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Multi-frequency weak signal detection based on multi-segment cascaded stochastic resonance for rolling bearings

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ABSTRACT

For rotating machinery, vibration signals excited by its faulty components provide rich condition information for its fault diagnosis and condition-based maintenance. However, strong noise severely influences the accurate detection of incipient faults. Thanks to the ability of enhancing weak input and suppressing the noise, the stochastic resonance (SR) has been applied to weak signal detection in some fields, and the improvement on its performance are still being concerned, especially in the mechanical engineering. For multi-frequency weak signals, this paper proposes an improved mechanism for the SR, called multi-segment cascaded stochastic resonance (MS-CSR). In this method, the input signal obtains segment enhancement by using some bistable SR models, and series connection of such a unit compose an improved cascaded SR (CSR) system, which can not only gradually enhance the weak signals of interest, but also pay more attention on the signal with relatively small amplitude at the initial. A modified measurement index, named alliance signal-to-noise ratio (ASNR) is defined to evaluate the detection performance of the proposed SR method, as well as the parameter selection for the MS-CSR system. In this index, a weight factor is introduced to influence the assignment of noise energy in the SR, so that the relatively weak signal in the multi-frequency input signal can obtain a high priority to make the resonance phenomenon happen and avoid the misdiagnosis. A simulated signal and an experimental vibration signal collected from a faulty bearing are used to verify the effectiveness of the proposed MS-CSR method. The results demonstrate that the MS-CSR is a useful tool for detecting weak signals with multiple characteristic frequencies.

1. Introduction

Critical components in rotating machinery, e.g. bearings and gears, always endure heavy loads under various operating conditions, and thus structural faults, such as wear, pitting, or breakage, may occur after a long period of running [1]. Vibration based signal analysis can provide rich information on the impulse period and intensity, and thus this technology is widely used for health monitoring and fault diagnosis of the rotating machinery [2,3]. However, if the critical machine component has a slight fault or works in bad environment, raw signals contain not only the vibration signal excited by the incipient fault, but also undesired noise from working environment and other vibrations from several competing sources, e.g. improper installation and surfacing of the mounted sensors, random impacts from friction and contact forces, external disturbances [4], the former of which is relatively weak and usually masked by strong noise. For the aim of accurate fault diagnosis, various signal detection methods are studied to extract the weak signal from a noisy signal.

Weak signal detection is a hot research topic and two kinds of methods have been developed for this purpose. One kind of methods is to directly cancel or suppress the noise and then its influence on the accurate fault diagnosis can be removed. After this processing, the remaining signal is viewed as the feature signal to be used for further fault diagnosis. Some popular methods include wavelet denoising methods, adaptive filtering methods, signal decomposition methods (e.g. wavelet transform [5–7], empirical model decomposition, local mean decomposition), etc. However, it is noteworthy that the suppression of noise will inevitably weaken the useful signal amplitude when removing the noise.

Distinct from noise suppression methods, the other kind of weak signal detection methods try to utilize the noise instead of suppressing it. Among them, the most typical ones are ensemble empirical mode decomposition (EEMD) [8] and stochastic resonance (SR) [9]. In the EEMD method, white noise is used to separate disparate time scales and improve the signal decomposition performance. However, when the raw signal has strong noise, there may be a lack of necessary extrema for the EEMD method to separate the feature signal from strong noise. To solve this problem, Guo et al. [10] proposed a hybrid signal processing method to combine the EEMD with a spectral-kurtosis-based bandpass filter. Žvokelj et al. [11] presented a signal denoising

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method which combines the strengths of kernel principal component analysis with EEMD to handle multi-scale system dynamics.

Another example of using noise for weak signal detection is the SR, which was firstly coined by Bentz et al. [9] and used to explain the Earth's climate switching. The following study on the SR phenomena and theory received much attention from the physics community, and further enriched its applications in many fields. The SR uses a nonlinear system to produce synergy between the input signal and the added noise to obtain a stronger output signal with the same period of the input. In a general bistable system, the SR utilizes the white noise to provide potential energy for Brownian particle movement from one stable stage to the other [9]. It provides the energy transmission from the added noise to the periodical signal, so that the detection of the weak signal and the improvement of the signal-to-noise ratio can be realized.

Compared with traditional methods, the SR can finish the tasks of weak signal enhancement and noise suppression at one time, thus it is suitable for weak fault feature extraction under strong noise. Positive results on incipient fault diagnosis have been reported. To improve the detection ability, SR are combined with other adaptive single processing methods [12,13]. To get rid of the limitation of small parameter requirement in the normal SR, He et al. [14] proposed multi-scale noise tuning to realize the SR at a fixed noise level; Lai and Leng [15] improved the SR for signals with large-amplitude, large-frequency and/or large-intensity noise; Lu et al. [16] designed a nonlinear mechanical vibration isolation system by adding a very low intensity of random noise to the harmonic excitation force. There are other improvements of SR, e.g. solutions for inherent output saturation [17], model stability [18], Woods–Saxon potential [19], multi-stable models [20,21], etc.

