Internal stochastic resonance in two coupled liquid membrane oscillators

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Internal stochastic resonance (ISR) is investigated in two coupled liquid membrane oscillators when only one oscillator is subjected to environmental noise in the absence of an external signal. Comparing the responses of both subsystems, it is found that enhancement or suppression of ISR for each oscillator depends on the coupling strength, that synchronization of the two oscillators can occur only at strong coupling strength, and that ISR *without tuning* can also occur under certain conditions in the above-mentioned models.

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I. INTRODUCTION

Stochastic resonance (SR) [1], a phenomenon in which a small periodic force can be amplified by an optimal environmental noise, has been extensively studied in many nonlinear systems, such as physical [2–4], chemical [5,6], biological [7,8], and sensory [9] systems. Later, internal SR (ISR) [10,11], or autonomous SR [12], or coherent resonance (CR) [13], was studied by replacing external signals with internal signals coming from noise-induced oscillation of the systems. Our group [14] described a type of ISR where the internal signal comes from the period-1 oscillation instead of an external signal or a noise-induced deterministic oscillation in the Belousov-Zhabotinsky reaction.

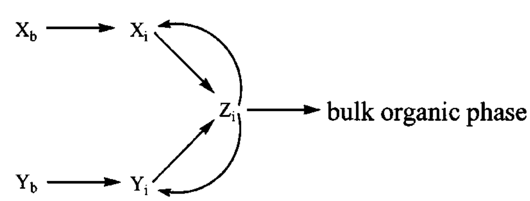
In studies of SR, coupled systems [15–30] have attracted much attention because coupled systems can well exhibit complex phenomena. Jung *et al.* [17] observed the amplification of a periodic force within a certain range of noise intensity in globally coupled bistable systems. Inchiosa and Bulsara [19] reported that coupling enhances SR in globally and nonlinearly coupled systems. Later, the two important phenomena of array-enhanced stochastic resonance (AESR) and spatiotemporal synchronization of coupled oscillators were demonstrated both in theory [18] and in experiment [31]. These studies show the positive roles of environmental noise, i.e., AESR and noise-induced synchronization, in coupled systems. The above-mentioned studies of SR are based on the idea of modulating the coupling strength and coupling chain length in coupled systems, while other studies of SR are not based on this idea, but on the idea of modulating other parameters. For instance, our group [26,27] has found that SR can occur in two delayed coupled oscillators by modulating the frequency and initial phase of the input signal with the perturbation of environmental noise. All of these studies indicate that coupling is very important in SR of nonlinear systems. Very recently, in the case without external signal, the phenomenon of coupling-enhanced CR [23] or array-enhanced CR [24,29,30] was studied in coupled neuron systems. Various synchronizations were found in coupled excitable [21], neuron [22–24,29,30] systems. Jiang and Xin stated that coupling can sustain the propagation of CR and that CR without tuning can occur under proper conditions in a one-way coupled system [32].

It is well known that bio-oscillation is one of the most important properties of living organisms and plays a key role in maintaining life [7,8]. Because of their same dynamic behaviors, membrane oscillators are considered to model the membranes of some sensory cells, such as olfactory and gustatory cells [7,33–35]. Various excitable artificial membranes have been extensively studied and used as effective models for bioexcitable systems [36]. Of them, the oscillation behavior of an oil-water liquid membrane is typical, and Yoshikawa and co-workers proposed a model for this liquid membrane from experiment results [33–35]. In this model, the SR phenomenon was studied theoretically by adding environmental noise in different environments [10,11,37]. So far there is apparently no report on ISR of two coupled oil-water liquid membrane oscillators. In the present paper, our major motivation is to investigate the behavior of ISR when the first oscillator is subjected to environmental noise without an input signal in two coupled liquid membrane oscillators. It is found that the system has many dynamic behaviors, for example, coupling enhancement or suppression of ISR for each oscillator, synchronization of the two coupled oscillators, and ISR without tuning. Due to the cooperative interaction of environmental noise and coupling, these phenomena cannot occur in the corresponding single oscillator.

II. DYNAMICAL MODELS

A. The original model

The model used in the present work was proposed by Yoshikawa and co-workers [33–35]. The whole process can be shown as follows:



(1)

in which X_b and Y_b are the concentrations of surfactant and cooperative species in the bulk aqueous phase, respectively; X_i, Y_i, and Z_i are the concentrations of surfactant, cooperative species, and their aggregate, respectively, near the oil-

