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Research of critical factors affect weak signal detection capability

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ABSTRACT

As an essential link in fields like communication, sonar and radar, weak signal detection has been widely applied to different areas and has been becoming the focus of studies. The significance of weak signal detection technology drives people to explore and study new theories and methods that could be used to detect weak signals buried in strong background noise in a more accurate and faster way. With the development of nonlinear science technology, a new method has been put forward to solve problems in weak signal detection against the background of limitation of traditional detection methods. While achievements have been scored in bistable stochastic resonance system technology, the application of noise array bistable stochastic resonance system could further improve weak signal detection capability. Combined with theory and numerical simulation, bistable stochastic resonance method was introduced to analyze output signal-to-noise gain. Three elements-array noise, the number of array units and external noise were selected to further explore their relationship with detection performance. The simulated result showed that, compared with bistable stochastic resonance system, array bistable stochastic resonance system enjoys a better weak signal detection capability.

KEYWORDS

Weak signal detection; SNR gain, Bistable stochastic resonance.

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INTRODUCTION

The concept of stochastic resonance was put forward by Benzi R in 1981. It was first discovered in the study on ancient meteorological glacier, and then was widely used in fields like signal process, nervous system, biology, etc. Study has found that, in signal processing, stochastic resonance, especially bistable stochastic resonance enjoys unique advantage in weak signals detection by magnifying them[1]. Usually, weak signals are interfered by strong noise. Under this circumstances, signals act on stochastic resonance system. Coordinated by nonlinear system, energy transfer occurs between signal and noise. During this process, resonance output happens and thus leads to the increase in SNR, which will finally achieve the goal of weak signal detection[2]. Study by Mcnamara B and his team found that the curve of SNR changes with the noise intensity is a bell curve which could be used to determine whether the system could produce resonance. SNR became the most commonly used measure after the above study. The ratio of output SNR to input SNR can be defined as SNR gain in signal detection technology[3]. It was proved by Loerincz K and his team that the value of SNR gain in stochastic resonance system can be greater than “1”. People then showed great interest in the part that greater than “1”.

With the development of the technology of stochastic resonance system, many experts and scholars introduced single bistable stochastic resonance technology into the study on amplified identification of weak signals. It also provided new research idea to weaker signal detection and increased SNR gain in the system significantly. How to further improve the identification capacity became the major task of scholars[4]. Chapeau F and his team built a Bistable stochastic resonance model which was a saturation threshold one. Under the action of array noise, array SNR gain is more than “1” compared with single SNR gain. Namely the input signal goes into the array stochastic resonance system, and then the array noise absorbs more information from signals. Maximam output occurs in this process. Bistable stochastic resonance model was introduced by Duan F and his team[5]. The analysis result was released in 2008 after initial theoretic analysis. See Figure 1. Combined theory and numerical simulation, this weak signal detection research further analyzed SNR gain in bistable stochastic resonance system by introducing array bistable stochastic resonance model.

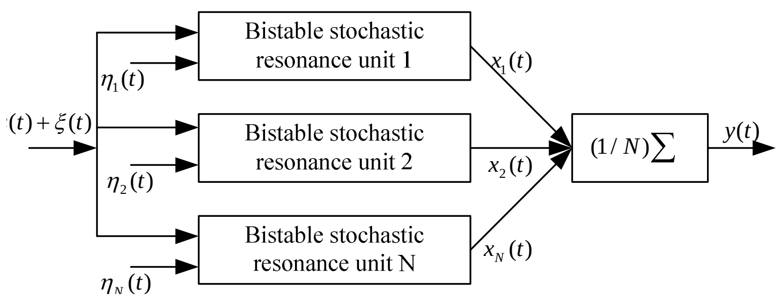


Figure 1 : Diagram of array bistable stochastic resonance system model

ARRAY BISTABLE STOCHASTIC RESONANCE SYSTEM MODEL

Model introduction

The above has presented the array bistable stochastic resonance system model. Weak sinusoidal signal designated by $s(t)$, external noise designated by $\zeta(t)$. Composite signal composed by the above two, so we designate it by $s(t)+\zeta(t)$ ($s(t)$ and $\zeta(t)$ are uncorrelated). Output signals in every array unit are composite signals. In the formula, $s(t)$ can be calculated by $A\cos(2\pi ft)$. The letter “A” represents signal amplitude. Mean value in white noise is 0, and the intensity is Dζ, namely $\zeta(t)$. Array internal noise, also called array noise, is uncorrelated with composite signals, designated by $\eta_i(t)$. the intensity of N array noise is Dη. Array noises are independent, and each stochastic resonance unit has its own equation.

