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A new adaptive cascaded stochastic resonance method for impact features extraction in gear fault diagnosis

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ABSTRACT

Gearboxes are widely used in engineering machinery, but tough operation environments often make them subject to failure. And the emergence of periodic impact components is generally associated with gear failure in vibration analysis. However, effective extraction of weak impact features submerged in strong noise has remained a major challenge. Therefore, the paper presents a new adaptive cascaded stochastic resonance (SR) method for impact features extraction in gear fault diagnosis. Through the multi-filtered procession of cascaded SR, the weak impact features can be further enhanced to be more evident in the time domain. By analyzing the characteristics of non-dimensional index for impact signal detection, new measurement indexes are constructed, and can further promote the extraction capability of SR for impact features by combining the data segmentation algorithm via sliding window. Simulation and application have confirmed the effectiveness and superiority of the proposed method in gear fault diagnosis.

1. Introduction

Gearboxes are widely used in engineering machinery, which often work in harsh environments and are therefore subject to failure on the gears. The failure may deteriorate mechanical performance and even lead to fatal breakdowns. Consequently, it is important to accurately extract fault features to detect the existence of faults as early as possible. Because of the inherent link between machinery operation state and vibration information, vibration signals collected from gearboxes carry abundant information on machinery health conditions. Therefore, vibration signal analysis [1–4] has been extensively investigated during the past decades. In order to obtain vital feature information from the vibration signals, various signal processing techniques, spectral kurtosis (SK) [5,6], variational mode decomposition (VMD) [7,8], local mean decomposition (LMD) [9], wavelet transform (WT) [10,11], etc., have been extensively studied and used in machinery fault diagnosis. Traditionally, noise is always considered an undesirable disturbance, thus these traditional signal processing methods have been focused on filtering noise to improve the detectability of signals. However, when the noise is reduced by using these filtering methods, the useful signal components may also be attenuated or even destroyed. In fact, noise is not just a source of signal contamination, but also describes a kind of signal energy. If the energy generated by noise can be used properly, it would be advantageous to extract the feature information from the signals submerged in strong noise. And, stochastic resonance (SR) [12,13] is a kind of typical noise-assisted data processing method. In comparison to the traditional methods for weak signal processing by filtering or masking noise, SR realizes the detection of weak signal by utilizing noise instead of eliminating noise, and the weak signal features are not weakened or destroyed but enhanced.

The concept of SR was first introduced in the 1980s, which was used to describe the periodicity associated with the Earth's ice ages in climatology [14,15]. SR, as a nonlinear physical phenomenon, emphasizes the synergistic effect between a nonlinear dynamic system, a small parameter signal and noise. When the optimal matching of resonance system, weak signal and noise is achieved, SR can transfer noise energy to weak signal to enhance the useful features. Based on the unique technological superiority of using noise to enhance weak signals, SR has been widely studied in machinery fault diagnosis field [16–18], but the researches are mainly focused on the applications of single SR in weak feature extraction. Although SR has a distinct advantage in the weak signal processing, when the signal-to-noise ratio (SNR) of vibration signals is low, the detection effect of single SR is not satisfactory. Because the output result of resonance system still contains a certain amount of noise, and features of the useful signal may not be evident enough to detect faults.

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To solve the above problem, it is necessary to conduct the research of SR enhancement techniques, such as cascaded SR [19], coupled SR [20] and parallel SR [21]. Through the authors' literature search, studies on performance characteristics of SR enhancement methods are few and the applications of SR enhancement methods to impact features extraction in gear fault diagnosis are even less. In a sense, SR can be regarded as a special low-pass filter [22]. However, the filtering effect of SR is better than the conventional low-pass filter, because SR "filters out" the high-frequency interference while also enhances the low-frequency signal. Consequently, based on the unique filtering characteristics of SR, a single SR can be used to process vibration signals repeatedly, namely "multi-filtered procession", and thus to further weaken noise and enhance the useful features. Cascaded SR, single bistable system connected in series, can realize the reutilization of noise by multi-filtered procession, which can further weaken high-frequency dithering to make the output waveform smoother and features of useful signal more evident. Therefore, cascaded SR has more advantages in processing the weak signals than a single SR.