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water interface. Briefly, the species X and Y arrive at the oil-water interface through diffusion from the bulk aqueous phase and form aggregates there. When the concentration of the aggregate reaches a critical value, it is abruptly transferred to the organic phase. The repeated formation and disruption of the monolayer of the aggregate on the interface results in oscillation. The related dynamic equations are expressed as follows [10,37]:

$$\frac{dX_i}{dt} = D_X(X_b - X_i) - K_1 Z_i, \tag{2}$$

$$\frac{dY_i}{dt} = D_Y(Y_b - Y_i) - K_2 Z_i, \tag{3}$$

$$\frac{dZ_i}{dt} = K_3(X_i + Y_i) - K_4 G(Z_i). \tag{4}$$

Here the first terms on the right-hand sides of Eqs. (2) and (3) denote the diffusion for the case where only a linear concentration gradient exists; the second terms represent the feedback from the decomposition of the aggregate Z_i. The first term in Eq. (4) gives the rate of formation of Z_i, and the second term corresponds to the rate of escape of Z_i from the interface to the bulk organic phase. $G(Z_i)$ is a nonlinear N-shaped function that enables the system to be excitable. It is generally expressed as follows:

$$G(Z_i) = K_5 Z_i^3 + K_6 Z_i^2 + K_7 Z_i + K_8. \tag{5}$$

For further details and the meaning of parameters of this model, we refer to Refs. [10,37].

B. Two coupled models

Styles of coupling include global, linear [17,19], local, and nonlinear [18,31]. In the present work, we adopt local and linear coupling and set the coupling only through the aggregate in Eq. (3), i.e., Z coupled with W. A coupled model for this kind of system is developed on the basis of the original model. Work on global coupling through X, Y, Z coupled with U, V, W, respectively, is under consideration and will be published in the future.

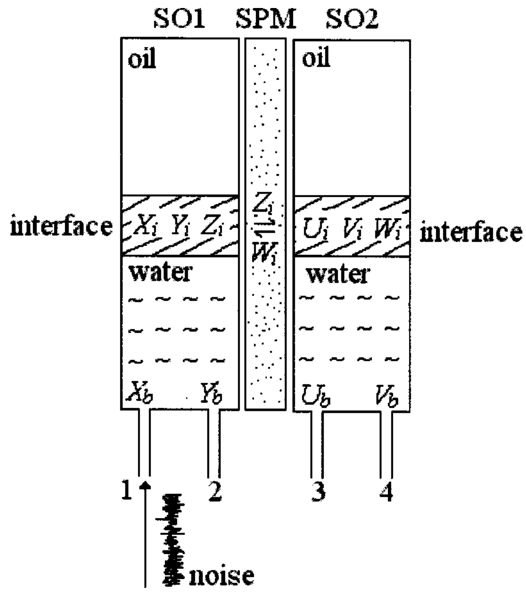

FIG. 1. An experimental arrangement corresponding to two coupled systems. SO1, the first stochastic oscillator; SO2, the second stochastic oscillator; SPM, the selective permeable membrane.

Here, the local and linearly coupled dynamic equations are expressed as follows. For the first stochastic oscillator (SO1),

$$\frac{dX_i}{dt} = D_X(X_b - X_i) - K_1 Z_i,$$

$$\frac{dY_i}{dt} = D_Y(Y_b - Y_i) - K_2 Z_i,$$

$$\frac{dZ_i}{dt} = K_3(X_i + Y_i) - K_4 G(Z_i) + K_d(W_i - Z_i); \tag{6}$$

for the second stochastic oscillator (SO2),

$$\frac{dU_i}{dt} = D_U(U_b - U_i) - K_1 W_i,$$

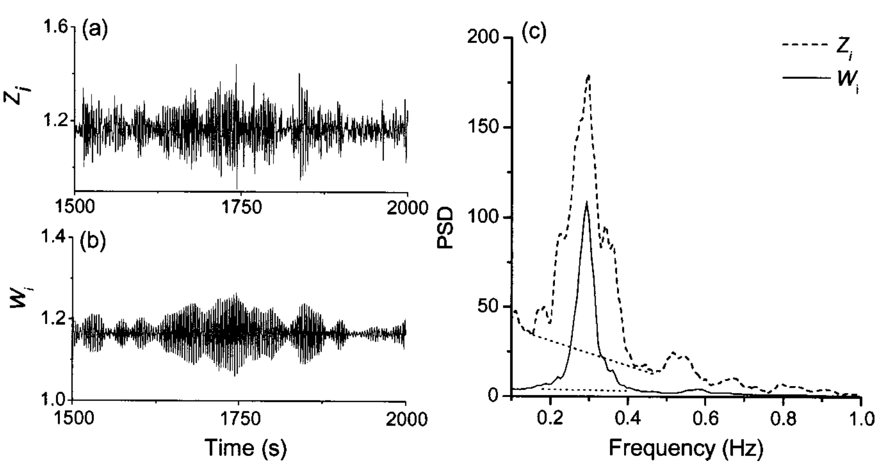

FIG. 2. Time series of Z_i (a) and W_i (b) and the corresponding power spectral density (PSD) (c) with β=0.002 and K_d=0.1. Parameters: $X_b^0 = U_b = 2.56$, $Y_b = V_b = 2.82$, $D_X = D_U = 0.30$, $D_Y = D_V = 0.05$, $K_1 = 0.6$, $K_2 = 0.1$, $K_3 = K_4 = 5.0$, $K_5 = 0.3$, $K_6 = -2.0$, $K_7 = 3.4$, $K_8 = -1.0$.

