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Stochastic resonance characteristic analysis of new potential function under Levy noise and bearing fault detection

Lifang He, Xicheng Zhou*, Tianqi Zhang

Chongqing Key Laboratory of Signal and Information Processing (CQKLS&IP), Chongqing University of Posts and Telecommunications (CQUPT), Chongqing 400065, China

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ABSTRACT

Based on the output saturation of classcial bistable stochastic resonance (CBSR), a new type of piecewise nonlinear bistable stochastic resonance (PNBSR) system is constructed. The mean signal-to-noise ratio gain is regarded as an index to measure the stochastic resonance phenomenon. The laws for the resonant output of piecewise nonlinear bistable system governed by *l, c, a, b* and *D* of Levy noise are explored under different characteristic index α and symmetry parameter β of Levy noise. The results show that the output of PNBSR system has increased 4 dB by comparing with the output signal-to-noise ratio of CBSR system. And the stochastic resonance phenomenon can be induced by adjusting the piecewise nonlinear system's parameters under any α or β of Levy noise. The interval of the parameters of system which induces good stochastic resonance is roughly the same. And the output signal waveform of resonance is very similar to the input signal waveform, which has some reference value for the signal recovery. Moreover, we can find the good stochastic resonance interval of the system parameters do not change with *D* of Levy noise under the different noise intensity *D* of Levy noise. On the basis of this, adjusting the intensity amplification factor *D* of Levy noise, which induces good stochastic resonance, and the interval does not change with α or β. At last, the piecewise nonlinear bistable system is applied to detect bearing fault signals, which achieves better performance compared with the classical bistable system.

1. Introduction

For weak signal, the methods of processing noise have singular value decomposition (SVD) and wavelet transform (WT), but these methods are often a harmful and unprofitable existence in the case of extremely low signal to noise ratio(SNR). Therefore, Benzi and others proposed the stochastic resonance [1] for the first time when studying the ancient meteorological glacier problem. Stochastic resonance,as a new signal processing method, has entered the field of view. In the 1990 s, Collins combined information theory and stochastic resonance to propose a nonperiodic stochastic resonance theory [2] that broadens the application of stochastic resonance. In nonlinear systems, the energy of the noise is transformed into the energy of the weak signal by the stochastic resonance system in a certain range of SNR, this can boost the signal energy and produce synergies. The novel method raised people's enthusiasm for stochastic resonance.

In weak signal detection, stochastic resonance system model is an important aspect of stochastic resonance research. And the environment of noise is mostly Gaussian noise, but Gaussian noise is an ideal noise and cannot represent random noise in nature. Such as animal noise, deep-sea noise, radar clutter, air noise et al. [3,4], which are non-Gaussian noise. The waveforms exhibit significant

* Corresponding author.
E-mail address: 1059282810@qq.com (X. Zhou).