$$dx_i(t)/dt = ax_i(t) - bx_i^3(t) + s(t) + \xi(t) + \eta_i(t)$$
$$i = 1, 2, ..., N \quad \textbf{(1)}$$

There are two real parameters, a and b, in the above equation. $x(t)$ is the output signal of array unit, and unit i can be designated by $x_i(t)$. The arithmetic mean value of all units is the output of array stochastic resonance.

$$R_{in} = \frac{4A^2}{2\pi^2 D_\xi \Delta B} \quad \textbf{(2)}$$

The above equation is the output SNR of array bistable stochastic resonance systems. Its input SNR can be indicated by formula (3). The output SNR of array unit can showed by formula (4) can be used to show the output SNR of array unit:

$$R_{out} = \frac{\left|\left\langle E\left[y(t)\exp(-j2\pi t/T)\right]\right\rangle\right|^2}{\left\langle \mathrm{var}(\left\langle y(t)\right\rangle)\right\rangle \Delta t \Delta B} \tag{3}$$

$$R_i = \frac{\left|\left\langle E\left[x_i(t)\exp(-j2\pi t/T)\right]\right\rangle\right|^2}{\left\langle \mathrm{var}(\left\langle x_i(t)\right\rangle)\right\rangle \Delta t \Delta B} \tag{4}$$

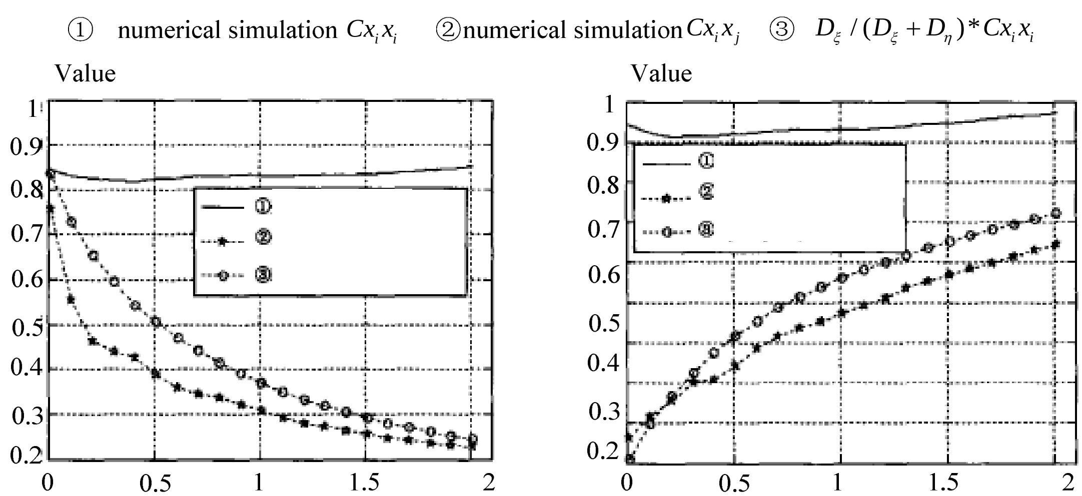
Since the stochastic resonance units are independent, based on the above formulas in array bistable stochastic resonance system we can get the output autocovariance calculation. The calculation formula, see formula (5). The values of i and j are not equal, but they are natural numbers.

$$\begin{aligned}&\left\langle \mathrm{var}(y[t])\right\rangle = \left\langle E[y(t)y(t)] - E[y(t)]E[y(t)]\right\rangle \\ &= \left\langle E[x_i(t)x_j(t)] - E[x_i(t)]E[x_j(t)]\right\rangle + \\ &\frac{\left\langle E[x_i(t)x_i(t)] - E[x_i(t)]E[x_j(t)]\right\rangle}{N}\end{aligned} \tag{5}$$

Array SNR gain

Array is characterized by nonlinear. This character relies on the interaction between array noise and external noise. Because of it, theoretical analysis of autocovariance and covariance is difficult in previous studies. However, analysis can be realized through numerical simulation. The setting value of signal amplitude is 0.1; of signal frequency and bandwidth are both 0.01Hz. The setting value of sampling frequency is 5Hz, and the two real parameters of the system are 1.