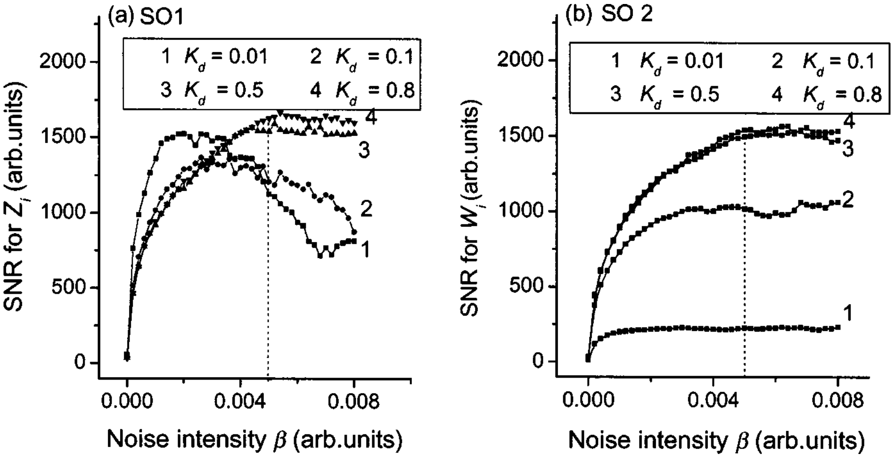

FIG. 3. The SNR against noise intensity for SO1 (a) and SO2 (b) at constant coupling strength: K_d =(1) 0.01; (2) 0.1; (3) 0.5; (4) 0.8. Other parameters as in Fig. 2.

$$\frac{dV_i}{dt}=D_V(V_b-V_i)-K_2W_i,$$

$$\frac{dW_i}{dt}=K_3(U_i+V_i)-K_4G(W_i)+K_d(Z_i-W_i) \tag{7}$$

where X_b, Y_b, X_i, Y_i, and Z_i are the same as above; U_b, V_b, U_i, V_i, and W_i are the corresponding variables of SO2; K_d is the coupling strength of the two oscillators. $G(Z_i)$ and $G(W_i)$ have the same expression:

$$G(Z_i)=K_5Z_i^3+K_6Z_i^2+K_7Z_i+K_8, \tag{8}$$

$$G(W_i)=K_5W_i^3+K_6W_i^2+K_7W_i+K_8. \tag{9}$$

Based on Eqs. (6)–(9) and Refs. [15,16], we suggest an experimental arrangement corresponding to the two coupled subsystems shown in Fig. 1. The right and left layers correspond to SO1 and SO2, respectively, and both layers are reaction layers, while the middle layer is a selective permeable membrane (SPM), which permits permeation of only Z_i and W_i, and is not permeable to other species. Thus the coupling between SO1 and SO2 is through diffusion of Z_i and W_i into or out of this layer. The coupling strength depends on the diffusion coefficients. The positions 1, 2, 3, and 4 show where X_b, Y_b, U_b, and V_b enters, respectively. In this way, the experimental arrangement is devised for a two-coupled-oscillator system. It is a pity that we could not do this experiment because of restrictions of conditions.

III. RESULTS AND DISCUSSION

To investigate ISR, the environmental noise is added only to the control parameter X_b of the first subsystem and X_b is replaced by

$$X_b=X_b^0+\beta\xi(t). \tag{10}$$

X_b^0 is the constant concentration of X at the steady state, and β is the intensity of Gaussian white noise $\xi(t)$ with zero mean value $\langle\xi(t)\rangle=0$ and unit variance $\langle\xi(t)\xi(t+\tau)\rangle=\delta(\tau)$. $\xi(t)$ is generated by a band-limited white noise generator. In the experimental arrangement, X_b is modulated by adding the white noise to the first entrance as shown in Fig. 1. We simulate Eqs. (6)–(10) numerically by using the Euler method for 2000 s with a time step of 0.01 s. To measure the ISR, the last 16 384 points are used to obtain frequency spectra by fast Fourier transform (amplitude). Based on frequency spectra, the signal-to-noise ratio (SNR) is defined as $H(\Delta\omega/\omega_f)^{-1}$ as in Ref. [12], where H is the height of the spectrum, ω_f is the frequency at the maximum peak,

