Mechanical Systems and Signal Processing 45 (2014) 488–503

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Stochastic resonance with Woods–Saxon potential for rolling element bearing fault diagnosis

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ARTICLE INFO

Article history:
Received 12 September 2013
Accepted 5 December 2013
Available online 31 December 2013

Keywords:
Stochastic resonance
Woods–Saxon potential
Parameter tuning
Weak signal detection
Bearing fault diagnosis

ABSTRACT

This paper proposes a weak signal detection strategy for rolling element bearing fault diagnosis by investigating a new mechanism to realize stochastic resonance (SR) based on the Woods–Saxon (WS) potential. The WS potential has the distinct structure with smooth potential bottom and steep potential wall, which guarantees a stable particle motion within the potential and avoids the unexpected noises for the SR system. In the Woods–Saxon SR (WSSR) model, the output signal-to-noise ratio (SNR) can be optimized just by tuning the WS potential's parameters, which delivers the most significant merit that the limitation of small parameter requirement of the classical bistable SR can be overcome, and thus a wide range of driving frequencies can be detected via the SR model. Furthermore, the proposed WSSR model is also insensitive to the noise, and can detect the weak signals with different noise levels. Additionally, the WS potential can be designed accurately due to its parameter independence, which implies that the proposed method can be matched to different input signals adaptively. With these properties, the proposed weak signal detection strategy is indicated to be beneficial to rolling element bearing fault diagnosis. Both the simulated and the practical bearing fault signals verify the effectiveness and efficiency of the proposed WSSR method in comparison with the traditional bistable SR method.

1. Introduction

Rotating machinery such as rolling element bearing is the key part of industrial equipments. The bearings always endure heavy loads and alternating forces when they work, and the stress on the contact surfaces of the rotating components (e.g. outer raceway, inner raceway and rolling element) may cause bearing fault after a long duration of running. A slight fault may force the machine stop, but a serious fault may lead to a catastrophe. Hence, bearing fault diagnosis and condition-based monitoring are of great significance [1]. The most common bearing fault diagnosis methods are based on signal analysis technique. Generally, the sensors acquire the vibrational or acoustic signals that contain the condition information of the bearing; and then the time domain, frequency domain or time-frequency domain analysis methods are utilized to extract useful features from the original signals; and finally the pattern recognition methods are applied to realize bearing fault detection or classification. However, the bearing is not an isolate part in an integrated machine, and the bearing's vibration always induces other machine components' resonance. Thus, the acquired bearing signals always contain

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0888-3270/$ - see front matter
http://dx.doi.org/10.1016/j.ymssp.2013.12.004

undesired noises from the machine resonance and the working environment. Even worse, sometimes the bearing signatures are overwhelmed in the heavy background noises. For this reason, attenuating the noise interference and extracting the desired signal are necessary in the pre-processing stage of bearing fault diagnosis.

Noise filtering is a common approach which can suppress the noise and improve the output signal-to-noise ratio (SNR). For example, an improved adaptive redundant lifting multiwavelet is suggested by Chen et al. for compound faults detection of rotating machinery [2]. A method of using higher order cumulants (HOCs) associated with wavelet transform (WT) is proposed by Yaqub et al. to improve the fault classification accuracy under poor SNR condition [3]. Moreover, in Ref. [4], a denoising procedure using wavelet packets is proposed for instantaneous detection of pantograph oscillations. In addition, the removal of discrete frequency noise using self-adaptive noise cancellation is also demonstrated for analyzing the vibration signals in Ref. [5]. And an adaptive filtering is performed for the background noise removal of vibration signals emanating from gearboxes based on Morlet wavelet analysis and conventional optimization methods in Ref. [6]. However, it is noteworthy that the above noise removal techniques are mainly manipulated in the frequency domain, and the noise suppression may attenuate the useful signal amplitude synchronously, which may cause possible trouble in fault diagnosis.

