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Quantitative evaluation on the performance and feature enhancement of stochastic resonance for bearing fault diagnosis

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ABSTRACT

Stochastic resonance (SR) has been widely applied in the field of weak signal detection by virtue of its characteristic of utilizing noise to amplify useful signal instead of eliminating noise in nonlinear dynamical systems. How to quantitatively evaluate the performance of SR, including the enhancement effect and the degree of waveform distortion, and how to accurately extract signal amplitude have become two important issues in the research on SR. In this paper, the signal-to-noise ratio (SNR) of the main component to the residual in the SR output is constructed to quantitatively measure the enhancement effect of the SR method. And two indices are constructed to quantitatively measure the degree of waveform distortion of the SR output, including the correlation coefficient between the main component in the SR output and the original signal, and the zero-crossing ratio. These quantitative indices are combined to provide a comprehensive quantitative index for adaptive parameter selection of the SR method, and eventually the adaptive SR method can be effective in enhancing the weak component hidden in the original signal. Fast Fourier Transform and Fourier Transform (FFT+FT) spectrum correction technology can extract the signal amplitude from the original signal and effectively reduce the difficulty of extracting signal amplitude from the distorted resonance output. The application in vibration analysis for bearing fault diagnosis verifies that the proposed quantitative evaluation method for adaptive SR can effectively detect weak fault feature of the vibration signal during the incipient stage of bearing fault.

1. Introduction

Mechanical fault diagnosis technology is of important significance in ensuring the long-term safe running of mechanical equipment with high reliability and efficiency. It's a technical guarantee of predictive maintenance. The fault feature extraction of vibration signals is an important factor affecting the accuracy of fault diagnosis. Therefore, many signal processing methods have been widely studied and successfully applied to the mechanical fault diagnosis [1,2], such as an

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extended wavelet spectrum analysis technique [3], time-frequency technique [4] and energy-based feature extraction technique [5]. However, the characteristic signal of a mechanical fault is often immersed in strong background noise, which makes it a challenging problem to accurately extract the fault features, especially in the early stage of the fault identification. Stochastic resonance (SR), a nonlinear method using noise to enhance weak signals instead of eliminating noise, provides an effective solution to the challenges in weak signal detection.

SR was first introduced by Benzi et al. [6,7]. It has been proved that the noise is not a useless energy any longer but a resource to enhance periodic signals in nonlinear systems. Since then, the principle of SR has been applied to many fields and it has been demonstrated that the output signal-to-noise ratio (SNR) of the SR system can be significantly amplified when the optimal matching of periodic signal, noise and dynamical system can be achieved [8–11]. Until the beginning of the 21th century, SR application has been studied in mechanical fault diagnosis extensively [12]. Aiming at overcoming the small parameter restriction (the values of the frequency and amplitude of periodic signal and noise intensity are all smaller than 1) of the classical SR and the larger parameter problem (the values of frequency and/or amplitude and/or noise intensity can be much larger than 1) involved in the engineering practice of mechanical fault diagnosis, the further improvement on SR has been achieved in the past years [5,13–18]. Adaptive SR was firstly proposed by Mitamin [19] who observed SR through tuning the noise level. Its application on mechanical fault diagnosis has been extensively investigated in recent years [20–27]. There are, however, still some common problems, such as how to quantitatively evaluate the performance of SR, including the enhancement effect and the degree of waveform distortion, and how to accurately extract signal amplitude in the engineering application of SR. Thus it can be seen that the adjustment of system parameters and the evaluation of detection results are two key problems in the searching process of SR algorithm [21–24,26–29]. The measurement index is to determine if SR has occurred and to evaluate the performance of SR quantitatively, which is a key factor affecting the accuracy and validity of the detection result. Now, there are several measurement indexes to evaluate the detection effect of SR, such as SNR [30,31], the mutual information [32], the approximate entropy [33], and weighted power spectrum kurtosis [34]. SNR has been used most widely among all of the measurement indexes. As we know, the accurate frequency of target signal, a necessity when using the SNR formula in the conventional sense to calculate the resonance output SNR, is not always obtained. Instead, only the rough frequency range can be estimated. Therefore, SNR is helpless when the target signal frequency cannot be estimated accurately. A weighted signal-to-noise ratio (WSNR) index to overcome this drawback was proposed [35], however the selection of exponential parameters in the formula is still dependent on personal experience.

Aiming at resolving the above problems, a quantitative evaluation system on the performance and feature enhancement of SR is proposed in this study to quantitatively evaluate the feature enhancement effect of SR. A quantitative evaluation index constructed in the quantitative evaluation system overcomes the limitation of accurate frequency requirement of classical SNR. The quantitative evaluation index is named as modified signal-to-noise ratio (MSNR) index. The specific algorithm of adaptive SR method based on the quantitative evaluation index is proposed. By means of the maximum of MSNR index, this method can implement optimal selection of system parameter adaptively, even though the signal frequency cannot be estimated accurately.

In addition, although SR has special advantages in detecting weak signal, it enhances the periodic feature of useful signal while also seriously distorts the output signal and damages the signal amplitude. It has always been a difficult problem to extract the exact amplitude of useful signal from the output signal of SR. Therefore, considering the difficulty of extracting useful signal amplitude from the resonance output, the Fast Fourier Transform and Fourier Transform (FFT+FT) spectrum correction technology is used to extract the useful signal amplitude from the original signal based on the detection result of SR in order to achieve the quantitative diagnosis based on the exact signal amplitude to quantitatively identify mechanical damages of different extent. The simulation experiments and engineering application demonstrate that the proposed method is effective in detecting the weak signals for mechanical fault diagnosis.

The classical SR theory and SR characteristics of periodic signals are presented in Section 2, and the quantitative evaluation system on the performance and feature enhancement is presented in Section 3. The specific algorithm of adaptive SR method based on the MSNR index in the quantitative evaluation system is described in detail in Section 4. Then, in Section 5, the effectiveness of the proposed method is verified by the simulation experiments and engineering application. Finally, conclusions are drawn in Section 6.

2. Basic theory of SR

2.1. Bistable SR model

As a nonlinear phenomenon of using noise to enhance useful signal, the dynamical behavior of SR can be described by the Langevin equation derived from the Brownian motion of particles. The overdamped SR equation based on the bistable model can be written as:

$$\frac{dx}{dt} = -\frac{dU}{dx} + n(t) \tag{1}$$

where $x(t)$ denotes the system output signal, $n(t) = \sqrt{2D}\xi(t)$ and $\xi(t)$ is a Gaussian white noise with zero-mean and unit