Mechanical Systems and Signal Processing 114 (2019) 128–145

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

A novel adaptive stochastic resonance method based on coupled bistable systems and its application in rolling bearing fault diagnosis

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ARTICLE INFO

Article history:
Received 19 August 2017
Received in revised form 14 April 2018
Accepted 1 May 2018

Keywords:
Rolling bearing fault diagnosis
Stochastic resonance
Coupled bistable systems
Weighted spectral peak SNR
Adaptive

ABSTRACT

Stochastic resonance (SR), as a typical noise-assisted signal processing method, has been extensively studied in weak signal detection by virtue of the advantage of using noise to enhance the feature of periodic signal. And how to better apply the SR method in engineering signal processing has always been the research hotspot. In this paper, a novel adaptive SR method based on coupled bistable systems (ACBSR) is proposed to further improve the performance of SR method for weak signal detection. Compared with the cascaded bistable SR system, the suggested coupled bistable SR (CBSR) system can enhance the target signal while suppressing the low-frequency and high-frequency interferences, whose output behavior exhibits good bandpass filtering characteristic. In addition, a weighted spectral peak signal-to-noise ratio (WPSNR) index is constructed by using spectral peak SNR, spectral correlation coefficient and zero-crossing ratio to serve as the measurement index of SR for periodic signal detection. The constructed WPSNR index is simple in form and easy to calculate, which can quantitatively evaluate the resonance effect of periodic signal, even though the target signal frequency cannot be estimated accurately. And the combination of WPSNR index and the CBSR system is beneficial to improve the performance of SR method in rolling bearing fault diagnosis. Experiments and engineering application are performed to verify the effectiveness and superiority of the proposed ACBSR method in comparison with the traditional SR method.

1. Introduction

Vibration-based condition monitoring and fault diagnosis technology of rotating machinery is playing an increasingly important role in reducing breakdown loss and promoting safe operation and status maintenance of equipment. And rolling bearings, as core components of rotating machinery, are prone to failure because of the harsh environments and complex working conditions. Moreover, the fault-induced feature information contained in the vibration signal is relatively weak and always be submerged in the strong background noise, which makes it difficult to be identified. Therefore, they have received a lot of attention in the field of vibration analysis. And various weak signal detection techniques, e.g., maximum correlated kurtosis deconvolution (MCKD) [1,2], spectral kurtosis (SK) [3,4], variational mode decomposition (VMD) [5],

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https://doi.org/10.1016/j.ymssp.2018.05.004
0888-3270/

time-frequency analysis [6,7], empirical mode decomposition (EMD) [8], etc., have been extensively investigated for effectively extracting the fault-induced signatures from background noise. And most of weak signal detection methods extract the weak signal features by filtering out the noise. In fact, if properly utilized, noise, as a kind of signal energy, is beneficial to the feature extraction of periodic signal. For example, ensemble empirical mode decomposition (EEMD) [9], as an improve method of EMD, was presented to alleviate the mode mixing problem in EMD by adding appropriate noise to signal. And, stochastic resonance (SR) is a typical noise-assisted data processing method. Unlike traditional denoising techniques, SR realizes the detection of weak signal by utilizing noise instead of eliminating noise, and the weak signal features are not weakened but enhanced.

Since the theory of SR was proposed by Benzi et al. [10,11], fault diagnosis technology based on SR principle has been investigated owing to its advantages in weak signal detection [12–15]. For instance, to overcome the shortcoming of output saturation of classical bistable SR, an adaptive unsaturated bistable SR method based on a piecewise bistable model for mechanical fault diagnosis was proposed in Ref. [16]. And an enhanced SR method based on full-wave signal construction strategy for bearing fault diagnosis was studied in Ref. [17]. In order to separate the harmonic vibration components from the original noisy vibration signal, an iterative approach based on SR with different frequency-scale ratios was explored in Ref. [18]. Aiming at the SR detection for large parameter signal in engineering signal processing, multiscale noise tuning SR method and its improved methods for mechanical fault diagnosis were, respectively, proposed in Refs. [19,20]. In order to increase the calculation speed and improve the weak feature detection performance, an adaptive and fast SR method based on dyadic wavelet transform and least square system parameters solving was proposed in Ref. [21]. These modified and optimized SR techniques have effectively promoted the development of SR theory and popularized the application of SR method in mechanical fault diagnosis field.

