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Effects of the colored noise on the resonance at the subharmonic frequency in bistable systems

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ABSTRACT

We investigate the colored noise induced resonance at the 1/3 subharmonic frequency in the overdamped and the underdamped bistable systems by numerical simulations. We find that the resonance at the 1/3 subharmonic frequency may be stronger than the traditional stochastic resonance that occurring at the excitation frequency in some cases. Moreover, we study the effects of the correlation time of the colored noises on the response in detail. If the colored noise is generated by the Ornstein–Uhlenbeck process, there are two major results discovered. Firstly, the critical noise intensity which induces the strongest resonance will increase with the increase of the correlation time. Secondly, when the noise intensity is large enough, the response amplitude at the considered frequency will also increase with the increase of the correlation time. If the colored noise is generated by the power-limited process, the corresponding results are contrary to those in the system under the colored noise excitation that is generated by the Ornstein-Uhlenbeck process. The results in this paper indicate that the type of the colored noise has important effects on the responses of the system.

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1. Introduction

In the last three decades, there are volumes of literatures focused on the stochastic resonance (SR) in a variety of disciplines [1–4]. For example, SR can be applied in many engineering fields, such as mechanical fault diagnosis [5–7], energy harvesting [8–10], image process [11,12], beam vibration [13], etc. Besides, the phenomenon of SR has also been found in p53 regulatory network and manifests a great biological significance [14]. Many different approaches has been adopted in a wealth of papers to quantitatively describe SR such as the multifractal characterization [15], the signal-to-noise ratio (SNR) [16], the mean output-amplitude gain (OAG) [17], etc. In [18] P. Jung provides a rigorous and comprehensive background for SR in bistable system.

However, most of the former works are limited to the linear response theory. There are a few papers which consider the SR in the nonlinear response theory framework. In [19], Khovanov et al. studied the nonlinear response of a noisy bistable system to biperiodic signals. In [20,21] Yang et al. studied the noise induced resonance at the superharmonic and

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subharmonic frequencies and found that the response amplitude at the nonlinear frequency may be stronger than that at the excitation frequency. In [22–28], the effects of various kinds of colored noises on SR are studied. In [29], Ma studied the dependence of the coherence resonance (CR) on the noise correlation by considering two types of colored noise. In their study, one kind of colored noise is the standard Gaussian colored noise generated by the Ornstein–Uhlenbeck (OU) process and the other kind of colored noise is generated by the so-called power-limited (PL) process. They found that the SNR is a bell-shaped function of noise correlation which indicates the enhancement of CR by the noise correlation time if the random excitation is in the OU type colored noise with noise intensity larger than a threshold. Moreover, the SNR may be shown in double resonances form for some values of the noise correlation time when the random excitation is in the PL type colored noise, which demonstrating a new kind of multi-resonances phenomenon. Furthermore, we know that colored noises are widely existed in different engineering fields. As a motivation, we investigate the colored noise induced resonance at the subharmonic frequency in this paper. The resonance at the excitation frequency, i.e., the traditional SR is also considered as a comparison.

The organization of this paper is as follows. In Section 2, we will investigate the phenomenon of SR at the excitation frequency and the colored noise induced resonance at the 1/3 subharmonic frequency induced by the OU colored noise and in the overdamped bistable system and underdamped system respectively. In Section 3, we will study the PL colored noise induced SR and 1/3 harmonic resonance. In Section 4, we will give the major conclusions of this paper.

2. The OU colored noise induced resonance

The colored noise is a random process that has a variable power in the band of a given bandwidth. Compared with the white noise, the colored noise exists much more widely in the engineering background. Therefore, researching on the colored noise induced resonance is of much more significant. In this section, we will focus on the OU colored noise induced resonance in the overdamped system and the underdamped system respectively.

2.1. The overdamped bistable system

Here, we consider a typical overdamped bistable system that is driven by a harmonic signal and the OU colored noise. It is described by the equation

$$\frac{dx(t)}{dt} = ax(t) - bx^3(t) + f\cos(\omega t) + \varepsilon_{OU}(t), \tag{1}$$

where a and b are positive parameters. The random process $\varepsilon_{OU}(t)$ is a typical standard Gaussian colored noise generated by the following OU process

$$\frac{d}{dt}\varepsilon_{OU}(t) = -\frac{1}{\tau_c}\varepsilon_{OU}(t) + \frac{\sqrt{\sigma}}{\tau_c}\xi(t), \tag{2}$$

where τ_c is the correlation time of the colored noise, σ is the noise strength and $\xi(t)$ is a Gaussian white noise with zero mean and unit variance [30,31]. The random process $\varepsilon_{OU}(t)$ is the OU colored noise.

According to the nonlinear dynamical theory, besides the excitation frequency, there are subharmonic, superharmonic and combined frequencies existing in the response of the nonlinear system. There are many literatures describing this fact [32–34]. Especially in [34], the authors clearly stated that the subharmonic frequency $\omega/3$ existing in the response when a Duffing oscillator with cubic term is excited by the harmonic signal with frequency ω. In this study, we focus on the response at the excitation frequency ω and the subharmonic frequency $\omega/3$ simultaneously.

In order to obtain $x(t)$, we need to solve Eqs. (1) and (2). However it is not easy to get the analytical solution in the nonlinear response regime. Therefore, we use numerical simulations to investigate the resonance phenomenon. The asymptotic solution of Eq. (1) can be written in the form of series [35],

$$\langle x(t)\rangle_{as} = \sum_i X_m(\omega_i)\cos[\omega_i - \varphi_m(\omega_i)] \tag{3}$$

where $\omega_i = k\omega$. Herein, k can be an integer or a fractional rational number. $X_m(\omega_i)$ and $\varphi_m(\omega_i)$ are the mean response amplitude and the phase lag respectively at the frequency ω_i. They are obtained by averaging a set of inhomogeneous processes $x(t)$, which have arbitrary initial conditions $x_0 = x(t_0)$ and are achieved by different random paths. In this paper, we choose 200 different stochastic processes to calculate the mean response amplitude. For every single path, the response amplitude and the phase lag at the frequency ω_i are computed by

$$X(\omega_i) = \sqrt{B_s^2 + B_c^2} \tag{4}$$

and

$$\varphi(\omega_i) = \tan^{-1}(B_s/B_c) \tag{5}$$

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