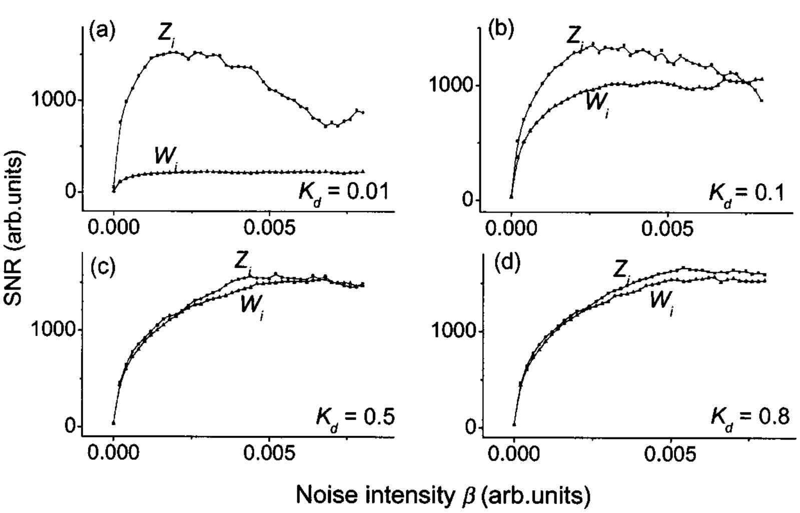

FIG. 4. The SNR versus noise intensity for constant coupling strength: K_d=(a) 0.01; (b) 0.1; (c) 0.5; (d) 0.8. Other parameters as in Fig. 2.

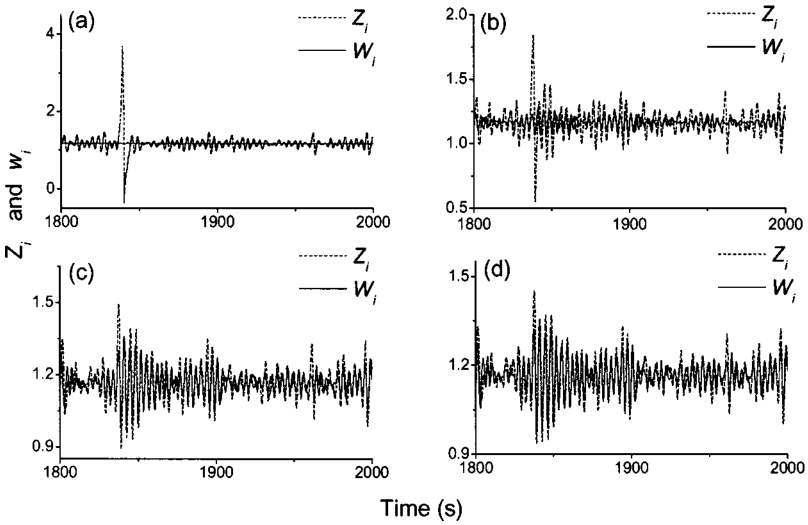

FIG. 5. Time series of Z_i and W_i at different coupling strength for $\beta=0.005$. $K_d=$(a) 0.01; (b) 0.1; (c) 0.5; (d) 0.8. Other parameters as in Fig. 2.

i.e., the frequency of noise-induced internal signal, and $\Delta\omega$ is the width of the peak at its half height. Thus the SNR depends on two factors. One is the height of the output peak of the system, because H changes with increase of noise intensity; the other is $\Delta\omega/\omega_f$, which is the relative width of the peak. Here, each point of the SNR versus noise intensity or coupling strength is obtained by averaging 20 runs.

When environmental noise is added only to the first oscillator, i.e., SO1, both SO1 and SO2 display the behavior of oscillation. This means that the oscillation is transmitted to SO2 by coupling. Diagrams of the time series of each oscillator and the corresponding power spectral density (PSD) are given in Fig. 2. By comparing Fig. 2(a) with Fig. 2(b), it is seen that the contour of W_i(SO2) is smoother than that of Z_i(SO1), which illustrates that the coupling suppresses the destructive role of noise and plays the role of a noise filter for SO2. From Fig. 2(c), it is found that the spectral peak of Z_i is higher and wider than that of W_i. These indicate that the coupling can transfer the noise-induced oscillation of SO1 to SO2 in a two-coupled-oscillator system when environmental noise is added only to SO1, and the coupling plays the role of a noise filter for SO2. We presume that the oscillation can be transferred to subsequent subsystems, i.e., the third, fourth, fifth, and so on. In the following sections, we will investigate the ISR of each oscillator by varying the noise intensity and coupling strength, respectively.

