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The theory analysis and design for large parameter weak signal detector based on bistable stochastic resonance

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Abstract **- We deduce the Kramers rate using the Fokker-Planck (FP) equation with the adiabatic approximation condition (the amplitude and frequency of signal detected are small <<1) and prove that stochastic resonance (SR) could enhance the signal-to-noise ratio (SNR) of the output signal under the adiabatic approximation condition in bistable system. We employ the signal modulation technique to transform the large frequency components into a small parameter signal to meet the adiabatic approximation requirement because the large frequency weak periodic signal and multi-frequency harmonic signal, which are more common in engineering practice, are difficult to detect using SR theory. Furthermore, a mixing simulation model is designed to generate SR. Initially, the signal frequency is selected using the model based on the difference of the frequencies of the test signal and a scanning signal. Then, the output from the model is input into a bistable system for signal detection. The simulation result shows that the modulation method can generate SR in a bistable system and detect large parameter weak signals from strong noise background.**

Index Terms **- Stochastic resonance, bistable system, probability equation, signal modulation, simulation experience**

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1. INTRODUCTION

The ability to detect weak signals from strong background noise effectively has always been a hot topic. Therefore, many studies using different approaches have been conducted. One such approach involves using the concept of stochastic resonance (SR) to detect weak signals[1-6].

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The concept of SR was first put forward by Benzi et al. in the early 1980s when the researchers were studying the glacial period in paleoclimatology. The cooperative phenomenon in which a small periodic signal and noise are combined in a nonlinear fashion was described[4-5]. In a linear system, the signal-to-noise ratio (SNR) at the output will decrease with increasing input noise. However, in a nonlinear system, when the input signal and noise are in a cooperative state, the energy stored in the noise can be transferred to the signal, resulting in a situation in which

the SNR will increase remarkably with the input noise increasing[4,9]. There is a rapidly increasing interest in signal detection using SR theory, and the topic has been extensively studied both theoretically and experimentally in many scientific fields[6,17]. From a theoretical perspective, theories such as the adiabatic approximation theory[6,8], linear response theory[9,10], and perturbation theory[11] have been employed to study the SR phenomenon. The effects of both internal and external noise have been investigated[12], and moreover, the design and performance analysis of a signal detector based on stochastic resonance[13]and the effects of time delay and noise correlation in an asymmetric bistable system have also been investigated[14,15]. From an experimental perspective, research has been carried out and advanced with respect to bistable Schmit triggers[16], optical systems[17], and simulations of weak signal detection[18].

The adiabatic approximation theory based on white noise can only describe the ideal system. As a result, colored noise, which is more similar to the noise observed in real systems, has recently been investigated extensively[19-21]. Research on SR has covered not only the scenario in which SR is riven by two different types of colored noise but also that in which SR with time-delayed feedback is driven by non-Gaussian noise in a bistable system[20-24].

Although SR theory enables the detection of weak signals from strong background noise, many studies have shown that the application of the theory is limited to systems under small parameter conditions[5-11]i.e., systems in which the signal amplitude, frequency, and noise intensity are much smaller than 1. However, in engineering practice, the large frequency signals, periodic impulse signals, and high harmonics signals are much more common but more difficult to detect. The application of SR theory to the detection of large frequency signals is currently becoming one of the most interesting topics in weak signal detection. In this paper, we study SR with respect to weak signal detection against background noise. Specifically, (1) we more concisely deduce the Kramers escape rate using the FP equation; (2) we then obtain the solution of the probability equation of a bistable system in the time and frequency domains and SNR by using the deduced Kramers escape rate. we prove that SR could enhance the SNR of the output signal under the conditions of only small parameters (the adiabatic approximation condition); (3) we modulate the large parameter weak periodic signal that satisfies the adiabatic approximation condition; (4) we use simulations to validate the feasibility of our method.

