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Novel synthetic index-based adaptive stochastic resonance method and its application in bearing fault diagnosis

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ABSTRACT

Stochastic resonance (SR), which is characterized by the fact that proper noise can be utilized to enhance weak periodic signals, has been widely applied in weak signal detection. SR is a nonlinear parameterized filter, and the output signal relies on the system parameters for the deterministic input signal. The most commonly used index for parameter tuning in the SR procedure is the signal-to-noise ratio (SNR). However, using the SNR index to evaluate the denoising effect of SR quantitatively is insufficient when the target signal frequency cannot be estimated accurately. To address this issue, six different indexes, namely, power spectral kurtosis of the SR output signal, correlation coefficient between the SR output and the original signal, peak SNR, structural similarity, root mean square error, and smoothness, are constructed in this study to measure the SR output quantitatively. These six quantitative indexes are fused into a new synthetic quantitative index (SQI) via a back propagation neural network to guide the adaptive parameter selection of the SR procedure. The index fusion procedure reduces the instability of each index and thus improves the robustness of parameter tuning. In addition, genetic algorithm is utilized to quickly select the optimal SR parameters. The efficiency of bearing fault diagnosis is thus further improved. The effectiveness and efficiency of the proposed SQI-based adaptive SR method for bearing fault diagnosis are verified through numerical and experiment analyses.

1. Introduction

Bearing fault diagnosis has long been studied to prevent severe mechanical equipment damage and ensure the long-term safe operation of mechanical equipment [1–4]. Unexpected machinery failure causes bodily injury and economic loss [5,6]. A typical process of bearing fault diagnosis can be described as follows: 1) the vibration signals are acquired from fault bearings, 2) envelope demodulation and frequency analysis methods are utilized to obtain the envelope spectrum, and 3) the existence and type of faults are confirmed [7]. Fault feature extraction of vibration signals is a key procedure in bearing fault diagnosis. Feature extraction can be performed on time-domain, frequency-domain, and time–frequency-domain signals [8]. However, extracting fault features is difficult because fault signals are always corrupted by heavy background noise.

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Stochastic resonance (SR) is a nonlinear filter that can effectively improve weak signal detection performance by using noise to enhance weak periodic signals [9–11]. Studies have proven that SR is more effective in weak signal detection than traditional linear finite impulse response (FIR) and infinite impulse response (IIR) filters [12,13]. Therefore, many SR methods have been proposed to enhance weak bearing signals and to facilitate bearing fault recognition. For instance, the multi-scale bistable SR array method that can be utilized for weak signal detection when noise intensity exceeds the optimal value of SR was proposed in Ref. [14]. An adaptive bistable SR method was applied to increase calculation speed and improve weak feature detection performance [15]. Time-delayed feedback SR method was introduced to enhance weak signals in bearing fault diagnosis [16]. Recently, an underdamped step-varying second-order SR (USSSR) method was proposed in Refs. [12,13]. Featured with a distinct secondary-filtering ability, the USSSR method demonstrated good performance in the detection of the weak signal submerged in heavy background noise.

From another aspect, SR is a parameterized filter, and its performance relies largely on the closed-loop feedback index that is utilized to evaluate the denoising effect quantitatively and to guide parameter tuning. Evaluation of detection results is an indispensable procedure in the process of using SR method to realize bearing fault diagnosis. The measurement index guarantees the accuracy and correctness of detection results. Many measurement indexes can be utilized to evaluate the denoising effect of the SR method, such as signal-to-noise ratio (SNR) [17], weighted power spectral kurtosis [18], root mean square error [19,20], and correlation coefficient [21], etc. SNR is the most popular among these indexes because it is simple and can be calculated conveniently. However, SNR has a disadvantage, namely, when the target signal frequency cannot be accurately determined, the SNR index cannot guide parameter tuning.

Given this, a new synthetic quantitative index (SQI) is proposed in the current study to overcome the inefficiencies of traditional SR methods, and a new adaptive SR (ASR) method based on USSSR method is accordingly introduced to improve bearing fault diagnosis performance. In particular, six indexes, namely, power spectral kurtosis, correlation coefficient, peak SNR [22,23], structural similarity [24,25], root mean square error, and smoothness, are fused into the SQI by using the back propagation neural network (BPNN). The fusion procedure utilizes the advantages and avoids the instabilities of each index through nonlinear weighted combination. The main advantage of the new SQI over the traditional SNR index is that it overcomes the requirement of knowing accurate frequency and thus realizes automatic enhancement of weak bearing fault signals. With the minimum SQI value, the optimal parameters can be adaptively obtained.

From another aspect, the efficiency of bearing fault diagnosis needs to be improved. If the bearing fault is determined immediately, the machine can be repaired and operated again quickly. The grid search (GS) strategy used in traditional SR methods could consume much time depending on the parameter search scopes. From this point of view, the traditional method is not conducive for immediate fault feature detection of vibration signals. Hence, the genetic algorithm (GA) method is introduced in this investigation to improve the efficiency of the proposed ASR for bearing fault diagnosis [26–28]. The proposed SQI-based ASR (SQIASR) method has three distinct merits as follows: 1) SQI can implement adaptive selection of SR filter's optimal parameters, 2) the GA method further improves the efficiency of parameters tuning, and 3) the proposed novel SQIASR method improves the effectiveness and efficiency of bearing fault diagnosis.

The rest of this paper is organized as follows. Section 2 provides a theoretical background of the USSSR method. Section 3 introduces the construction procedure of SQI and performs the simulation analysis to assess the performance of SQI. Section 4 introduces the theoretical background of the GA method and performs the simulation analysis to evaluate the GA method in comparison with the traditional GS method. Section 5 provides the algorithm flowchart of the proposed SQIASR method. Section 6 verifies the practicability of the proposed SQIASR method by analyzing defective bearing signals and provides discussions. Section 7 provides a summary of this study.

2. Basic theory of USSSR

2.1. Underdamped second-order SR Model

The basic principle of bistable SR behavior can be described as follows. A particle is driven by a weak periodic signal and noise; when the noise, the periodic signal, and the system match one another, the particle transits to another potential well from the original potential well. The system output switches between two potential wells according to the signal modulation frequency. Switching speed synchronizes the output signal and the weak periodic signal. The small periodic component of the system output signal is then enhanced. Benefiting from this distinct merit, SR has been widely applied in weak signal detection. The underdamped second-order SR equation is

$$\frac{d^2x}{dt^2} = -\frac{dU(x)}{dx} - \gamma\frac{dx}{dt} + Z(t), \tag{1}$$

where

$$Z(t) = S(t) + N(t), \tag{2}$$

is the system input signal, $x(t)$ denotes the system output signal,$N(t) = \sqrt{2D}\xi(t)$is a noise item, $\xi(t)$is an additive Gaussian white noise with zero mean and unit variance, $\sqrt{2D}$ is the noise intensity, $S(t) = A\cos(2\pi f_d t + \varphi)$ is a periodic signal in which