A. Varying noise intensity with constant coupling strength

Figure 3 shows the SNR for Z_i and W_i of the two oscillators versus noise intensity at constant coupling strength. For SO1 when K_d is small, not larger than 0.1, the SNR increased initially and then dropped with increase of noise intensity. It is seen that the maximum peak of the SNR at $K_d=0.01$ is higher than that of the SNR at $K_d=0.1$. When the coupling strength increases to $K_d\geqslant 0.5$, the curve of the SNR shows a plateau at high noise intensity. The height of the plateau is greater than the height of the maximum SNR at $K_d=0.01$. This implies that the value of the coupling strength, i.e., coupling, can influence the ISR of SO1. For SO2, however, the SNR always increased with increase of noise intensity at any K_d value and came to a plateau. The height of the plateau increased with increase of coupling strength, which implies that the ISR of SO2 is enhanced by

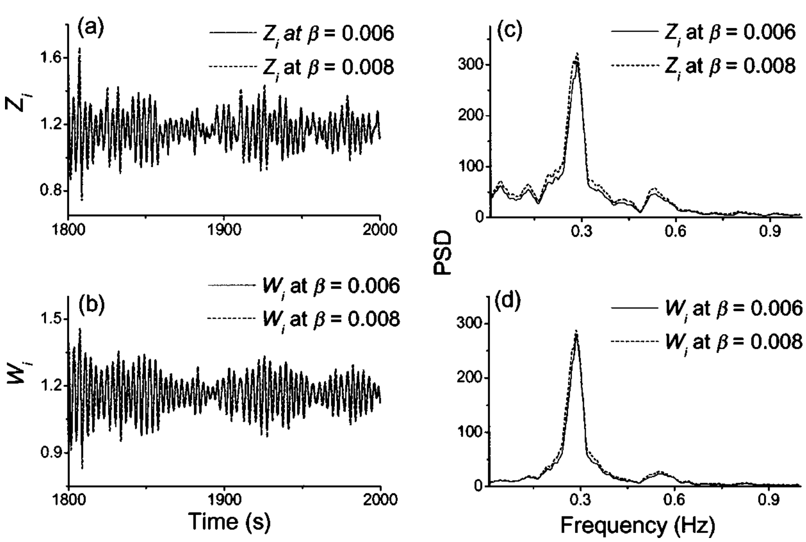

FIG. 6. Time series of Z_i (a) and W_i (b) and the corresponding PSD of Z_i (c) and W_i (d) at β=0.006 (solid line) and 0.008 (dashed line) for $K_d=0.8$. Other parameters as in Fig. 2.

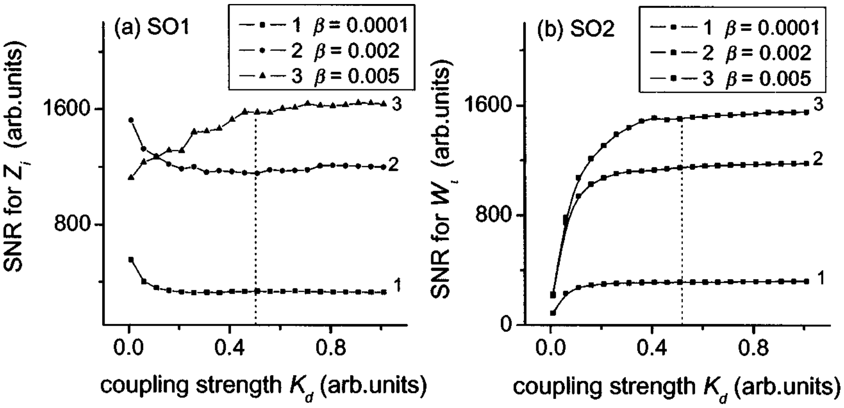

FIG. 7. The SNR against coupling strength for SO1 (a) and SO2 (b) at constant noise intensity: β=(1) 0.0001; (2) 0.002; (3) 0.005. Other parameters as in Fig. 2.

increasing coupling strength. These results suggest that the enhancement or suppression of ISR for SO1 and SO2 depends on the coupling strength.

Gammaitoni *et al.* [38] put forward the idea of controlling SR in a modified Schmitt trigger and later did extended and extensive work on controlling SR [39]. They realized control of SR by adding into the system another periodic modulation and considered the initial phases of the two periodic signals as a tunable parameter, which leads to the enhancement and suppression of SR. In the present work, we give a way of controlling ISR in a coupled system by varying the coupling strength between two coupled subsystems.

In order to show clearly the ISR for two oscillators, the curves 1, 2, 3, and 4 in Figs. 3(a) and 3(b) are compared in Figs. 4(a), 4(b), 4(c), and 4(d), respectively. It is seen from Fig. 4 that the difference of the SNR values of Z_i and W_i is very large at $K_d=0.01$, and this difference decreases at $K_d=0.1$; when the coupling strength is strong, i.e., $K_d \geqslant 0.5$, however, the two curves become almost identical. This indicates the occurrence of synchronization for two coupled subsystems when the coupling strength is large enough, $K_d \geqslant 0.5$. To confirm the phenomenon of synchronization of the two oscillators, the time series of the two oscillators are shown in Fig. 5. When K_d is small ($K_d=0.01$), i.e., a weak interaction between SO1 and SO2, SO1 transferred only a little energy to SO2, which resulted in a weak oscillation of SO2. As the coupling strength exceeded a specific value, 0.5, SO1 exchanged energy efficiently with SO2, which enhanced the amplitude of SO2 almost identically to that of SO1. This is synchronization of the two coupled oscillators. Synchronization of CR has been reported in coupled excitable systems at an optimal noise intensity [21] and in neuron systems at not too high noise intensity [23,24]. Our result shows that the synchronization can appear not only at an optimal noise intensity, and at not too high noise intensity, but also at high noise intensity when the coupling is very strong.