2. The theory of SR in a bistable system

2.1 The bistable system model

A naive bistable system can be described by the Langevin equation as follows

$$\frac{dx}{dt} = \mu x(t) - x^3(t) + A_0 \sin(\Omega t + \varphi) + \eta(t) \quad (1)$$

where μ is a parameter of the system, μ>0. A_0 and Ω are the signal amplitude and frequency, respectively, and $\eta(t)$ denotes zero-mean, Gaussian white noise with the following autocorrelation function

$$\begin{cases} <\eta(t)>=0 \\ <\eta(t)\eta(t+\tau)>=2D\delta(\tau) \end{cases} \quad (2)$$

Here, τ is the time interval, and D is the noise intensity. The nonlinear bistable system is

$$\frac{dx}{dt} = \mu x(t) - x^3(t) \quad (3)$$

The potential of a simple symmetric bistable system can be expressed as follows

$$U(x) = -\frac{\mu}{2}x^2 + \frac{1}{4}x^4 \quad (4)$$

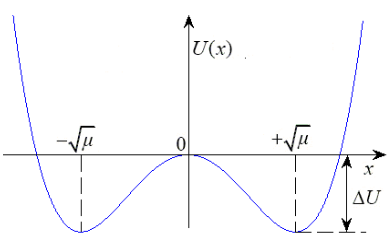

Fig. 1. The quartic bistable potential

Eq. (3) and (4) indicate that there is an unstable state located at $x = 0$ and two stable states located at $x_s = \pm\sqrt{\mu}$. $\Delta U = \mu^2/4$ is the height of the potential barrier under static conditions, as shown in Fig. 1.

2.2 The solution of the FP equation and Kramers escape rate

The FP equation of a bistable system [6] can be expressed as follows

$$\frac{\partial \rho(x,t)}{\partial t} = \frac{\partial}{\partial x}[U'(x)\rho(x,t)] + D\frac{\partial^2}{\partial x^2}\rho(x,t) \quad (5)$$

where $\rho(x,t)$ is the probability distribution function, $U'(x)$ is the first derivative of the potential function with x, and D is the noise intensity. Suppose that the initial probability distribution meets the adiabatic approximation condition[6], that is $A_0 << 1$, $D << 1, \Omega << 1$, or when t = 0, the probability distribution is concentrated in one potential well

$$\rho(x,0) = \delta(x - x_s) \quad (6)$$

Additionally, suppose that the probability current does not vary with time, i.e., $\frac{\partial \rho(x,t)}{\partial t} = 0$. Thus, we can obtain the following steady-state solution

$$U'(x)\rho(x,t) + D\frac{\partial}{\partial x}\rho(x,t) = J \quad (7)$$

Here, *J* is the intensity of the steady-state current. For the homogeneous solution (*J* = 0), which is equal to the steady-state solution, Eq. (7) can be written as the t-independent form of the ordinary differential equation, as expressed below

$$\rho(x) = Ne^{-\frac{U(x)}{D}} \quad (8)$$

Because

$\delta(x - x_s) = Ne^{-\frac{U(x)}{D}}$ and $\int \delta(x - x_s)dx = N\int e^{-\frac{U(x)}{D}}dx$, we can obtain

$$N = 1\Big/\int e^{-\frac{U(x)}{D}}dx \quad (9)$$

Then, by setting $\rho(x) = V(x)e^{-\frac{U(x)}{D}}$ in Eq. (7), we can obtain the non-homogeneous solution $V(x) = \frac{J}{D}\int e^{\frac{U(x)}{D}}dx$

Therefore,

$$\rho(x) = \left[\frac{J}{D}\int e^{\frac{U(x)}{D}}dx\right]e^{-\frac{U(x)}{D}} \quad (10)$$

By taking time t into consideration and letting $\rho(x,t) = N(t)e^{-\frac{U(x)}{D}}$, we obtain

$$J = DN(t)\Big/\int_{x_s}^{A} e^{\frac{U(x)}{D}}dx \quad (11)$$

Given the range ($-\infty, A$), the total probability $P(t)$ at time t is

$$P(t) = \int_{-\infty}^{A} \rho(x,t)dx = N(t)\int_{-\infty}^{A} e^{-\frac{U(x)}{D}}dx \quad (12)$$

Because J is the intensity of the steady-state current, i.e. , the rate of total probability $P(t)$ at the steady state, we can obtain

$$\frac{dP(t)}{dt} = J = \frac{DN(t)}{\int_{x_s}^{A} e^{\frac{U(x)}{D}} dx} = \frac{DP(t)}{\int_{-\infty}^{A} e^{-\frac{U(x)}{D}} dx \int_{-\infty}^{A} e^{\frac{U(x)}{D}} dx} \quad (13)$$

Therefore,

$$P(t) = P(0)e^{-Rt} = e^{-Rt} \quad (14)$$

Where

$$R^{-1} = \frac{1}{D}\int_{-\infty}^{A} e^{-U(x)/D} dx \int_{-\infty}^{A} e^{U(x)/D} dx \quad (15)$$

Here, R is the Kramers escape rate of the probability flowing into the unstable region.

