the particles. For example, Chen and Varshney [13] analyzed the OBSR in a changeable detector. Heinsalu et al. [26] studied the effect of the confining conditions on the occurrence of the OBSR with a bistable confining potential, which is helpful to model a better bistable system for weak characteristic detection. Jha and Chouhan [27] proposed a novel OBSR-based technique for robust extraction of a grayscale logo from a tampered watermarked image. Qiao et al. [28] explored the influence of potential asymmetries on the OBSR subject to multiplicative and additive noise, and the results indicated that asymmetry is helpful to improve the enhancement capability of SR in weak characteristic extraction. Lei et al. [29] presented a gearbox fault diagnosis method based on both OBSR and highpass filters, where the rescaling factor is fixed as a constant arbitrarily. Tan et al. [30] studied the OBSR with frequency-shifted and rescaling transform for bearing fault diagnosis. He et al. [31] utilized wavelet transform to achieve the noise tuning in the OBSR for identifying mechanical faults. Zhang et al. [32] proposed an OBSR method with a joint Woods-Saxon and Gaussian potential for bearing fault diagnosis, where the rescaling factors are not optimized rather than fixed subjectively. Leng et al. [33] presented an OBSR method with the rescaling transform to extract large-parameter characteristics and further diagnose incipient faults of rolling element bearings. Hu et al. [34] utilized an OBSR method to extract early rub-impact faults of rotor systems. Qiao et al. [35] established a new piecewise OBSR model to overcome the output saturation of traditional bistable SR and further planetary gearbox faults are diagnosed by using the proposed method. Obviously, either OMSR or OBSR has been widely applied to fault diagnosis of rotating machinery. In addition, Lu et al. [36] improved the enhancement performance of the OBSR by virtue of full-wave signal construction and further achieved bearing fault diagnosis. Even Li et al. [37] investigated overdamped multistable SR (OMUSR) with a multistable potential and moreover a method based on OMUSR was proposed to extract the impact characteristics imbedded vibration signals and further identify the gearbox faults of a steel rolling mill, where the rescaling factor is fixed as a constant and system parameters are determined by particle swarm optimization. Moreover, there is no consideration that different input signals match with stable-state types. Since impact characteristics to be detected have a wide frequency-band distribution, they are easier or more suitable to make the intrawell oscillation of Brownian particles in monostable potentials or any one well in bistable and tristable potentials, where the experimental results also demonstrate such a behavior. To further develop SR potential, some researchers also focused on underdamped bistable SR (UBSR). For example, Alfonsi et al. [38] investigated the UBSR phenomenon in an underdamped bistable system, where an intrawell SR can exist together with the conventional interwell SR and a double SR was discovered. Rebolledo-Herrera and FV [39] employed the UBSR to extract the small-parameter characteristics buried in heavy background noise, where the damping factor is fixed as a constant that is dependent on system parameters. Lu et al. [40] suggested that the damping factor and integral step in the UBSR have an important effect on output responses of the underdamped bistable system. Even Zhang et al. [41] examined the UBSR behavior with a pinning potential and presented an underdamped pinning SR method for weak characteristic detection.

Among the preceding research on OBSR, OMSR, OMUSR and even UBSR, however, there exist three disadvantages as follows. (1) For OBSR, OMSR and UBSR, their potential structures characterized by single stable-state type are insufficient to match with the complicated and diverse bearing vibration signals. The OMSR, OBSR or UBSR is just able to excite the single intrawell oscillation or interwell transition of Brownian particles. For various input signals with different energy, intrawell