Now we would like to go back to Fig. 3 to discuss the plateaus of the SNR. For SO1, the plateau appeared when $K_d \geqslant 0.5$ and $\beta \geqslant 0.005$, the dotted line in Fig. 3(a). For SO2, the plateau appeared at any K_d value, if $\beta \geqslant 0.005$, the dotted line in Fig. 3(b). The phenomenon that the SNR at plateau does not change with increasing noise intensity may be called *ISR without tuning* for the noise intensity in coupled systems. This phenomenon is further confirmed in Fig. 6. It is found that the time series of Z_i in Fig. 6(a) and the corresponding PSD in Fig. 6(c) at $\beta=0.006$ almost overlap with those of $\beta=0.008$ when $K_d=0.8$, and W_i has similar results to Z_i in Figs. 6(b) and 6(d). This illustrates that Z_i and W_i do not change in the plateau range of $\beta \geqslant 0.005$.

The phenomenon of ISR without tuning for noise intensity can be understood from the definition of the SNR. At $K_d \geqslant 0.5$, when the noise intensity is less than 0.005, the first factor H and the second factor $\Delta\omega/\omega_f$ increase with increase of noise intensity, but H increases more quickly than $\Delta\omega/\omega_f$, which leads to the increase of the SNR with increasing noise intensity. When noise intensity is equivalent to or more than 0.005, H and $\Delta\omega/\omega_f$ are almost constant as shown in Figs. 6(c) and 6(d), which result in the situation

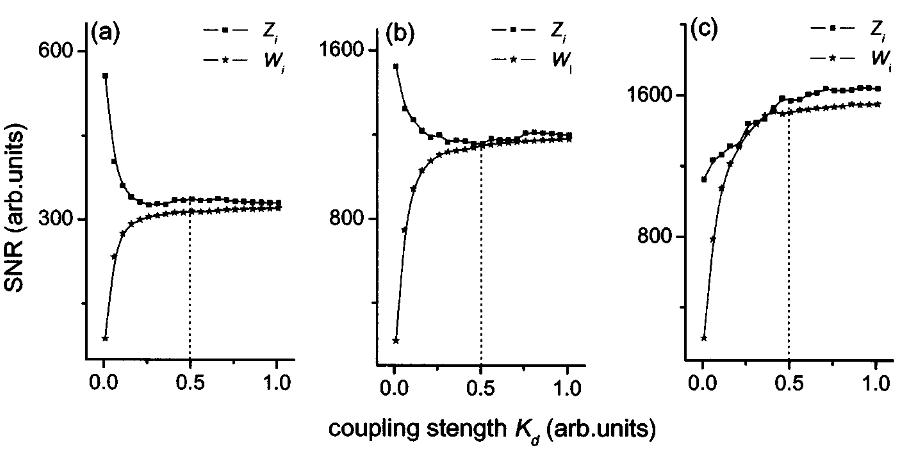

FIG. 8. The SNR against coupling strength for Z_i (squares) and W_i (pentagons) at constant noise intensity. β=(a) 0.0001; (b) 0.002; (c) 0.005. Other parameters as in Fig. 2.

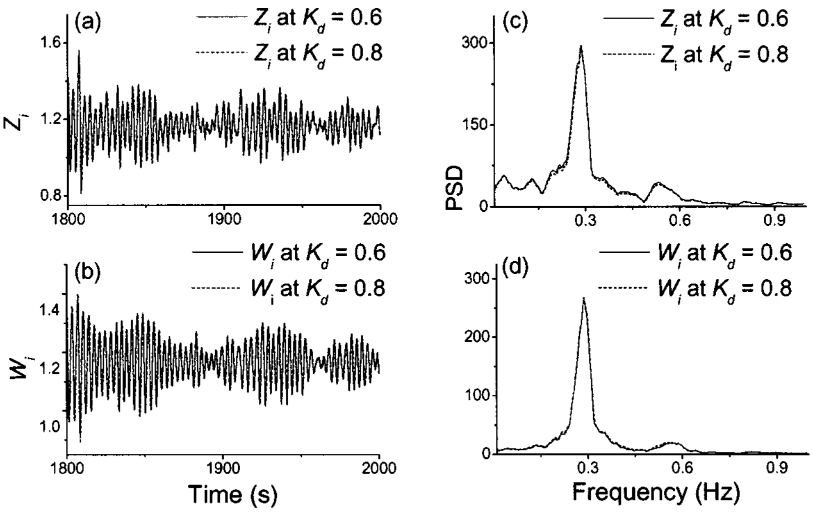

FIG. 9. Time series of Z_i (a) and W_i (b) and the corresponding PSD of Z_i (b) and W_i (d) at $K_d=0.6$ (solid line) and 0.8 (dashed line) for $\beta=0.005$. Other parameters as in Fig. 2.