2.3 The equation for a bistable system and its solution

According to Eq.(14), we obtain

$$p(t) = dP(t)/dt = -Re^{-Rt} = -RP(t)$$

Where $p(t)$ is the probability current, we define that $p\_(t)$ is the probability current of the left potential well, and $p_+(t)$ is that of the right potential well, $P(t)$ is the total probability of two potential wells. Considering that the flow of the two potential well is opposite, We can establish the probability equation for the bistable system shown in Fig. 1 as follows

$$\begin{cases} p_-(t) = \dfrac{dP_-(t)}{dt} = -R_-P_-(t) + R_+P_+(t) \\ p_+(t) = \dfrac{dP_+(t)}{dt} = +R_-P_-(t) - R_+P_+(t) \end{cases} \quad (16)$$

where R_- is the escape rate from the left potential well to the right potential well, and R_+ is opposite to R_-.

The solution of Eq. (16) can be obtained as follows

$$\begin{cases} P_-(t) = \dfrac{R_+}{R_- + R_+}\left(1 + \dfrac{R_-}{R_+}\mathrm{e}^{-(R_- + R_+)t}\right) \\ P_+(t) = \dfrac{R_-}{R_- + R_+}\left(1 - \mathrm{e}^{-(R_- + R_+)t}\right) \end{cases} \quad (17)$$

When reaching the steady state, $R_- = R_+ = R$, the above equation can be written as follows

$$\begin{cases} P_-(t) = \dfrac{1}{2}(1 + e^{-2Rt}) \\ P_+(t) = \dfrac{1}{2}(1 - e^{-2Rt}) \end{cases} \quad (18)$$

Thus, the probability current in the time domain can be written as follows

$$\begin{cases} p_-(t) = \dfrac{dP_-(t)}{dt} = -Re^{-2Rt} \\ p_+(t) = \dfrac{dP_+(t)}{dt} = +Re^{-2Rt} \end{cases} \quad (19)$$

In each potential well of a bistable system, the size of the modulus at any moment are $|p_-(\omega)|$ and $|p_+(\omega)|$, thus we can obtain the probability current in the frequency domain by taking the Fourier transform as follows

$$\begin{cases} |p(\omega)| = |p_-(\omega)| + |p_+(\omega)| = \dfrac{2R}{\sqrt{(2R)^2 + \omega^2}} \\ \varphi(\omega) = \arctan\left(\dfrac{\omega}{2R}\right) \end{cases} \quad (20)$$

where $|p(\omega)|$ and $\varphi(\omega)$ represent the modulus and phase angle of the probability current, respectively.

2.4 The response of periodic driving and SNR[6]

Assuming that the noise background contains periodic signal $s(t) = A_0 \cos\Omega t$, when A_0 is very small, the response of the bistable system to the periodic input signal can be expressed as follows

$$\langle x(t) \rangle = \bar{x}(D)\cos(\Omega t - \bar{\varphi}) \quad (21)$$

where $\langle x(t) \rangle$ represents the mean value of the response, $\bar{x}(D)$ is the amplitude, and $\bar{\varphi}$ is the phase lag. From Eq. (20), when the driving frequency equals the signal frequency detected, or $\omega = \Omega$ (the analog resonance phenomena), $\bar{x}(D)$ can be written approximately as

$$\begin{cases} \bar{x}(D) = \dfrac{A_0\langle x^2 \rangle_0}{D}\dfrac{2R}{\sqrt{(2R)^2 + \Omega^2}} \\ \bar{\varphi}(D) = \arctan\left(\dfrac{\Omega}{2R}\right) \end{cases} \quad (22)$$

where $\langle x^2 \rangle_0$ is the D-dependent variance of the stationary unperturbed system ($A_0 = 0$). It is clear that the amplitude response is dependent on the change of the noise. The power spectrum can be obtained through the Fourier transform of the autocorrelation function as follows