Use the model to simulate after the default setting. Figure 2 is the simulation result. Figure 2(a) is the curve of autocovariance and covariance vary with the intensity of array noise; Figure 2(b) is the curve of autocovariance and covariance vary with the intensity of external noise. Curve (1) in Figure 2(a) is autocovariance variation changed along with the intensity of array noise when the input value of the array noise is 0.1[6]. Curve (2) shows the covariance variation changing along with the intensity of array noise when the array input value of the external noise is 0.1. Curve (1) in Figure 2(b) shows the autocovariance variation changing along with the intensity of external array noise when the input value of external noise is 0.1; curve (2) is the covariance variation changing along with the intensity of external array noise when the array input value of the external noise is 0.1.



(a) curve changed along with the intensity of array noise

(b) curve changed along with the intensity of array external noise

Figure 2 : Curves of autocovariance and covariance changing along with noise

According to relative theories and the relationship between autocovariance and covariance showed in Figure 2, the can draw the following conclusions: (1) In array noise, when noise is 0, autocovariance and covariance are equal; in external noise, when noise is 0, autocovariance and covariance are unrelated, and covariance is 0. (2) In Figure 2(a), we can see that the value of fixed external noise remains unchanged and the increase of covariance in array noise is gradually decreased, namely, the principle autocovariance. This is similar to inverse relation. (3) Figure 2(b) shows that, when fixed array noise value remain unchanged, covariance increaseing along with the rise of external array noise, and it has the trend to become more close to autocovariance.

Based on the analysis of the above, we could get the covariance formula, as showed in Formula (6).

$$Cx_i x_j = \frac{D_\xi}{D} C_{x_i x_i}, D = D_\xi + D_\eta \quad (6)$$

With this formula, we can calculate the covariance value under the variation of internal array noise and external array noise, and then draw the curve. We can use curve (3) to designate in internal array noise. We can see the curve we got is basically accordant with the numerical simulated covariance curve; curve (3) also used to designate in external array noise. Besides, this curve is also basically accordant with the numerical simulated covariance curve. This proved the rationality of covariance hypotheses in formula (6). Before putting the assumed covariance into the covariance formula, its not difficult for us to get the array SNR gain equation, shown as formula (7).

$$G_{array} = \frac{R_{out}}{R_{in}} = \frac{G_1 D}{D_\xi + D_\eta / N} \quad (7)$$

G1 represents SNR gain in array units. We can see from formula (7) that, SNR gain is not only related with the intensity of internal array noise, but also closely related with variation of the intensity of the external array noise. Besides, the variations of SNR gains in the number of array units and units themselves are also affect it. Compared with single SNR gain, it is reasonable that array SNR gain is above “1”.

ANALYSIS OF SNR GAIN

In order to research the performance of bistable stochastic resonance systems in detecting weak signals, this paper also studied the influence exerted on array SNR by the changes of internal array noise, the number of array units and external noise[7]. When the signal amplitude was set to 1, the values of signal frequency and bandwidth are 0.01Hz. The setting value of sampling frequency is 5Hz, and the two real parameters of the system are set to 1. Figure 3 shows the trend curve of array SNR gain changed along with array noise intensity. It also shows the SNR gain variation trend when facing different external noise intensity. Five kinds of external noises are presented. We can see from the figure that no mater how the external noise changes, array SNR gain could always reach the maximum peak through array noise tuning. The maximum peak is also the array stochastic resonance peak value. Usually, the maximum peak first goes high and then goes low along with the increase of the intensity of external noise[8]. Thus we could draw the conclusion that, resonance could be realized through array noise tuning with the application of array bistable stochastic resonance technology. Selecting external noise intensity within the range of optimal intensity could achieve the best result in weak signal detection with the application of array bistable stochastic resonance systems.