Actually, distinct from the traditional noise suppression techniques, some techniques can utilize the noise to enhance the output signal. Among them, the most typical ones include the Ensemble Empirical Mode Decomposition (EEMD) [7] and the stochastic resonance (SR) [8]. Specially, SR is suitable for detecting weak signal that is submerged in background noise, and the effects have been verified in different practical systems [9–15]. In Ref. [11], a method for detecting signals buried in noise via nanowire transistors using SR is suggested. In Ref. [12], weak signal detection in rotating machine is conducted with multiscale noise tuning SR. And in Ref. [13], an application of parameter-induced SR to target detection in shallow-water reverberation is introduced. Besides, two adaptive SR methods for gearbox fault diagnosis are introduced in Refs. [14,15], respectively. The SR methods have revealed capacities in enhancing output signals by the assistance of proper noise. On the basis of the SR theory [8], the SR effect is greatly affected by the potential model. Most of current SR researches focus on the traditional bistable potential which contains one potential barrier and two potential wells [9–13,15–20]. The optimal effect of weak signal enhancement in the bistable potential is under the assumption that the interwell oscillation is realized. However, in the practical situation, the interwell oscillation is not easy to be realized due to the rigorous requirement that the potential, the periodic signal and the noise should be matched with each other synchronously. Besides, even if the interwell oscillation has been triggered, the particle needs to cross the barrier back and forth under the periodic force driving; and once the periodic force is non-stationary (bearing fault signal is always non-stationary), the particle may not cross the barrier when the periodic force energy is insufficient; as a result, the unexpected noise may be introduced in the output signal. Therefore, based on the issues remained for the present bistable SR, it is necessary to find a new potential model that can replace the bistable one to realize SR. In fact, some researchers have conducted studies on the non-bistable SR. For example, a tristable SR cantilever for signal amplification and filtering is suggested in Ref. [21]; the multi-stable SR and its application research on mechanical fault diagnosis is proposed in Ref. [22]; the divergent SNR and SR in monostable systems is reported in Ref. [23]; the monostable array-enhanced SR is demonstrated in Ref. [24]. Nevertheless, the above non-bistable applications are either too limited in a certain field or too complicated in practical applications. Therefore, this paper intends to further study the interaction between the SR effect and the potential model in application of weak signal detection.

Our work is motivated by a report that the Woods–Saxon (WS) potential can be used for wide spectrum energy harvesting based on the SR principle [25]. In this study, we extend the application of Woods–Saxon Stochastic Resonance (WSSR) to the weak signal detection area. The WS potential was firstly proposed by Woods and Saxon [26]. It is a mean-filed symmetric potential for single nucleon states within the shell model of nuclear structure. The WS potential is monostable, and it will present different shapes with different potential height, width and wall steepness by tuning its system parameters. Different shapes of WS potential in SR system can yield different outputs for the same input signal. Hence, the optimal SR output can be achieved by tuning the WS potential's structural parameters. Based on the WSSR, a new strategy to realize weak impulse signal detection for bearing fault diagnosis is further proposed. The proposed strategy has three distinct merits: (i) it overcomes the limitation of the small parameter requirement of the classical bistable SR [27], and can thus detect the signals with different driving frequencies; (ii) it is insensitive to the noise, and can detect weak signals with different noise levels; and (iii) the WS potential can be designed accurately dues to its parameter independence, which implies that the WSSR can be matched to different types of input signals adaptively.

In the following, Section 2 introduces the framework of WSSR and further proposes a strategy to realize weak signal detection based on WSSR. Section 3 utilizes the simulated bearing fault signals to evaluate the proposed strategy on different aspects in comparison with traditional bistable SR. Section 4 verifies the effectiveness of the proposed method by testing two sets of practical bearing signals carrying fault information. Finally, this paper is concluded in Section 5.

2. WSSR model

2.1. Theoretical model

Most of the researches on SR focus on the traditional bistable model. The classical bistable SR phenomenon can be described as: a particle is driven by the periodic force and the random forces (noises) in a bistable potential, and the periodic motion can be enhanced by the assistance of proper noises. The governing equation that illustrates such a phenomenon