And through the literature search, it can be found that the engineering signal processing methods based on SR are almost implemented in the framework of single resonance system with different potential functions. However, apart from these SR methods based on single resonance system, there are coupled SR [22,23], cascaded SR [24], etc. And the phenomenon of SR in these systems have also been investigated in different ways [25–27]. Cascaded SR system is constituted by multiple subsystems connected in series. In cascaded SR system, the output of the former stage subsystem is used as the input of the latter subsystem, and through the repetitive processing of multi-level systems for the input signal, the noise can be further weakened, thereby realizing the enhanced extraction of weak signal feature. However, cascaded SR system does not consider the influence of the interaction between the subsystems on the system output. Coupled SR system, as described in Ref. [27], is composed of multiple subsystems coupled together by the coupling coefficient. In coupled SR system, each subsystem has an independent external input signal, and through the ensemble mean of all subsystem output, to achieve the enhanced extraction of signal features. Ref. [28] investigated the phenomenon of SR of coupled systems driven by pinning noise, and found that the system with switching noise can lead to a more pronounced resonance effect than partial noise. Although the coupled SR system considers the effect of the interaction between multiple subsystems on the system output, it ignores the ability of reprocessing input signal by multi-level subsystems. Meanwhile, SR is a parameterized filter, and its filtering performance is bound up with the system parameters. And how to adjust the system parameters to obtain a satisfying detection result is a key problem in the weak signal detection. Therefore, measurement index is necessary to quantitatively evaluate the detection effect and ensure the validity and accuracy of detection result of SR for input signal. At present, there are several measurement indexes to evaluate the denoising effect of SR method, such as signal-to-noise ratio (SNR) [29], weighted power spectral kurtosis [30], and approximate entropy [31], etc. As for the SR method for periodic signal detection, SNR index is the most widely used among these indexes because it is simple and easy to calculate. However, it is well known that the accurate frequency of target signal is a necessary condition for calculating SNR of resonance output, whereas it is not easy to be satisfied in engineering signal processing, thus limiting its application to some extent. In Ref. [32], the six quantitative indexes were fused into a synthetic quantitative index via a back propagation neural network to guide the parameter selection of the SR procedure. Although the synthetic quantitative index overcomes the requirement of knowing accurate frequency, the corresponding explicit mathematical expression is not given, and the calculation is complicated.

Given the above, a novel adaptive SR method based on coupled bistable systems (ACBSR) is presented in the paper to improve the performance of weak signal detection in rolling bearing fault diagnosis. The improved coupled bistable SR (CBSR) system realizes the complementary advantages of cascaded SR system and coupled SR system, which not only inherits the strong processing ability of cascaded SR on weak signal, but also takes into account the influence of the interaction between subsystems on the system output. The suggested CBSR system behaves like a bandpass filter, which can not only enhance the periodic feature of target signal, but also attenuate the low-frequency and high-frequency interferences. In particular, according to the characteristic of SR detecting periodic signal, a weighted spectral peak signal-to-noise ratio (WPSNR) index is constructed in consideration of the advantages and disadvantages of spectral peak SNR, spectral correlation coefficient and zero-crossing ratio. The constructed WPSNR index is simple, easy to calculate, and it doesn't need the accurate frequency of target signal. And based on the maximum of WPSNR index of resonance output, the proposed ACBSR method can achieve an optimal selection of system parameters, thus realizing the adaptive extraction of periodic signal feature. Experiments and engineering application demonstrate that the proposed ACBSR method is effective in extracting the periodic features in rolling bearing fault diagnosis.

The rest of the paper is organized as followed: Section 2 introduces the CBSR model, and analyzes its performance; the construction process of WPSNR index is described in detail in Section 3. Then, Section 4 provides the algorithm flow of the