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Study on non-linear filter characteristic and engineering application of cascaded bistable stochastic resonance system

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Abstract

This paper addresses the problem of cascaded bistable stochastic resonance system (CBSRS) with large parameters, and reveals its non-linear low-pass filter characteristic. The study results show that weak characteristic frequency component located in low-frequency area can be extracted gradually from strong noise background owing to the energy transfer mechanism from high-frequency area to low-frequency area, as a result, a novel low-pass filter can be achieved ultimately. Compared with conventional digital filter, low-pass filter based-on CBSRS has the advantage of extracting some certain weak low-frequency characteristic components while implementing low-pass filter. Simulated experiments and mechanical fault diagnosis examples are presented in order to demonstrate that CBSRS is a powerful tool for signal processing.
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Keywords: Stochastic resonance; Cascaded bistable system; Noise; Filter

1. Introduction

Stochastic resonance (SR) [1–7] is a physical phenomenon that generally occurs in non-linear dynamical systems, and includes mono-stable systems, multi-stable systems and threshold systems. SR is commonly characterised by the response of a system to noise, the signal-to-noise ratio (SNR).The SNR rises sharply to a maximum value, then gradually decreases for higher noise intensities, which means SR occurs as proper noise is added to a system. Recently, SR has been extensively drawn attention to in wide fields, such as weak signal detection [8–11], circuit experiment [12], speech recognition [13], image visualisation [14], soft-decision decoding [15], sensory neurons [16,17], noisy ICA blind separation [18], et al. The study on SR at present is mainly focused on the adiabatic elimination theory, which will cause the negative results of SR study scope confined to the small parameters object, namely driving force frequency and amplitude that are far less than 1 [19]. Undoubtedly, it will be kept within close bounds owing to the fact of large parameters environment in most engineering applications. Leng et al. [20,21] have solved this technical issue through STSR.

The present study on SR has mostly paid attention to the single stable system; only a few relative literatures with two or more bistable systems [21,22] can be found. The emphasis in this paper is aiming at revealing the

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characteristic of CBSRS in detail, and applying it to the engineering applications for demonstrating its practicality and prospect.

2. The SR mechanism of a single bistable system

The three basic ingredients of producing SR phenomenon is shown in Fig. 1: a single non-linear bistable system $U(x)$, a weak coherent input (such as a periodic signal) $s(t)$ and a source of noise $n(t)$ that is inherent in the system, or that adds to the coherent input. $S_n(t)$, consisted of $s(t)$ and $n(t)$, denotes the input signal of single bistable system. For a convenient description, considering the overdamped motion of a Brownian particle in a bistable potential in the presence of noise and single periodic forcing

$$\mathrm{d}x/\mathrm{d}t = -U(x)' + A\sin(2\pi f_0 t) + n(t), \tag{1}$$

where $U(x)$ denotes the quartic bistable system potential function

$$U(x) = -\tfrac{1}{2}ax^2 + \tfrac{1}{4}bx^4 \tag{2}$$

with $a>0$, $b>0$.Then Eq. (1) can be rewritten as

$$\mathrm{d}x/\mathrm{d}t = ax - bx^3 + A\sin(2\pi f_0 t) + n(t), \tag{3}$$

where A and f_0 are the amplitude and the modulation frequency of periodic input signal, respectively. $n(t)$ denotes noise with $n(t) = \sqrt{2D}g(t)$ and $\langle n(t)n(t+\tau)\rangle = 2D\delta(t)$, where D is noise intensity and $g(t)$ implies a zero-mean , unit variance Gaussian white noise. Eq. (3) is also called non-linear Langevin equation [19].

According to Eq. (3), the fixed equation $f(x) = ax - bx^3$of non-linear bistable system has the two stable fixed points at $x = \pm\sqrt{a/b}$ and one meta-stable fixed point at $x = 0$ when $A = D = 0$. These fixed points are the minima and local maximum of the potential function $U(x)$.The height of the potential barrier between the two minima is $\Delta U = a^2/4b$. The bifurcation of the fixed equation $f(x)$ is shown in Fig. 2.

Under the condition of adiabatic elimination, supposing signal amplitude is rather small ($A \ll 1$), the Brownian particle is in one of the two potential wells indefinitely because the bistable system has not enough driving energy to force the particle to move from one potential well to another one in the absence of additional noise. It is also assumed that the signal period is longer than some characteristic intrawell relaxation time for the system. The presence of periodic forcing will incline potential function and create conditions of transfer from one potential well to another for Brownian particle [1,2]. Here, the potential function $U(x)$ will change with the signal $A\sin(2\pi f_0 t)$ and become

$$U(x,t) = -\tfrac{1}{2}ax^2 + \tfrac{1}{4}bx^4 + Ax\sin(2\pi f_0 t) + n(t)x. \tag{4}$$

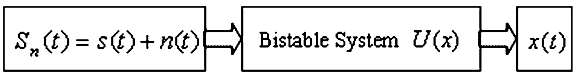

Fig. 1. The framework of single bistable system.

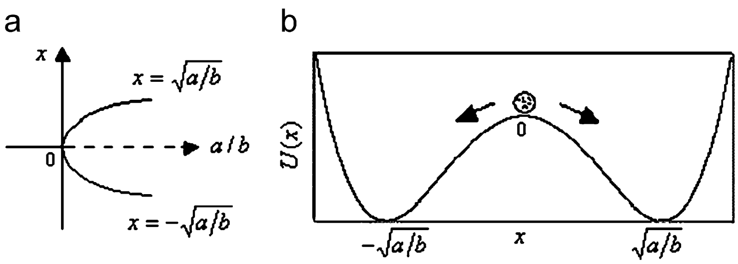

Fig. 2. (a) Denotes the bifurcation of the fixed equation $f(x) = 0$ with a/b > 0 and bifurcation point occurs at $(x, a/b) = (0, 0)$. (b) Presents the quartic bistable potential function $U(x)$ with two stable fixed points $x = \pm\sqrt{a/b}$. According to (a) and (b), the system will achieve the stable points at $x = \pm\sqrt{a/b}$ ultimately when given an initial value $x_0 > 0$.

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