Although the SR is proven to be quite versatile in a broad range of applications for detecting weak signals, as summarized in Ref. [22], there are two major problems that restrict its application on fault diagnosis of rotating machinery. One problem concerns efficiently detecting impact signals with different impact amplitudes [22]. The difference on the impact amplitudes may be generated by one kind of faults or more than one fault. Li et al. [22] proposed to use data segmentation based on sliding window to detect the signal generated by two local faults; Lei et al. [23] proposed to use the ant colony algorithms to optimize system parameters; Qin et al. [24] combined dyadic wavelet transform and least square system to speed up the SR parameter optimization. He and Wang [25] analyzed the effects of the SR using multiple scales for weak signal detection. As for the detection of multi-frequency signals buried in noise, Han et al. [26] combined the wavelet transform and parameter compensation band-pass multi-stable stochastic resonance for weak signal detection; Shi et al. [27] combined the orthogonal wavelet transform with the SR for multi-frequency signal under colored noise; Qin et al. [28] analyzed the frequency range selection characteristic of re-scaling frequency SR and iteratively used SR to extract vibration components with different frequencies. Lu et al. [29] designed an underdamped step-varying second-order SR method that can attenuate effect of the multi-scale noise in high-and(or) low-frequency domains.

Based on the above analyses, the resonance effect of the SR is greatly influenced by the amplitudes and the period of weak signals to be detected. It makes the application of the SR in mechanical engineering difficult, especially when amplitudes of impulses are greatly different. In engineering applications, it is very common that a variety of frequency components with different amplitudes is mixed in one raw signal, in which the relatively weak component is easily missed. Therefore, a novel and practical mechanism for the SR system is needed for such detection and an appropriate measurement index is needed to efficiently evaluate its performance on the weak signal detection.

Motivated by the idea of data segmentation [22,30] and cascaded SR (CSR), a modified mechanism for the SR, called multi-segment cascaded stochastic resonance (MS-CSR), is designed for the detection of a multi-frequency weak signal. In this method, the noisy signal is firstly divided into some segments, each of which can be individually processed by a bistable SR (BSR) model, so that the resonance effects for different signals can take effect. The mechanism of the CSR is then used to gradually enhance the output signal of single SR model. Considering that more than one signal need to be enhanced, the original measurement index SNR is modified, so that the general performance of multiple signal detection can be measured; at the same time, the enhancement of a relatively weak signal component can be a priority to avoid the unexpected misdiagnosis.

The remaining of this paper is organized as follows. Section 2 briefly introduces the principle of a normal bistable SR model and then analyzes its problem on the detection of a multi-frequency signal. In Section 3, a multi-segment cascaded stochastic resonance (MS-CSR) system is proposed, which mainly include signal segmentation, progressive signal enhancement, and quantitative measure. After that, a simulated signal is used to demonstrate the proposed method in Section 4. Section 5 shows the application of extracting a multi-frequency weak impact signal of a rolling element bearing. Analyses and comparisons are also given in the simulation and experiment. Finally, conclusions are drawn in Section 6.

2. Fundamental theory of bistable stochastic resonance

2.1. Basic theory of BSR

The most commonly used model of the SR is a bistable nonlinear system driven by a weak period input signal and added white noise, which are three essential elements of the SR. The bistable Langevin equation can be written as [9]:

$$\frac{dx(t)}{dt} = -U'(x) + s(t) + n(t), \tag{1}$$

where $x(t)$ denotes the system output, $s(t)$ is the input signal, $n(t) = \sqrt{2D}\varepsilon(t)$is noise input, D is the noise intensity and $\varepsilon(t)$ represents Gaussian white noise with zero mean and unit variance; $U(x)$ is the nonlinear potential function, and it is a fourth-order potential function:

$$U(x) = -\frac{1}{2}ax^2 + \frac{1}{4}bx^4, \tag{2}$$

where a and b are parameters of potential wells, and thus the nonlinear bistable Langevin model can also be expressed as:

$$\frac{dx(t)}{dt} = ax(t) - bx(t)^3 + s(t) + n(t), \tag{3}$$

A bistable SR model in Eq. 3 consists two potential wells and one potential barrier. When there is no input signal and added noise, the system has two stable points, $x_s = \pm\sqrt{a/b} = \pm 1$, and one critical stable point $x_0 = 0$. The height of the potential barrier between two wells is $\Delta U = a^2/4b$. At this time, the position of the particle (the solution of Langevin equation) moves around its initial position.

If two inputs are given to the model, as shown in Fig. 1, the motions of the particle would be determined by these two signals. If both of them are very small or weak, the particle still moves around its initial position and cannot overcome the blocking of the potential barrier due to no enough energy. Once the added noise, the input signal and the system match well, and then the particle obtain energy from the added noise to surmount the barrier and move into another potential well. With the period of the input signal, the particle moves between

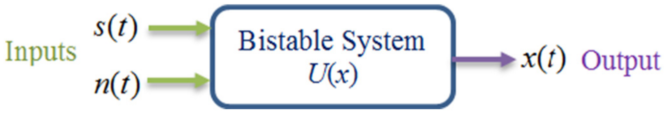

Fig. 1. Framework of single bistable system [31].

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