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An improved multiscale noise tuning of stochastic resonance for identifying multiple transient faults in rolling element bearings

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ABSTRACT

Stochastic resonance (SR), a noise-assisted tool, has been proved to be very powerful in weak signal detection. The multiscale noise tuning SR (MSTSR), which breaks the restriction of the requirement of small parameters and white noise in classical SR, has been applied to identify the characteristic frequency of a bearing. However, the multiscale noise tuning (MST), which is originally based on discrete wavelet transform (DWT), limits the signal-to-noise ratio (SNR) improvement of SR and the performance in identifying multiple bearing faults. In this paper, the wavelet packet transform (WPT) is developed and incorporated into the MSTSR method to overcome its shortcomings and to further enhance its capability in multiple faults detection of bearings. The WPT-based MST can achieve a finer tuning of multiscale noise and aims at detecting multiple target frequencies separately. By introducing WPT into the MST of SR, this paper proposes an improved SR method particularly suited for the identification of multiple transient faults in rolling element bearings. Simulated and practical bearing signals carrying multiple characteristic frequencies are employed to validate the performance improvement of the proposed method as compared to the original DWT-based MSTSR method. The results confirm the good capability of the proposed method in multi-fault diagnosis of rolling element bearings.

1. Introduction

Stochastic resonance (SR) is a counterintuitive phenomenon characterized by energy transfer from noise to information content with the consequence of signal-to-noise ratio (SNR) improvement, which thereby has attracted sustained attentions in a wide range of research fields during the past three decades. First put forward by Benzi et al. [1], the SR was just a theory proposed to explain the periodically recurrent ice ages [2]. Now the SR is a genetic phenomenon in a certain condition with a mature level of understanding [3–14]. The classical theory of SR has been well established and its applications are in various areas [13]. The engineering applications via SR mainly focus on enhancing the periodic information by the assistance of noise, especially in the area of signal processing, such as the identification of periodic transient faults in rolling element bearings from noise-contaminated vibration signals.

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The classical SR can be described as follows: the output SNR of periodic signal of a certain nonlinear system first increases and then decreases after reaching a maximum with the increase of noise intensity. This leads to an intuitive belief that the SR effect can be realized by optimizing the noise level [15,16]. However, the strength of noise involved in the system may exceed the resonance regions; reducing noise may not be an option in reality. In this case, tuning the system parameters is an alternative for realization of SR [17,18]. An important issue should be addressed that the adiabatic approximation theory [19] and linear response theory [20] in conventional bistable SR both call for small parameters: the intensity of noise and the values of frequency/amplitude of driving signal should be all much smaller than 1. In order to break these restrictions for a wider range of applications, the SR strategies dealing with large parameter problems have been explored in recent few years, including some frequency shift techniques [21–24], scale normalization of bistable SR system [25], increasing the calculation step of SR numerical model [26], and using the Woods–Saxon potential [27]. However, the system parameters should still be adjusted in the above large parameter stochastic resonance (LPSR) techniques, which increases the complexity of these methods in multi-parameter optimization process. Furthermore, the foundation of the above SR theory is based on Gaussian white noise. The effect of colored noise ubiquitous in practice is not talked about.

As a matter of fact, the SR could also be excited by colored noise, which has been investigated extensively [28–39]. Most recently, our group studied the effects of $1/f$ noise on SR for weak signal detection and proposed a new LPSR method called multiscale noise tuning SR (MSTSR) [40]. It was discovered that the SR with $1/f$ noise has the advantages of insensitivity to noise intensity, activity of multiple scale noise and capability of detecting high frequency. In the MSTSR model, there is no demand for tuning the noise intensity and system parameters or shifting the high target frequency to the low frequency area. Until now, this kind of model has been used in various applications [41–45], demonstrating very good performance. However, these applications only concentrate on enhancing single-frequency weak signal; the detection of multiple periodic components contained in single-channel signal has not been concerned. The latter condition is possible to be encountered in fault diagnosis of rolling element bearings when more than one defects appear in different bearing components so that multiple transient faults need to be identified.

For multi-fault diagnosis of rolling element bearings from single-channel signal, several methods have been proposed. Wang and Tse [46] used a blind component separation method to separately extract the low-frequency periodic component caused by shaft misalignment or rotor unbalance, and the high-frequency transient component incited by bearing localized faults. The mixed signal contains two types of mechanical faults, but they only considered one kind of fault on the observed bearing. Hong and Liang [47] separated different bearing characteristic frequencies from a single-channel mechanical signal mixture by using a joint wavelet decomposition and Fourier transform approach. But the method requires a pre-denoising process for the mixed signal if heavy noise is involved. Wang et al. [48] proposed a new technique based on the dual-tree complex wavelet transform for both signal denoising and multiple fault signatures detection. Wang and Liang [49] adopted the adaptive spectral kurtosis method for identification of multiple transient faults in bearing. Nevertheless, the above two methods assume that different fault information is hidden in different sub-bands in a vibration signal; they are not suitable when different transient components tangle up with each other in the spectrum.

This paper intends to identify multiple transient faults of bearing from a single-channel signal by using the MSTSR method. It should be noted that the multiscale noise tuning (MST) in our previous work was implemented based on the discrete wavelet transform (DWT) [40]. It is known in the DWT that only the approximation coefficient vectors are split into two parts while the detail coefficient vectors are not. The decomposition mode of DWT restricts the application of MSTSR. First, the number of multiscale wavelet bands is insufficient and the frequency resolution of high-frequency region is poor, resulting in a rough tuning to form the $1/f$ noise, especially when the decomposition level is small for high frequency weak signal detection. Second, if two or more frequency components are so close that they are decomposed into the same wavelet band by DWT, they will coexist in the output because the frequencies in the same sub-band are adjusted to be the same level by MST. The coexistence of target frequencies is a kind of interference for identification of each one. Shi et al. [50] attempted to apply the DWT-based MSTSR to detect multi-frequency signal. Nevertheless, the multiple frequencies must be in different vectors of detail coefficients after addressing DWT on the signal; the frequencies in the same vector are difficult to be separately detected. Furthermore, the bearing used in Ref. [50] still contains only one localized fault.

The way to overcome the aforementioned deficiencies and achieve the paper's aim is to extend the generation of multiscale noise from DWT to a more general wavelet packet transform (WPT) [51]. Therefore, an improved method using WPT to implement the MST of SR is proposed in this paper. The WPT is adopted because it is a generalization of wavelet decomposition that splits both the approximation coefficients and detail coefficients with the same approach in each step, offering numerous expansions of a given signal for a finer noise tuning. Besides, the WPT uses a rich library of redundant bases with arbitrary time-frequency resolution, and so enables separating adjacent frequency components into different wavelet packet (WP) nodes. The merits of WPT make it possible to further improve the output SNR and to detect multiple weak frequencies separately by the improved SR method. Hence the WPT-based MSTSR method is well-suited for identification of multiple transient faults in rolling element bearings. Moreover, the target type of our noise tuning is no longer limited to $1/f$ noise but is optimized from various $1/f^{\beta}$-like (β is the color level) noise to reach the highest output SNR. Both simulations and experiments have been conducted in this paper to test the improved performance of the proposed method.

The remainder of this paper is arranged as follows. Section 2 first introduces the theory of bistable SR and the DWT-based MST method. Then, Section 3 describes the details of improved MST method based on WPT. The procedure of