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Asymmetric delay feedback stochastic resonance detection method based on prior knowledge particle swarm optimization

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ABSTRACT

For the adjustable parameters stochastic resonance system, the selection of the structural parameters plays a decisive role in the performance of the detection method. The vibration signal of rotating machinery is non-linear and unstable, and its weak fault characteristics are easily concealed by noise. Under strong background noise interference, the detection of fault features is particularly challenging. Therefore, a type of weak fault feature extraction method, named knowledge-based particle swarm optimization algorithm for asymptotic delayed feedback stochastic resonance (abbreviated as KPSO-ADFSR) is proposed. Through deduction under adiabatic approximation, we observe that both the asymmetric parameters, the length of delay and the feedback strength, impact the potential function. After adjusting the asymmetric parameters of the system, the output signal-to-noise ratio (SNR) is used as the fitness function, and the setting of the relationship between the noise intensity and barrier height is used as the prior knowledge of the particle swarm algorithm. Through this algorithm, the delay length and the feedback strength are optimized. This method achieves global optimization of system parameters in a short time; it overcomes the shortcomings of the traditional stochastic resonance method, which has a long convergence time and tends to easily fall into local optimization. It can effectively improve the detection of weak fault features. In the bearing rolling body pitting corrosion failure experiment and steel field engineering experiment, the proposed method could extract the characteristics of a weak fault more effectively than the traditional stochastic resonance method based on the standard particle swarm algorithm.

1. Introduction

With the increasing function of mechanical equipment, its composition and structure are increasing in complexity. In the study of mechanical failure, the collected signals are generally accompanied by strong background noise, hindering the detection of the failure signal. In traditional fault diagnosis methods such as wavelet analysis [1–3], SVD [4–7], the useful weak signal is weakened while filtering out the noise. To overcome these shortcomings, we combine stochastic resonance (SR) with the capability to transfer part of the noise energy to weak signals and improve the weak fault characteristics while attenuating a few of the noise characteristics. The KPSO-ADFSR weak fault feature extraction method is proposed.

SR was first proposed by Benzi et al. [8–10] when explaining glacial cyclical recursion. Subsequently, on this basis, a large number of experiments and theoretical studies were carried out, rendering stochastic resonance widely used in fault diagnosis and other fields [11–23]. Hu et al. [11] had started to apply stochastic resonance theory earlier, departing from the past trend of limiting

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the application of SR only to the detection of lower frequency signals, and applied it to the early detection of mechanical systems. Zhong et al. [14] studied the stochastic resonance phenomenon of the second-order under-damped linear harmonic oscillator model with two noises of mass and frequency fluctuations. When the parameters are selected appropriately, the steady-state response amplitudes of the system exhibit apparent changes with respect to the noise intensity formant. Lai and Leng [15] proposed a weak signal detection method based on large parameter stochastic resonance and verified the feasibility of the proposed method in initial fault diagnosis. Tan et al. [16] proposed a signal inversion algorithm based on cosine fitting assisted by frequency-shift variable-scale stochastic resonance and achieved reasonable results in the fault diagnosis of rolling bearings. Zhang et al. [17] proposed an adaptive SR method based on the grey wolf optimizer (GWO) algorithm for mechanical fault diagnosis and adaptively obtained optimal SR output matching the input signal by using optimized parameters. It achieved reasonable results in the gear fault diagnosis of electric locomotives. Chen et al. [18] proposed a SR weak signal detection method to adaptively adjust the system parameters by using the signal-to-noise ratio (SNR) gain as a signal enhancement measure, for diagnosing rotor early rub failure. Zhang et al. [19] proposed the corresponding exponential type single-well SR (ESR) system driven by Levy noise. In bearing fault detection, the detection effect of the ESR system is superior to that of the bistable SR system. Yang and coworkers [20] proposed a new model with periodic potential traps to induce adaptive SR and used the enhanced artificial fish swarm algorithm to optimize the system parameters in order to improve the SNR. Li et al. [21] proposed a method based on ensemble empirical mode decomposition (EEMD) for multi-component global average SR weak fault diagnosis. By selecting the appropriate component for adaptive SR, the original signal noise is effectively reduced, and the SNR is improved. Qiao et al. [22] proposed a piecewise bistable potential model to overcome the output saturation characteristics of the traditional SR. This method has been verified through experiments using bearings and planetary gearboxes. Lu et al. [23] proposed an underdamped second-order SR method to generate an optimal SR system by matching weak-period signals, noise, and potential functions in the second-order SR state, to further improve the output SNR.