$$S(\omega) = \int_{-\infty}^{+\infty} \langle x(t)x(t+\tau) \rangle \mathrm{e}^{-\mathrm{j}\omega\tau} d\tau \quad (23)$$

where $S(\omega)$ is the power spectrum of the response. Before the periodic signal is input to the system, the output power spectrum can be expressed as follows

$$S_N^0(\omega) = 4R\langle x^2 \rangle_0 / (4R^2 + \omega^2) \quad (24)$$

After inputting the periodic signal to the system, which meets the small parameter condition $(A_0 << 1, \Omega << 1)$, the output power spectrum can be expressed as follows

$$S(\omega) = (\pi/2)\bar{x}^2(D)\left[\delta(\omega-\Omega)+\delta(\omega+\Omega)\right]+S_N(\omega) \qquad (25)$$

Here, $S_N(\omega) = S_N^0(\omega) + 0(A_0^2)$; therefore, the SNR is

$$SNR = 2\left[\lim_{\omega\to\Omega}\int_0^\infty S(\omega)d\omega\right]\Big/S_N(\Omega) = \pi(\frac{A_0 x_m}{D})^2 R \qquad (26)$$

For the bistable system, we can obtain $x_m = \sqrt{\mu}$ and $R = \frac{\mu}{\sqrt{2\pi}}e^{-\frac{\mu^2}{4D}}$. By substituting this expression into Eq. (26), we obtain

$$SNR = \frac{\sqrt{2}\mu^2 A_0^2 e^{-\frac{\mu^2}{4D}}}{2D^2} \qquad (27)$$

According to Eq. (25) and Eq. (27), when the small parameter signal in a system are in a cooperative state (i.e., satisfy the requirement of the adiabatic approximation), the system is in a state of synergy and produces SR. In engineering practice, a large frequency periodic signal and multi-frequency harmonic signal are more common. However, these signals do not meet the adiabatic approximation requirement and therefore are difficult to detect. Thus, we use a signal modulation technique to transform the large frequency components into small parameter signals to enable the transfer of energy from noise to useful signals.

3. MODULATED SR AND ITS REALIZATION

3.1 The theory of modulated SR

The modulation process is shown in Fig. 2. The signal and noise are input to one end of the mixer model. In addition, the scanning signal is input to the mixer model. The output signal of the mixer model is input to the nonlinear bistable system, in which the signal detection is realized using SR.

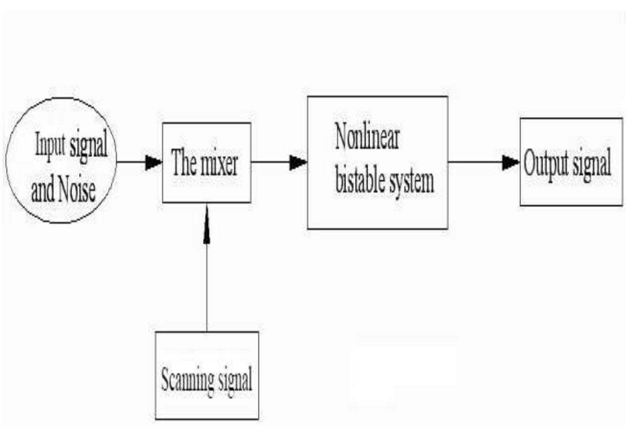

Fig. 2. A diagram of modulation SR

The signal containing noise can be described as follows

$$x_n(t) = a_0 + \sum_{n=1}^{\infty}(a_n\cos 2\pi n f_0 t + b_n \sin 2\pi n f_0 t) + n(t)$$
$$= a_0 + \sum_{n=1}^{\infty} A_n \cos(2\pi n f_0 t + \varphi_n) + n(t) \qquad (28)$$

Where $A_n = \sqrt{a_n^2 + b_n^2}$, $\varphi_n = -arctg\frac{b_n}{a_n}$, and $n(t)$ is noise.