Whether single SR methods or SR enhancement methods are applied to extract the useful features from vibration signals, there is a common problem that how to select the appropriate system parameters to generate SR. For this purpose, adaptive SR algorithm has been developed in the past decade [23–25]. In view of the differences of resonance behavior of impact signal and periodic signal by using SR [26], resonance detection of impact signal is a typical multi-component features extraction problem which is more sensitive to system parameters. Thus the existing measurement indexes of SR and single parameter optimization strategy are difficult to satisfy the requirements of impact signal detection. Note that periodic signal refers to the signal that is composed of the sine/cosine signals and theirs harmonic components, and impact signal refers to the signal that contains a single impact component or periodic impact components. According to the above-mentioned problems, the present study investigates cascaded SR technology and proposes a new adaptive cascaded SR method for impact features extraction in gear fault diagnosis. The performance and characteristics of cascaded SR are analyzed. And through the multi-filtered procession of cascaded SR, the weak impact features can be further enhanced to be more evident in the time domain. By analyzing the characteristics of non-dimensional index for impact signal detection, new measurement indexes are constructed to further promote the extraction capability of SR for impact features. Meanwhile, a data segmentation algorithm via sliding window is adopted to eliminate the influence of multiple impact components on the measurement index and realize the effective extraction of impact features. Through the genetic algorithm, multiple system parameters can be adjusted simultaneously, thus improving the performance and efficiency of the proposed method. Experiment and engineering application demonstrate that the proposed method is effective in extracting the weak impact features in gear fault diagnosis.

The remaining parts of this paper are arranged as follows. Section 2 is mainly dedicated to provide the theoretical background of SR. Section 3 analyzes the performance and characteristics of cascaded SR for weak signal detection and introduces the impact signal detection strategy based on the proposed adaptive cascaded SR method. Section 4 performs simulation analysis and engineering application to evaluate the proposed method in comparison with other methods and provides further discussions. Conclusions are given in Section 5.

2. Basic theory of SR

SR is a nonlinear physical phenomenon where the weak signal is enhanced and noise is weakened through the interaction of a small parameter signal and noise with a nonlinear system model. Generally, the nonlinear Langevin equation of Brownian particles is applied to describe the dynamical behavior of SR. Therefore, the overdamped SR equation with classical bistable model can be written as follows:

$$\frac{\mathrm{d}x(t)}{\mathrm{d}t} = -\frac{\partial U(x,t)}{\partial x} + s(t) + n(t) \tag{1}$$

where $x(t)$ denotes the resonance system output, $s(t)$ is a input periodic/aperiodic signal, and $n(t)$ is a Gaussian white noise with zero mean and D variance. $U(x, t)$ describes a nonlinear system model with symmetric double well potentials, which is generally expressed as follows:

$$U(x,t) = -\frac{a}{2}x(t)^2 + \frac{b}{4}x(t)^4 \tag{2}$$

where system parameters a and b are positive real number. The potential function $U(x)$ has two stable points $x = \pm\sqrt{a/b}$ and one critical stable point $x_0 = 0$ with a barrier height $\Delta U = a^2/4b$.

According to the Langevin equation of Brownian particles, the system output $x(t)$ is actually the Brownian particle trajectory in the potential function $U(x)$ under the combined action of input signal and noise. Only in the presence of the periodic input signal, the Brownian particle moves in one of the two potential wells and fails to transfer between two potential wells. However, with the assistance of appropriate noise, the particle can accumulate enough energy to cross the barrier and jump between the two potential wells back and forth, and SR phenomenon happens. Accordingly, the particle movements in single potential well are amplified to the transition motions between double potential wells to realize the feature enhancement of input signal. Therefore, it is important to construct an evaluation function, namely measurement index, to determine whether SR occurs and whether the resonance effect is satisfactory. The crucial process of using SR to detect weak signal is to adjust the noise intensity or system parameters to optimize the measurement index of SR, so as to achieve the detection of weak signal.

3. Adaptive cascaded SR scheme for impact features extraction

3.1. Cascaded SR

From the viewpoint of mathematics, the system response of SR is essentially the solution of differential Eq. (1) that is obtained by integral calculation. And the integrator is essentially a low-pass filter in signal processing. Therefore, in a sense, SR can be regarded as a special low-pass filter whose filtering effect is better than the conventional low-pass filter. Based on the peculiar filtering characteristics of SR, when two or more bistable systems are connected in series, the latter bistable systems will continue to transfer the noise energy to the low-frequency area according to the approximated Lorentz distribution after the first-stage bistable system achieves a resonance state. Consequently, the high-frequency dithering is further weakened and the contour-feature of time domain waveform is highlighted. Cascaded SR, single bistable system connected in series, not only makes the amplitude of characteristic frequency more outstanding in the frequency domain, but also can further eliminate high-frequency dithering and make the output waveform smoother in the time domain. Hence, cascaded SR has more advantages in processing weak signals in comparison to single SR. The framework of cascaded SR system is shown in Fig. 1.

Fig. 1 indicates that the resonance response of the former stage resonator is the system input of the latter stage resonator in