The SR method mentioned above exhibits certain enhancements in weak fault feature extraction. However, there are certain shortcomings such as the short memory system and the potential function structure not being adjustable. Under strong background noise, the local optimization of the SR system potential model parameters reduces the output signal-to-noise ratio, which affects the extraction of weak fault features.

The classical SR model is a short memory system, whereas for discrete SR, the present output depends only on the previous output. Moreover, the impact of time delay, which always appears in mechanical system, is generally omitted in the traditional SR theory. Therefore, if historical information can be added to the negative feedback of SR in an appropriate manner, the detection effect of weak period signal will be significantly improved. Wu et al. [24] studied the SR phenomenon of bistable systems driven by non-Gaussian noise with delay feedback based on small delay approximation, path integral, and unified colored noise approximation. Wang et al. [25] proposed that multiplicative noise can suppress the effect of SR. Weak additive noise can stimulate the effect of SR. The effect of the length of delay on the SNR differs with the parameters. Shao and Chen [26] studied the bistable system with delayed feedback driven by weak periodic force. Under adiabatic approximation, the SNR of the weak periodic system decreases with increase in feedback strength.

Most of the systems in nature are asymmetrical, and SR has been gaining importance in asymmetric systems in recent years [27–31]. Asymmetric potential SR exhibits the characteristics of symmetrical potential SR and can independently adjust the position of the potential barrier and the slope of the potential wall to obtain a richer potential function regulation structure. Therefore, with respect to the asymmetry of the potential structure, the proposed asymmetric time-delay feedback method solves the problem of local adjustment apparent in traditional methods. The above improved method optimizes the potential structure so as to more effectively extract the weak fault features under a strong noise background.

In recent years, a few scholars have also studied the asymmetric bistable system with time-delay. Guo et al. [32] theoretically analyzed the effects of additive noise, multiplicative noise, static asymmetry, and delay time on the SNR. Static asymmetry was verified to suppress stochastic resonance, and delay time could enhance stochastic resonance. However, the effect of the feedback strength on the bistable system was not considered in the study nor was the actual experiment used to verify the correctness of the theory. Dong et al. [33] studied the problem of average first-pass-through time in asymmetric bistable systems with time delay terms. A number of its system parameters were subjective selections, and there was no guarantee that the parameters of the stochastic resonance system had attained the optimal state. This paper proposes an asymmetric delay feedback stochastic resonance detection method based on the prior knowledge of particle swarm optimization. After adjusting the asymmetric parameter of the system, the output SNR is used as the fitness function; moreover, the relationship between the noise intensity and barrier height is used as the prior knowledge of the particle swarm algorithm. After improving the algorithm, the delay length and the feedback strength are optimized. This method achieves short-time global optimization of system parameters; this overcomes the shortcomings of the traditional stochastic resonance method, which has a long convergence time and tends to fall into local optimization straightforwardly. In the bearing rolling body pitting corrosion failure experiment and steel field engineering experiment, the proposed method can effectively extract the characteristic of weak fault, and the result is more effective than that of the traditional stochastic resonance method based on the standard particle swarm algorithm.

The general arrangement of the article is as follows. In Section 2, we mainly introduce the ADFSR model and complete the derivation of the SNR. In Section 3, the particle swarm algorithm based on prior knowledge is introduced. In Section 4, the general flow of the KPSO-ADFSR method for extracting weak fault features is introduced. Sections 5 and 6 describe the verification of the effectiveness of the proposed method by the bearing weak pitting corrosion test and the steel plant engineering experiment, respectively. Finally, Section 7 presents the conclusions.

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