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Realizing reliable logical stochastic resonance under colored noise by adding periodic force

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HIGHLIGHTS

- The LSR system driven by colored noise and periodic force is proposed.
- The LSR system under colored noise can output 100% correct logic response by adding periodic force.
- The LSR system can operate reliably at higher noise levels under colored noise and periodic force.
- The influence of different parameters on the LSR system is discussed.

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ABSTRACT

Some noisy nonlinear systems could be exploited to operate as reliable logic gate in an optimal window of noise intensity, which is termed as logical stochastic resonance (LSR). Recent studies show that under additive colored noise,the reliable logic operation cannot be obtained when correlation time is in intermediate or large range. In the paper, the LSR effect in bistable systems driven by colored noise is investigated by adding periodic force. In contrast with the case without periodic force, we show that the optimal band of correlation time that can output reliable logic response is extend to a larger range. Two kinds of LSR effect are presented. It has been found that the reliable logic operation can be obtained in an optimal window of noise intensity, as well as correlation time. We show that one can obtain the desired logic response by adjusting the correlation time and periodic force. Compared with the case under white case and periodic force, the system can operates reliably at higher noise levels, due to the constructive interplay of colored noise and periodic force. These results show that the system under colored noise can work reliably as logic gate by adding periodic force.

1. Introduction

In recent years, it has become increasingly clear that noise can play a constructive role in helping nonlinear dynamical systems to produce reliable logical response [1]. Murali et al. showed that a bistable system with an input of different logic combinations, in an optimal window of moderate noise, can operate correct logical operations, which is termed as logical stochastic resonance (LSR). The studies of the LSR have received much attention. The phenomena of LSR has been demonstrated in many scenarios such as electrical systems, nanomechanical systems, optical systems, chemical systems and biological system [2–9].

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In most model systems, the stochastic forces are usually taken into account as white noise, which has zero correlation time. However, for many cases the assumption is insufficient and real fluctuations are always correlated [10,11]. Recently, there is a growing interest in studying the LSR in the dynamical system driven by colored noise. A. Dari et al. investigated the LSR effect in gene regulatory networks with internal and external noises. When internal noise and external noise are correlated, one can obtain reliable logic operation [12]. Zhang et al. investigated the LSR effect in triple-well potential systems under additive colored noise and multiplicative colored noise [13]. It is verified that the reliable logic operation cannot been obtained under additive colored noise, but the reliability of the system can be enhanced by adjusting the multiplicative colored noise. The LSR effect is also investigated in bistable system under Gaussian colored noise and dichotomous colored noise [14,15]. It is shown that reliable logic operation cannot be obtained when correlation time is in intermediate or large range. Although the reliability of the system versus correlation time displays an non-monotonic behavior, the reliable logic operation cannot be realized by increasing correlation time. It deserves deep research to find another way to enhance the LSR effect under colored noise.

Recently, Gupta et al. investigated the noise-free LSR in bistable systems driven by periodic force instead of noise [16]. It has been found that such a system, despite having no stochastic influence, still yield reliable logical response in an appropriate window of frequency and amplitude of periodic force. Further, Kohar et al. verified that the LSR effect could be enhanced by utilizing the constructive interplay of the zero-correlated noise and periodic force [17]. Due to the existence of periodic force, the reliable logical operation can be obtained when noise level is below the minimum threshold required for the traditional LSR. This opens up the possibility of realizing the reliable logic operation under colored noise by adding periodic force.

In this paper, we simulate the bistable system under colored noise and periodic force, with various combinations of inputs. Our focus will be the effect of periodic force and colored noise on the LSR in bistable systems. Due to the existence of periodic force, it deserves deep research whether noise color can enhance the LSR effect under additive noise in the presence of periodic force. Here, we will show that under certain condition noise color enhancing the LSR effect is indeed possible by adding periodic force. The reliable logic operation even can been realized by adjusting correlation time and periodic force. The paper is organized as follows: Section 2 is to introduce the model and the measurement of the LSR. In Section 3, the effect of colored noise on the LSR is discussed. In Section 4, the effect of periodic force on the LSR is discussed. Finally, the conclusions are made.

2. Model and measurement of LSR

The system can be formally represented by the Langevin equation

$$\begin{aligned} \dot{x} &= -U'(x) + I + b + \eta(t) + Af(\omega t) \\ \dot{\eta} &= -\frac{\eta}{\tau_c} + \frac{\sqrt{D}}{\tau_c}\xi(t). \end{aligned} \tag{1}$$

where *U(x)* is a symmetric two-well potential. I is the sum of the two square pulses encoding two logic inputs and b is a bias parameter to control asymmetry of the two-well potential. The function form of the periodic force is f, and A is the amplitude and ω is the frequency of the force. The noise $\eta(t)$ is the Gaussian colored noise, which is an Ornstein–Uhlenbeck stochastic process driven by Gaussian white noise $\xi(\mathrm{t})$ with zero mean and correlation

$$\langle \eta(t)\eta(t') \rangle = \frac{D}{\tau_c} \exp\left(-\frac{|t-t'|}{\tau_c}\right). \tag{2}$$

where D is the noise intensity and τ_c is the correlation time of noise [10,13].

The logic input signals I is the sum of two aperiodic square waves, $I = I_1 + I_2$. With no loss of generality, the value of the two inputs I_1 and I_2 is taken as *0.2* when the logic input is *1*, and -0.2 when the logic input is *0*. The unit of input I_1 and I_2 is dimensionless. The input $I = I_1 + I_2$ is encoded as a three-level square wave: -0.4 corresponding to input set (*0*, *0*), *0* corresponding to input set (*0*, *1*)/(*1*, *0*), *0.4* corresponding to input set (*1*, *1*). We now explicitly demonstrate the LSR phenomenon under sinusoidal signal and colored noise, in a cubic nonlinear system,

$$\begin{aligned} \dot{x} &= x - x^3 + I_1 + I_2 + b + \eta(t) + A\sin(\omega t) \\ \dot{\eta} &= -\frac{\eta}{\tau_c} + \frac{\sqrt{D}}{\tau_c}\xi(t). \end{aligned} \tag{3}$$

For the cubic-like nonlinear system, the output for the threshold value is 0. The output $x > 0$ represents logic *1*, and $x < 0$ represents logic *0*. One is able to obtain different logic gates by adjusting bias parameter b.

The success probability *P(logic)* of obtaining desired logic output is calculated as follows: each input set (I_1, I_2) drives the system over some reasonably long time interval, and then switches to another set; different input streams are fed to the system and its output is checked according to truth table of basic logic relationships, with each run being a permutation of four such input sets, like for example, may be, Run 1: *(0,0)* followed by *(0,1)* followed by *(1,0)*, followed by *(1,1)*; Run 2: *(1,0)* followed by *(0,1)* followed by *(1,1)*, followed by *(0,0)*, etc. [1]. Only when the outputs of all four input sets in the run match