Let the scanning signal be $y(t) = \cos 2\pi f_c t$. The output signal of the mixer model can be expressed as follows

$$x_m(t) = x_n(t)y(t)$$
$$= [a_0 + \sum_{n=1}^{\infty} A_n\cos(2\pi n f_0 t + \varphi_n) + n(t)]\cos 2\pi f_c t$$
$$= a_0\cos 2\pi f_c t + \frac{1}{2}\sum_{n=1}^{\infty} A_n\cos[2\pi(nf_0 - f_c)t + \varphi_n]$$
$$+\frac{1}{2}\sum_{n=1}^{\infty} A_n\cos[2\pi(nf_0 + f_c)t + \varphi_n] + n(t)\cos 2\pi f_c t \qquad (29)$$

In Eq. (29), when we adjust the scanning frequency f_c towards nf_0 gradually, $\Delta f = nf_0 - f_c << 1$, the system will satisfy the condition of the adiabatic approximation theory, which means that it can realize SR.

3.2 The model design of modulated SR

Based on the technique described above, we design the mixer model of a bistable system in which we have an adjustable parameter μ to control the system's behavior. The mixer model is used for multiplication of the measurable signal and the scanning signal. Therefore, the frequency of the output signal contains both the sum and the difference of the frequencies of the measurable signal and the scanning signal.

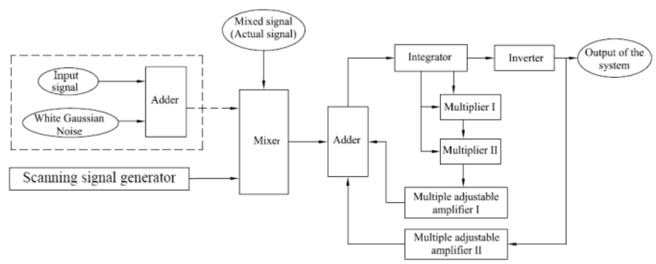

Fig. 3. Modulating simulation model of SR

The flow chart of the SR modulating simulation model is shown in Fig.3. The components in the dotted-line block are used to generate a noise-added signal to mimic the signal in practice. The test signal and the scanning signal are input into the mixer model, whose output signal is then input into a nonlinear bistable system, which consists of an integrator, an adder, an inverter, two multipliers, and two amplifiers. The amplification coefficients of the two amplifiers I and II are 1 and μ, respectively, where μ is adjustable. If we assume the output of the inverter is $-x$, then the outputs of multiplier I and II are k_1x^2 and $k_1k_2x^3$, respectively. Therefore, the outputs of amplifier I and II are $k_1k_2x^3$ and μx, respectively. This entire system can be described by the following model

$$x = \int [\mu x - k_1k_2x^3 + x_n(\mathrm{t})] \cdot y(t)dt \tag{30}$$

In this paper, we set μ= 0.8 and $A_0 = 0.6$ and $k_1 = k_2 = 1$

In practice, we should first adjust the frequency of the scanning signal until it is close to that of the test signal ($\Delta f = nf_0 - f_c << 1/2\pi$). Therefore, the output signal frequency spectrum can be obtained using SR theory. By successively stepping the scanning signal, we can obtain the peak of the frequency spectrum of the output signal, from which we can determine the frequency of the test signal.

3.3 The simulation of the system

We first carry out a simulation of the designed simulation model (as shown in Fig. 3) to make sure SR can be produced.

3.3.1 The simulation of a single-frequency signal without modulation

We input a single-frequency signal $s(t) = A_0 \cos 2\pi ft + n(t)$, where A_0 is the amplitude of the test signal. We let f = 0.01 Hz and f = 10 Hz be the test signal frequencies. $n(t)$ is the noise. The output waveform of the bistable system is shown in Fig. 4 and Fig. 5.