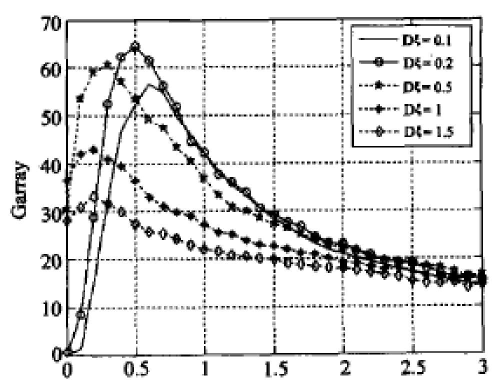


Figure 3 : Array SNR gain curve against different intensities of external noise

When the setting value is 1, the setting values of signal frequency and bandwidth are both set to 0.01Hz. The value of sampling frequency is set to5Hz, and the two real parameters are set to 1. Figure 4 shows trend curve of array SNR gain changing long with array noise intensity when the number of units is different. We can see from Figure 4 that the peak of the ratio of array SNR gain to array unit SNR gain gradually rise when the number of array units are increased. That means the weak signal performance of array bistable stochastic resonance is prominently improved compared with single stochastic resonance. It is worth noting that while the performance improved significantly when the number of array units is below 100, the improvement of performance is not that prominent when the number of array units is large enough.

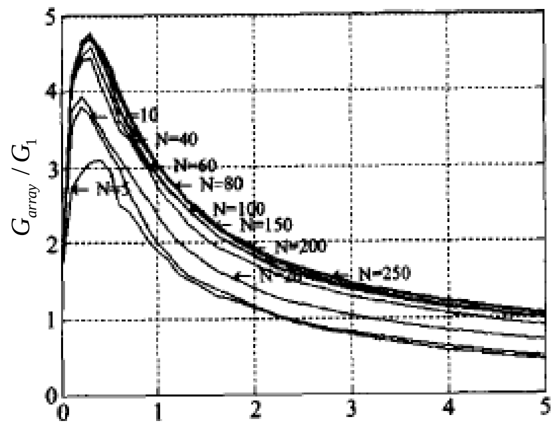


Figure 4 : Variation of the ratio of array SNR gain to unit SNR gain when the numbers of array units is different

ANALYSIS OF SIMULATION RESULT

Analysis of array bistable stochastic resonance model and SNR gain has been done in the above of this paper. In order to test the weak detection performance, we select weak periodical signals in carrying out the simulation test. In setting the value of simulated parameter in the test, signal amplitude is set to 1, and signal frequency and bandwidth are both set to 0.01Hz. The setting value of sampling frequency is 5Hz, and two parameters of the system are 1. The number of array units is set to 100 and the intensity of array noise is 0.2. Figure 5 shows the performance comparison between array bistable stochastic resonance and single stochastic resonance in weak signal detection. The compared with SNR gain of single stochastic resonance, part of the ratio of array SNR gain to single stochastic SNR gain is above “1” when limited external noises within the optimal noise intensity range. That means the ratio of array SNR gain is obviously larger. The improvement of weak signal detection of array bistable stochastic resonance is more significant compared with single stochastic resonance[9]. However, with the intensification of external noise, the weak signal detection performance is degraded. The louder the external noise is, the closer it becomes to the performance of single stochastic resonance. This result is completely accordant with theoretical analysis.

CONCLUSIONS

With the development of nonlinear Science, achievements have been scored in bistable stochastic resonance system technology, and the application of noise array bistable stochastic resonance system could further improve weak signal detection capability. This study introduced array bistable stochastic resonance method and combined theory and practice with numerical simulation to analyze output SNR gain by selecting the three factors — array noise, the number of array units and external noise to further explore their relationship with the detection capability. The following conclusions have been drawn by the performance comparison between array bistable stochastic resonance and single stochastic resonance:

(1) Array SNR gain can reach the maximum peak through array noise tuning no mater how the external noise changes, and the maximum peak is also the peak value of array stochastic resonance.

(2) The peak value of array stochastic resonance goes from high to low along with the increase of intensity of external noise.

(3) Array SNR gain rises gradually when the number of array units is no more than 100, and its detection performance improved prominently at the same time. But the performance improvement is not satisfactory when the number of array units is large enough.

(4) When adopting weak periodical signals to do the simulation test, the improvement of weak detection performance of array bistable stochastic resonance system is more significant compared with single stochastic resonance in the same conditions. However, with the intensification of external noise, the weak signal detection performance of array bistable stochastic resonance system is degraded, and the louder the external noise is, the closer its performance becomes to that of the single stochastic resonance system.

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