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pulse characteristics and trailing characteristics. In recent years, the stochastic resonance induced by Levy noise has attracted the attention of scholars [5,6] in order to accurately simulate the noise in industry. The research on stochastic resonance induced by system parameters has made great progress. Wang and Xu et al. studied the stochastic resonance of FHN model under Levy noise [5]. He et al. studied the stochastic resonance characteristics of tristable system under Levy noise [6]. Zhang and He et al. [7] studied stochastic resonance in an underdamped system with pinning potential for weak signal detection. Sun hu et al. [8] studied the weak signal detection of cascade linear stochastic resonance, and the detection effect is superior to the traditional cascaded bistable system. Lu Siliang [9] puted forward a stochastic resonance system based on the Woods-Saxon potential well, and finded that it is superior to classical stochastic resonance in bearing detection, and the system has strong robustness to noise. Leng Yonggang et al. [10] discussed the signal detection of the second order linear system. Guo and Shen et al. [11] studied the application of a new nonlinear model under additive white noise and multiplicative non-Gaussian noise in stochastic resonance, and carried out numerical analysis and simulation. Shi et al. [12] proposed a new asymmetric bistable system based on SR tuning by unrelated multiplicative and additive noise to detect signals. Zhang and Song et al. [13] studied stochastic resonance in a single-well system with exponential potential driven by Levy noise, and the output laws of the system is analyzed under different parameters of Levy noise. Tian and Leng et al. [14] studied parameter-adjusted stochastic resonance of first-order linear system. Liu et al. [15] studied the stochastic resonance of a tri-stable system with α stable noise. Lai and Leng et al. [16] studied the dynamic response and stochastic resonance of a tri-stable system. Zhang and He et al. [17] proposed an underdamped system with pinning potential baseded on SR to detect weak signals. In practical application, the rotating machinery are widely used in industrial production as the key moving parts of transportation vehicles, aircraft engines, electric engines and other equipments. The rolling bearings are an essential part of rotating machinery. Therefore, the safe and reliable operation of rolling bearing is an important guarantee to reduce economic losses and avoid personal injury. In the operation of mechanical equipment, it is inevitable to be interfered by noise from other mechanical equipment and work environment. When the rolling bearing fails, fault signals which are often submerged in strong noise can be not identified. In recent years, many scholars have carried out a lot of research on fault diagnosis of rotating machinery and put forward many effective methods. Guo and Zhou et al. [18] proposed multi-segment cascaded stochastic resonance to detection rolling bearings. Lei et al. [19] investigated the SR in a bistable or multistable system by calculating its output spectral amplification, then examined the effect of both damping and rescaling factors on output responses and finally presented a promising underdamped SR method with different stables matching for incipient bearing fault diagnosis. Qiao et al. [20] put forward a SVD principle analysis to detect fault diagnosis for bearings based on the correlation coefficient. Lu and He et al.[21] proposed the full-wave signal construction to enhance stochastic resonance for rotating machine fault diagnosis. Wang et al. [22] proposed a new method based on the dual-tree complex wavelet transform for both signal denoising and multiple frequencies detection. From the above-mentioned potential well model, it can be seen that these potential well models have significant advantages over classical mature bistable models. The research shows that the classical bistable stochastic resonance system (CBSR) has the inherent 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, so a novel piecewise nonlinear stochastic resonance system is proposed in order to overcome the output saturation. Moreover, the non-Gaussian Levy noise closer to the industrial environment is introduced into the syetem, and the white noise is a special form of Levy noise in the characteristic index $\alpha = 2$. In this paper, the stochastic resonance characteristics analysis of piecewise nonlinear stochastic resonance (PNBSR) system under the Levy noise of different $\alpha(0 < \alpha < 2)$ and $\beta(-1 < \beta < 1)$ is studied. It also discusses the output law of the system resonance under system parameters *l, c, a, b* and noise intensity *D*, and the PNBSR is applied to the CWRU bearings fault detection.

2. PNBSR system model and performance index

The stochastic resonance phenomenon can be described as: a particle is driven by weak periodic signal and random force in a bistable system, and the periodic motion can be heightened with the assistance of moderate noise. The Langevin equation under overdamped nonlinear system model, which ignores inertia terms, can be described as:

$$\frac{\mathrm{d}x}{\mathrm{d}t} + \frac{\mathrm{d}V(x)}{\mathrm{d}x} = A\sin(2\pi ft) + D\xi(t) \tag{1}$$

Where A is the amplitude of the weak periodic signal, f is the characteristic frequency of the weak periodic signal, $V(x)$ is the system potential function, ξ(t) is the non-Gaussian Levy noise, D is the noise intensity factor.

2.1. Unsaturated characteristics of CBSR

For stochastic resonance of the classical bistable system, its potential function is $V_c(x) = -a_c x^2/2 + b_c x^4/4$. Where a > 0 and b > 0, a and b are constant. According to the theory of adiabatic approximation, it can get $A \ll 1$ and $D \ll 1$. Then suppose that there are no input signals (i.e., $A = 0$ and $D = 0$) in Eq. (1), then x is calculated as:

$$x = \pm\sqrt{\frac{a\exp(2at)}{1 + b\exp(2at)}} \tag{2}$$