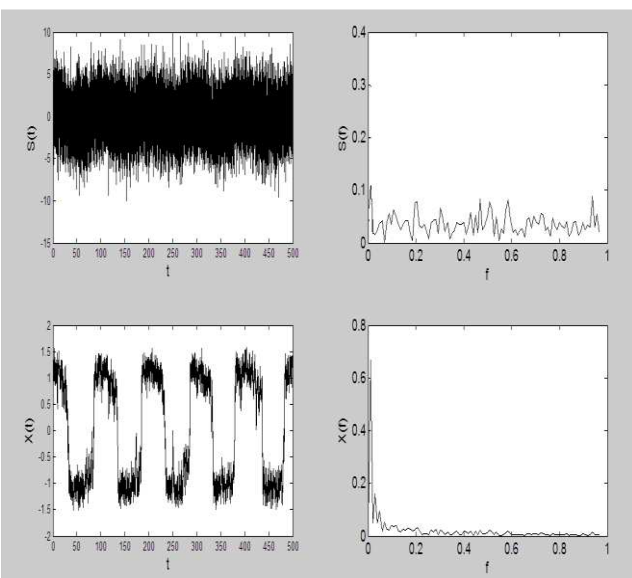

Fig. 4. In this case, f = 0.01 Hz, μ = 0.8, $A_0 = 0.6$, and D = 2.The waveforms of the input and output of the bistable system are shown. (*S(t)* is the input in the time domain, *X(t)* is output in the time domain, *S(f)* is the input in the frequency domain, and *X(f)* is the output in the frequency domain.)

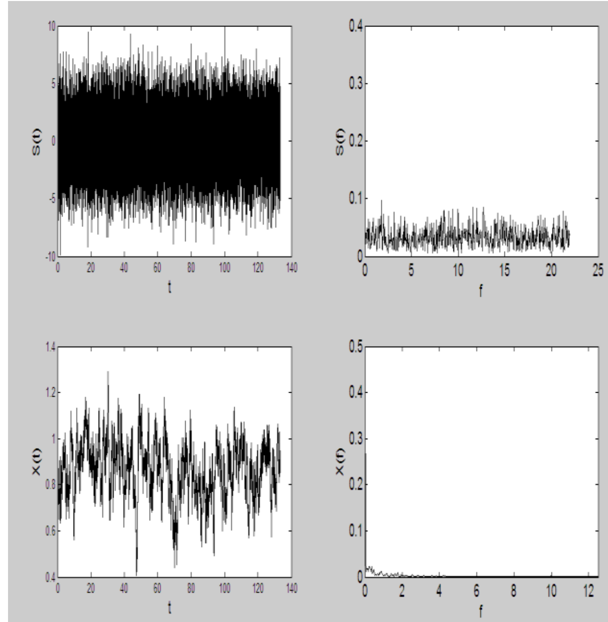

Fig. 5. In this case, f = 10 Hz, μ = 0.8, $A_0 = 0.6$, and D = 2. The waveforms of the input and output of the bistable system are shown. (*S(t)* is the input in the time domain, *X(t)* is output in the time domain, *S(f)* is the input in the frequency domain, and *X(f)* is the output in the frequency domain.)

Fig. 4 shows that the peak of the frequency spectrum of the output occurs when the frequency is as low as 0.01 Hz, which meets the condition of small parameter. Fig.5 shows that the peak of the frequency spectrum of the output cannot be observed when the frequency is as high as 10 Hz, which does not meet the condition of small parameter; therefore, SR does not occur in the bistable system. Through the experiment, we can find that when the frequency and amplitude meet the small parameter condition, increasing the noise intensity in a certain rang, it also can realize the SR.

3.3.2 The simulation of single-frequency signal modulation SR

We input the single-frequency signal $s(t) = A_0 \cos 2\pi ft + n(t)$, where $A_0 = 0.6$ and $f = 10HZ$ are the amplitude and frequency of the test signal, respectively. $n(t)$ is the noise, and D = 2. Suppose the scanning signal is $y(t) = A_c \cos 2\pi f_c t$, where A_c and f_c are the amplitude and frequency of the scanning signal, respectively. After the test signal is modulated by the mixer model, we can express it as follows

$$\begin{aligned} x_m(t) &= s(t)y(t) = [A_0 \cos 2\pi ft + n(t)] \cdot (A_c \cos 2\pi f_c t) \\ &= \frac{A_0A_c}{2}[\cos 2\pi(f - f_c)t + \cos 2\pi(f + f_c)t] \\ &\quad + A_c n(t) \cos 2\pi f_c t \end{aligned} \tag{31}$$