that the value of the SNR does not change with increase of noise intensity. It seems that the two coupled oscillators could be resistant to the effect of noise at high noise intensity when $K_d \geqslant 0.5$. It is very important to study the role of noise in coupled bioexcitable systems.

B. Varying coupling strength with constant noise intensity

Figure 7 shows the SNR versus coupling strength at several constant noise intensities. It is found from Fig. 7(a) that the SNR of Z_i decreased with initial increase of coupling strength both at $\beta=0.0001$ in curve 1 and at $\beta=0.002$ in curve 2, while increasing monotonically at $\beta=0.005$ in curve 3. However, at each noise intensity the SNR of W_i increased with increasing coupling strength as shown in Fig. 7(b). The comparison of SO1 (Z_i) with SO2 (W_i) is shown in Fig. 8. The decrease of Z_i at low noise intensity, i.e., $\beta \leqslant 0.002$, is in contrast with the increase of W_i, which is a consequence of energy transfer from SO1 to SO2 when coupling occurs. At high noise intensity, the energy transfer did not lead to a decrease of the SNR of Z_i due to a sufficient supply of energy from noise. At any noise intensity, the values of Z_i and W_i go to stable values, that is, plateaus appear, when $K_d \geqslant 0.5$. The values of Z_i and W_i are about 300 in Fig. 7(a), 1200 in Fig. 7(b), and 1600 in Fig. 7(c), respectively. It indicates an occurrence of synchronization when coupling strength is strong, i.e., $K_d \geqslant 0.5$. Similarly, we call the phenomenon ISR without tuning for coupling strength in coupled systems. To confirm this phenomenon, the time series of each oscillator are plotted in Fig. 9. The time series of Z_i in Fig. 9(a) and the corresponding PSD in Fig. 9(c) at $K_d=0.6$ almost overlap with those of $K_d=0.8$ when $\beta=0.005$. Similarly, the time series of W_i in Fig. 9(b) and the corresponding PSD in Fig. 9(d) at $K_d=0.6$ almost overlap with those of $K_d=0.8$ when $\beta=0.005$. The phenomenon of ISR without tuning for coupling strength can be attributed to high coupling strength, which unites the two oscillators by fast transfer of energy. It seems that in a coupled system the two coupled oscillators could be resistant to coupling at high coupling strength. It is very important to study the role of coupling in coupled bioexcitable systems.

Collins *et al.* [40] found that SR without tuning can occur in a single oscillator in the presence of an input signal. Jiang and Xin [32] found that the phenomenon of CR without tuning for noise intensity can occur at a certain coupling strength in a one-way coupled Brusselator model in the absence of an input signal. Our result is in good agreement with theirs, and the phenomenon of ISR without tuning for coupling strength can also occur at a certain noise intensity in the absence of an input signal. ISR without tuning is very important to internal signal processing and transferring, and we expect that such SR, CR, and ISR without tuning could occur in neural networks and other systems.

IV. SUMMARY

The internal SR of two coupled oil-water membrane oscillators is investigated only when the first oscillator is subjected to environmental noise. It is found that coupling strength is a key factor in the dynamic behaviors of the coupled systems. When coupling strength is small, i.e., $K_d < 0.5$, the synchronization of the two oscillators cannot occur due to the weak coupling effect between the two oscillators; when $K_d \geqslant 0.5$, however, the synchronization of the two oscillators can occur due to the strong coupling effect. It should be recognized that enhancement or suppression of ISR for two oscillators depend strongly on the coupling strength. Furthermore, ISR without tuning can occur versus noise intensity at $K_d \geqslant 0.5$ for SO1 and at any K_d value for SO2. Similarly, ISR without tuning can also occur versus coupling strength at $K_d \geqslant 0.5$ both for SO1 and for SO2, regardless of the β value. From the present and previous work [18,19,32], it seems that the main observation above is a general phenomenon of nonlinear oscillatory systems, especially biosystems when processing biological information [8]. We expect the present result could contribute to the study of SR and ISR in many coupled systems.

