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Stochastic resonance in periodic potentials driven by colored noise☆

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HIGHLIGHTS

- Stochastic resonance exists in the underdamped periodic potential system.
- The colored noise delays the transitions between these two dynamical states.
- Noise correlation time can improve the stochastic resonance.

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ABSTRACT

We studied the motion of an underdamped Brownian particle in a periodic potential subject to a harmonic excitation and a colored noise. The average input energy per period and the phase lag are calculated to quantify the phenomenon of stochastic resonance (SR). The numerical results show that most of the out-of-phase trajectories make a transition to the in-phase state as the temperature increases. And the colored noise delays the transitions between these two dynamical states. The each curve of the average input energy per period and the phase lag versus the temperature exist a mono peak and SR appears in this system. Moreover, the optimal temperature where the SR occurs becomes larger and the region of SR grows wider as the correlation time of colored noise increases.
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1. Introduction

Stochastic resonance proposed by Benzi et al. [1] and Nicolis and Nicolis [2] is a phenomenon where the response of a dynamical system subject to an input is enhanced by the addition of an optimal amount of noise. Since SR was proposed, it has been extensively investigated both theoretically and experimentally in many fields [3–10]. In order to detect this phenomenon, there are several observables to quantify SR. For example, Benzi et al. [1] used the intensity of a peak in the power spectrum to quantify SR. Zhou et al. [11] employed the residence-time distribution to explain SR as a resonance synchronization phenomenon. Stochastic energetics were first proposed by Sekimoto [12], which enable us to analyze the energetics of both thermodynamical processes [13–15] and non-equilibrium processes [16,17] described by the Langevin equations and the Fokker–Planck equations as their equivalent counterparts. Stochastic energetics mainly explore some concerning energies of the system like the work done by some external agent. When the resonant motion is enhanced, the work is expected to become larger. Toshiya Iwai [18] numerically analyzed SR by the method of the stochastic energetic and the results were quite satisfactory.

Periodic potential is quite common in some physical and biological systems like Feynman's ratchet and Josephson junction. However, most of these studies considered the bistable systems; only a few publications dealt with SR in periodic

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potential systems [19–21]. Among them, Kim and Sung [19] found the resonance behavior in the frequency-dependent mobility in a periodic potential by using a linear-response theory. Saikia and co-workers [20] explored the possibility of the occurrence of SR in a periodic sinusoidal potential with a Gaussian white noise by using input energy and hysteresis loop area as quantifiers. Their numerical work shows that the periodic potential system indeed exhibits SR in the high-frequency regime. Reenbohn and co-workers [21] employed the stochastic energetics to study the motion of an underdamped Brownian particle in a bistable periodic potential and a washboard potential subjected to a sinusoidal external field. They found that SR did occur.

Generally, Gaussian white noises without any time correlation are used to describe the environment fluctuations for simplicity. However, in most situations the correlation times are long enough not to be ignored and colored noises are necessarily considered. Previous investigations show that the colored noise plays an important role for SR [22–26]. Kiss et al. [22] reported that the colored noise could be used as additive noise for SR in a physical system. Zhang et al. [23] investigated a single-mode laser cubic model driven by multiplicative colored noise and discussed the effects of cross-correlation between real and imaginary parts of quantum noise on first-passage time. Ghosh [24] studied the diffusion rate for an overdamped Brownian particle in a cosine potential with colored noise and found that the rate could be enhanced by the finite correlation time. Jin et al. [25,26] studied the effects of two different kinds of colored noises on the mean first-passage time and SR. To our knowledge, the SR of an underdamped Brownian particle in a periodic potential subject to a harmonic excitation and a colored noise has not been reported yet. In this article, we show the effects of colored noise on the motion of an underdamped Brownian particle in a periodic potential driven by Gaussian colored noise. In Section 2, we numerically calculate the input energy and the phase lag, which can be used to explore the possibility of the occurrence of SR. In Section 3, we present the summary of our results and discussions.

2. The model and some numerical results

2.1. The periodic potential model

Consider an underdamped Brownian particle in a periodic potential subject to a harmonic signal and a colored noise, the output of which is described by the following Langevin equation:

$$\frac{d^2x(t)}{dt^2} = -\gamma_0 \frac{dx(t)}{dt} + \cos x(t) + \eta(t) + F(t), \tag{1}$$

where γ_0 is the friction coefficient, and $F(t) = F_0 \cos(\omega t)$ is the harmonic signal. The noise term $\eta(t)$ represents the inherent random fluctuation in the system and is colored noise, which satisfies the following statistical properties:

$$\langle \eta(t) \rangle = 0, \qquad \left\langle \eta(t)\eta(t') \right\rangle = \frac{\sqrt{\gamma_0 T}}{\tau} \exp\left(-\frac{\left|t - t'\right|}{\tau} \right); \tag{2}$$

here T is the environment temperature and is in the units of the Boltzmann constant k_B. T represents the noise intensity. In the following, the values of system parameters are fixed as $\gamma_0 = 0.12$, $F_0 = 0.2$, $\omega = \pi/4$, $\tau = 0.6$, and some numerical results can be given by using the stochastic energetics.

Using the stochastic energetics formulation proposed by Sekimoto [12], the input energy, or work done by the field on the system W in a period $\tau_\omega = \frac{2\pi}{\omega}$, is calculated as

$$W(t_0, t_0 + \tau_\omega) = \int_{t_0}^{t_0+\tau_\omega} \frac{\partial U(x(t), t)}{\partial t} dt, \tag{3}$$

where the potential $U(x(t), t) = -\sin x - F_0 x \cos(\omega t)$. The average input energy per period over an entire trajectory $\overline{W}$ is

$$\overline{W} = \frac{1}{N} \sum_{n=0}^{N} W\left(n\tau, (n+1)\tau\right). \tag{4}$$

In the following numerical simulation, the number of periods is chosen as $N = 2500$ and the initial conditions are taken as $v(0) = 0$ and $x(0)$ at $N_1 = 100$ equispaced intervals, $x_i = -\pi/2 + i * 2\pi/100$, $i = 1, 2, \ldots, 100$. Numerical calculations of the model are performed for various values of T by the Heun method. The average input energy per period $\left\langle \overline{W} \right\rangle$ is calculated by averaging $\overline{W}$ over all the trajectories.

2.2. The input energy

Fig. 1 shows the plot of input energy $\overline{W}$ averaged over a trajectory with initial position $x(0)$ at different temperatures T. From Fig. 1(a), it is seen that $\overline{W}$ is confined to two narrow bands around 0.062 and 1.217 corresponding to $x(0)$ values at very low temperature. That is, the trajectories exist for two dynamical states and are quite stable at the low temperature $T = 0.001$. In Fig. 1(b), the trajectories are given for the temperature $T = 0.021$. It is observed that there are only a few transitions from the higher value (out-of-phase state) to the lower value (in-phase state). And in Fig. 1(c) and (d), the

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