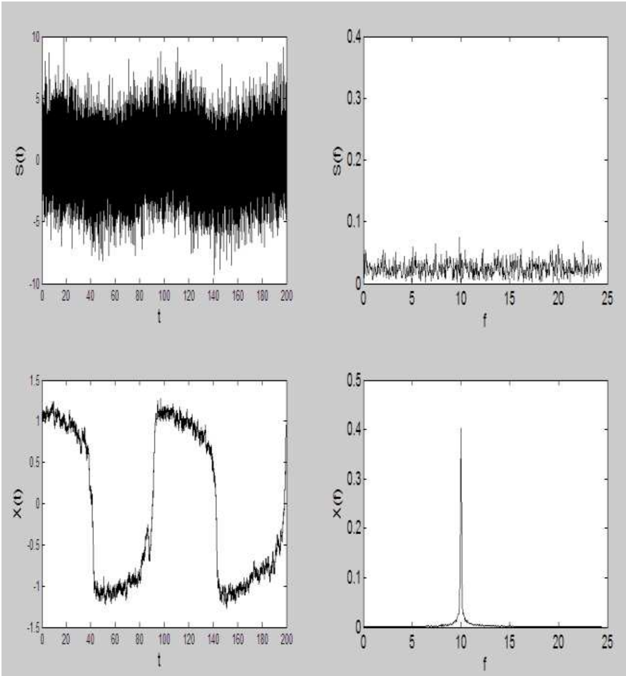

Fig. 6. In this case, $\mu = 0.8$, $f = 10$ Hz, $A_0 = 0.6$, $D = 2$, and $f_c = 9.9$ Hz. The output waveform of the modulating SR is shown. (*X(t)* is the output in the time domain, and *X(f)* is the output in the frequency domain.)

The simulation result shown in Fig. 5 indicate that the system does not produce SR when the signal is directly input into the bistable system because the frequency is too high to meet the condition of SR. However, if the signal passes through the mixer model first, the system can produce SR when the scanning frequency is 9.9 Hz $(f - f_c << 1/2\pi)$, as shown in Fig. 6.

3.3.3 The simulation of multi-frequency signal modulation SR

We input a multi-frequency signal with noise

$$s(t) = \sum_{n=1}^{\infty} \frac{A_0}{2n-1} \sin 2\pi f_n t + n(t) \quad , n = 1, 2, 3... \tag{32}$$

where $\frac{A_0}{2n-1}$ is the test signal amplitude and $f_n = (2n-1)f$ is the frequency. After the test signal is modulated by the mixer, we can express the signal as follows:

$$\begin{aligned} x_m(t) &= s(t)y(t) \\ &= [\sum_{n=1}^{\infty} \frac{A_0}{2n-1} \sin 2\pi f_n t + n(t)] \cdot A_c \sin 2\pi f_c t \\ &= \sum_{n=1}^{\infty} \frac{A_0 A_c}{2(2n-1)} [\cos 2\pi (f_n - f_c)t - \cos 2\pi (f_n + f_c)t] \\ &+ A_c n(t) \sin 2\pi f_c t \end{aligned} \tag{33}$$

For the multi-frequency signal, we cannot achieve the detection at once. We have to detect gradually from low frequency signals to higher ones. By using our method, the first three frequency components f_1, f_2, and f_3 of the test signal are detected as shown in Fig.7 to Fig. 9.

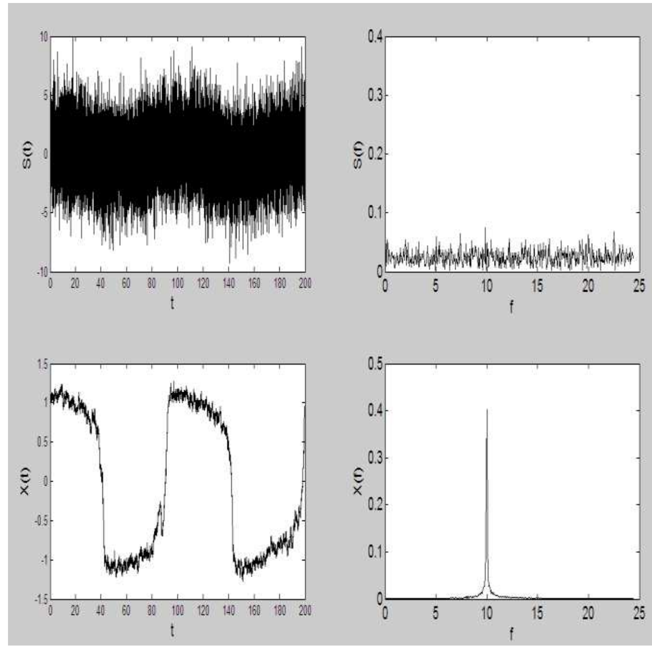

Fig. 7. The spectrum of the output of the SR system, where A_0 =0.6, $\mu = 0.8$, $f_1 = 10$ Hz, $D = 2$, and $f_c = 9.9$Hz.