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[1] L. Gammaitoni, P. Hänggi, P. Jung, and F. Marchesoni, Rev. Mod. Phys. **70**, 223 (1998).
[2] P. Jung and P. Hänggi, Phys. Rev. A **44**, 8032 (1991).
[3] K. Wiesenfeld and F. Moss, Nature (London) **373**, 33 (1995).
[4] S. M. Bezrukov and I. Vodyanoy, Nature (London) **385**, 319 (1997).
[5] L. F. Yang, Z. H. Hou, and H. W. Xin, J. Chem. Phys. **110**, 3591 (1999).
[6] R. Zhu, Q. S. Li, and Z. C. Liu, Chem. Phys. Lett. **351**, 410 (2002).
[7] J. K. Douglass, L. Wilkens, E. Pantazelou, and F. Moss, Nature (London) **365**, 337 (1993).
[8] P. Hänggi, Chem. Phys. Chem. **3**, 285 (2002).
[9] J. E. Levin and J. P. Mille, Nature (London) **380**, 165 (1996).
[10] S. Zhong and H. W. Xin, Chem. Phys. Lett. **321**, 309 (2000).
[11] Q. Feng and H. W. Xin, Biophys. Chem. **90**, 175 (2001).
[12] G. Hu, T. Ditzinger, C. Z. Ning, and H. Haken, Phys. Rev. Lett. **71**, 807 (1993).
[13] A. S. Pikovsky and J. Kurths, Phys. Rev. Lett. **78**, 775 (1997).
[14] Q. S. Li and R. Zhu, J. Chem. Phys. **115**, 6590 (2001).
[15] L. F. Yang, M. Dolnik, A. M. Zhabotinsky, and I. R. Epstein, Phys. Rev. Lett. **88**, 208303 (2002).
[16] L. F. Yang and I. R. Epstein, Phys. Rev. Lett. **90**, 178303 (2003).
[17] P. Jung, U. Behn, E. Pantazelou, and F. Moss, Phys. Rev. A **46**, R1709 (1992).
[18] J. F. Lindner, B. K. Meadows, W. L. Ditto, M. E. Inchiosa, and A. R. Bulsara, Phys. Rev. Lett. **75**, 3 (1995).
[19] M. E. Inchiosa and A. R. Bulsara, Phys. Lett. A **200**, 283 (1995).
[20] M. Löcher, D. Cigna, and E. R. Hunt, Phys. Rev. Lett. **80**, 5212 (1998).
[21] H. Hempel, L. Schimansky-Geier, and J. Garcia-Ojalvo, Phys. Rev. Lett. **82**, 3713 (1999).
[22] S. K. Han, T. G. Yim, D. E. Postnov, and O. V. Sosnovtseva, Phys. Rev. Lett. **83**, 1771 (1999).
[23] Y. Q. Wang, D. T. W. Chik, and Z. D. Wang, Phys. Rev. E **61**, 740 (2000).
[24] B. Hu and C. S. Zhou, Phys. Rev. E **61**, R1001 (2000).
[25] J. T. Ariaratnam and S. H. Strogatz, Phys. Rev. Lett. **86**, 4278 (2001).
[26] Q. S. Li and R. Zhu, Phys. Rev. E **64**, 051116 (2001).
[27] R. Zhu and Q. S. Li, Phys. Lett. A **292**, 58 (2001).
[28] M. G. Rosenblum and A. S. Pikovsky, Phys. Rev. E **64**, 045202 (2001).
[29] Y. J. Shinohara, T. Kanamaru, H. Suzuki, T. Horita, and K. Aiharal, Phys. Rev. E **65**, 051906 (2002).
[30] C. S. Zhou, J. Kurths, and B. Hu, Phys. Rev. E **67**, 030101 (2003).
[31] M. Löcher, G. A. Johnson, and E. R. Hunt, Phys. Rev. Lett. **77**, 4698 (1996).
[32] Y. J. Jiang and H. W. Xin, Phys. Rev. E **62**, 1846 (2000).
[33] K. Yoshikawa and Y. Matsubara, J. Am. Chem. Soc. **105**, 5967 (1983).
[34] K. Yoshikawa and Y. Matsubara, J. Am. Chem. Soc. **106**, 4423 (1984).
[35] K. Yoshikawa and M. Makino, Chem. Phys. Lett. **25**, 623 (1989).
[36] R. Larter, Chem. Rev. Lett. **90**, 355 (1990).
[37] X. B. Zuo, Z. H. Hou, and H. W. Xin, J. Chem. Phys. **109**, 6063 (1998).
[38] L. Gammaitoni, M. Löcher, A. R. Bulsara, P. Hänggi, J. Neff, K. Wiesenfeld, W. Ditto, and M. E. Inchiosa, Phys. Rev. Lett. **82**, 4574 (1999).
[39] M. Löcher, M. E. Inchiosa, J. Neff, A. Bulsara, K. Wiesenfeld, L. Gammaitoni, P. Hänggi, and W. Ditto, Phys. Rev. E **62**, 317 (2000).
[40] J. J. Collins, Carson C. Chow, and Thomas T. Imhoff, Nature (London) **376**, 236 (1995).