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An adaptive unsaturated bistable stochastic resonance method and its application in mechanical fault diagnosis

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In mechanical fault diagnosis, most traditional methods for signal processing attempt to suppress or cancel noise imbedded in vibration signals for extracting weak fault characteristics, whereas stochastic resonance (SR), as a potential tool for signal processing, is able to utilize the noise to enhance fault characteristics. The classical bistable SR (CBSR), as one of the most widely used SR methods, however, has the disadvantage of inherent output saturation. The output saturation not only reduces the output signal-to-noise ratio (SNR) but also limits the enhancement capability for fault characteristics. To overcome this shortcoming, a novel method is proposed to extract the fault characteristics, where a piecewise bistable potential model is established. Simulated signals are used to illustrate the effectiveness of the proposed method, and the results show that the method is able to extract weak fault characteristics and has good enhancement performance and anti-noise capability. Finally, the method is applied to fault diagnosis of bearings and planetary gearboxes, respectively. The diagnosis results demonstrate that the proposed method can obtain larger output SNR, higher spectrum peaks at fault characteristic frequencies and therefore larger recognizable degree than the CBSR method.

1. Introduction

Vibration signals excited by mechanical faults are important carriers of machinery health conditions [1,2]. The fault characteristics in the vibration signals are usually overwhelmed by heavy background noise from other machine components and the operating environment, which makes some mechanical faults difficult to be diagnosed. Hence, a lot of signal processing methods such as singular value decomposition [3], ensemble empirical mode decomposition [4] and wavelet transform [5], have been widely studied and applied in early fault diagnosis to effectively identify various mechanical faults. These signal processing methods, however, are to suppress or cancel the noise imbedded in vibration signals [6]. As a result, weak fault characteristics are unavoidably weakened or destroyed in the denoising process. Therefore, these traditional methods for signal processing are not good enough for extracting the fault characteristics submerged in heavy noise.

With the help of stochastic resonance (SR), the noise can be utilized to enhance the fault characteristics and improve the output signal-to-noise ratio (SNR). The SR was first introduced by Benzi and his coworkers [7] to explain the periodicity of ancient earth's ice ages. Originally, the SR suffers from the small frequency limitation ($f << 1\,\text{Hz}$) under adiabatic approximate conditions [8]. To break this limitation, many researchers have made some noteworthy contributions to make the

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SR more universal [9,10], such as frequency-shifted and rescaling transform [11], normalized scale transform, and modulation and demodulation [12]. The classical bistable SR (CBSR) is one of the most widely used SR methods [11–20]. Nishiguchi and Fujiwara [13] suggested a CBSR method for detecting the weak fault characteristics buried in the noise via nanowire field-effect transistors. Chapeau-Blondeau and Rousseau [14] investigated the noise-assisted performance to obtain an optimal Bayesian estimator by using CBSR. Lei et al. [15,16] proposed an adaptive CBSR method and a cascaded CBSR method for mechanical fault diagnosis. Zheng et al. [17] investigated the harvesting of energy from mechanical vibrations utilizing CBSR. He et al. [18] proposed an adaptive multiscale CBSR method to extract the weak defective characteristics in train bearings. He and Wang [19] presented a new multiscale noise-tuning CBSR method to extract weak characteristics. Li et al. [20] put forward a new noise-controlled second-order enhanced CBSR method based on Morlet wavelet transform to extract the weak fault characteristics from the vibration signals of the wind turbines. These studies mainly focus on the CBSR subject to the influence of output saturation. Zhao et al. [21] suggested that the output saturation in the CBSR can reduce its output SNR. Rousseau et al. [22] demonstrated that the output saturation produces a local optimal output signal. Gosak et al. [23] pointed out the existence of the output saturation limits the enhancement performance of the CBSR in weak characteristic extraction. However, these studies still do not propose effective methods to overcome the output saturation. This shortcoming makes the CBSR difficult to extract the weak characteristics submerged in heavy noise, as well as limits the enhancement performance of CBSR. Therefore, it is still significant that how to effectively avoid the output saturation in the CBSR for extracting weak fault characteristics.

To overcome the shortcoming of CBSR methods, this paper presents an adaptive unsaturated bistable SR (AUBSR) method, in which a piecewise bistable potential model is established to avoid the output saturation. The AUBSR method is therefore expected to perform well in extracting weak fault characteristics for mechanical fault diagnosis. The method is applied to fault diagnosis of both bearings with slight flaking faults and planetary gearboxes with a chipped tooth and a missing tooth, respectively. The experimental results demonstrate that the method is able to discover incipient fault characteristics and diagnose mechanical faults.

The rest of this paper is organized as follows. Section 2 briefly describes the CBSR and discusses its saturated behaviors. Section 3 establishes a new piecewise bistable potential model, investigates its unsaturated behaviors and proposes a novel AUBSR method to extract incipient fault characteristics. Section 4 evaluates the enhancement performance and the anti-noise capability of the proposed method by simulation illustrations. Section 5 verifies the effectiveness of the method by both bearing and planetary gearbox experiments. The conclusions are drawn in Section 6.

2. Saturated behaviors of the CBSR

The CBSR phenomenon can be described as: a particle is driven by periodic force and random force in a classical bistable system, and the periodic motion can be heightened with the assistance of moderate noise. The Langevin equation that describes such a phenomenon under the overdamped condition is written as [8,24]

$$\frac{dx}{dt} = -\frac{dU_c(x)}{dx} + A\sin(2\pi f_d t + \varphi) + N(t) \tag{1}$$

where A is the amplitude of the periodic signal, i.e., periodic force, f_d is the corresponding fault characteristic frequency, φ is the corresponding phase and x is the output signal of the classical bistable system. $U_c(x) = -a_c x^2/2 + b_c x^4/4$ is the classical bistable potential, i.e., the potential function of the classical bistable system, where $a_c > 0$ and $b_c > 0$. The SR phenomenon in the classical bistable system is called CBSR. $N(t)$ stands for an additive Gaussian white noise (AGWN) with zero mean, i.e., the random force, and satisfies the following conditions.

$$\begin{cases} \langle N(t)\rangle = 0 \\ \langle N(t)N(t+\tau)\rangle = 2D\delta(\tau) \end{cases} \tag{2}$$

where D is the noise intensity and τ is the time interval.

Suppose that there is no input signals (i.e., $A = 0$ and $D = 0$) in Eq. (1), then x is calculated as

$$x = \pm\sqrt{\frac{a_c\exp(2a_c t)}{1 + b_c\exp(2a_c t)}} \tag{3}$$

in which if assuming that $t = 0$, $x = \pm\sqrt{a_c/(1 + b_c)}$; if $t \to +\infty$, $\lim_{t\to+\infty} x = \pm\sqrt{a_c/b_c}$. It is seen that the variation of $\mathrm{abs}(x)$ is limited between $\sqrt{a_c/(1 + b_c)}$ and $\sqrt{a_c/b_c}$ as shown in Fig. 1. For example, when $a_c = b_c = 1$, the $\mathrm{abs}(x)$ varies between $\sqrt{2}/2$ and 1 as described by the curve with five-pointed stars. However, the $\mathrm{abs}(x)$ approaches 1 asymptotically with the continuous increase of time t. This phenomenon is named as output saturation. It is an inherent characteristic of the classical bistable system and is independent of the input signals. With regard to the input signals in Eq. (1), the output signal x varies