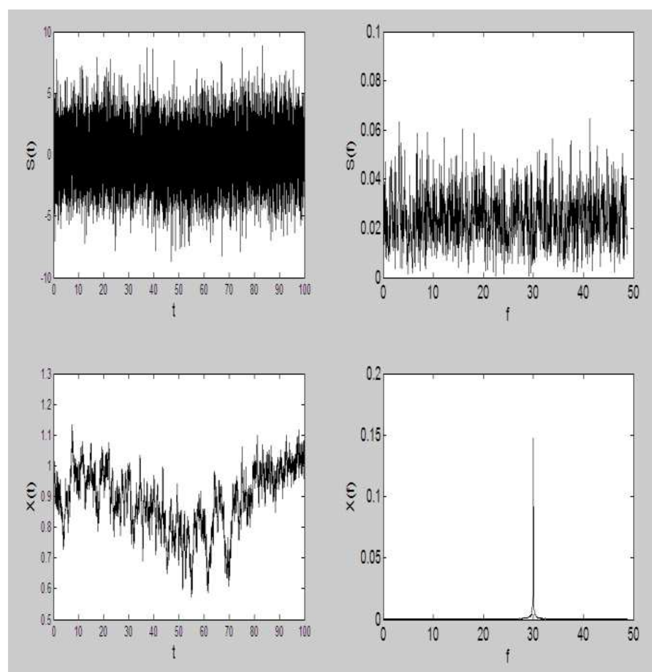

Fig.8. The spectrum of the output of the SR system, where A_0 =0.6, $\mu = 0.8$, $f_2 = 30$ Hz, $D = 2$, and $f_c = 29.9$ Hz.

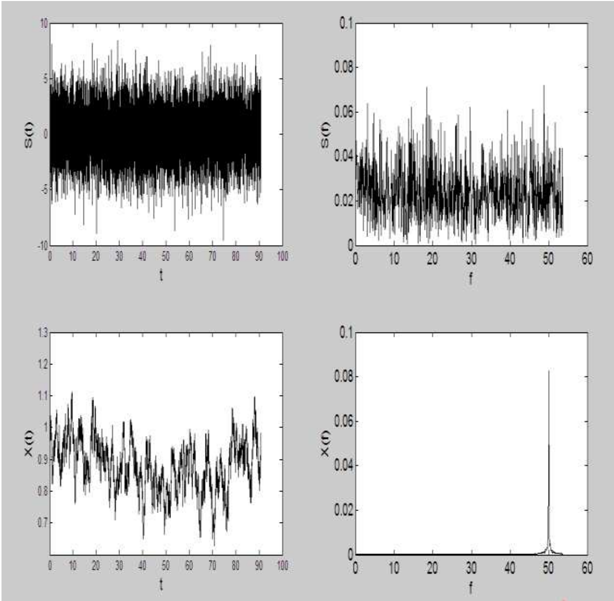

Fig. 9. The spectrum of the output of the SR system, where A_0 =0.6, μ = 0.8, f_3 = 50 Hz, D = 2, and f_c = 49.9 Hz.

As shown in Fig. 7 to Fig. 9, when the scanning frequency is close to the test signal, the system produces the spectrum peak. That result indicates that when the difference between the scanning frequency f_c and the measurable signal frequency f_n is smaller $(\Delta f = f_n - f_c << 1/2\pi)$, the system can produce the SR.

4. Conclusion

Although SR can be used to detect weak signal from strong noise background, it can only when the small parameter signal meets the adiabatic approximation requirement. Although large frequency periodic signals and multi-frequency harmonic signals are common in engineering practice, they are difficult to detect using SR. In this paper, we use signal modulation to transform these signals into small parameter signals so that the weak signal detection technique based on SR theory can be implemented. The feasibility of our method is verified using simulations.

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