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Elimination of spiral waves and spatiotemporal chaos by the pulse with a specific spatiotemporal configuration*

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Spiral waves and spatiotemporal chaos are sometimes harmful and should be controlled. In this paper spiral waves and spatiotemporal chaos are successfully eliminated by the pulse with a very specific spatiotemporal configuration. The excited position D of spiral waves or spatiotemporal chaos is first recorded at an arbitrary time (t_0). When the system at the domain D enters a recovering state, the external pulse is injected into the domain. If the intensity and the working time of the pulse are appropriate, spiral waves and spatiotemporal chaos can finally be eliminated because counter-directional waves can be generated by the pulse. There are two advantages in the method. One is that the tip can be quickly eliminated together with the body of spiral wave, and the other is that the injected pulse may be weak and the duration can be very short so that the original system is nearly not affected, which is important for practical applications.

Keywords: spiral wave, spatiotemporal chaos, elimination
PACC: 8220M, 0547, 0565

1. Introduction

Spiral wave exists popularly in excitable and self-oscillating media,[1−4] such as cardiac muscle, the oxidation of CO on platinum, and reacting chemical systems, for example, the Belousov–Zhabotinsky (BZ) reaction. Spiral waves are a kind of beautiful patterns in nature, but sometimes they are undesirable because of their harmfulness and can lead to unpredictable results. For example, spiral waves in cardiac muscle can be a cause of tachycardia. Repetitive breakup of spiral waves can lead to spatiotemporal chaos, which is believed to be a mechanism of ventricular fibrillation (VF). VF and sudden cardiac death are the leading cause of cardiovascular mortality in industrialized countries.[5,6] The effective therapies of VF are massive electrical shocks (about 600 V), which are extremely painful and may create scars promoting future episodes of VF. Controlling and eliminating the fast spatiotemporal chaos of VF through low-amplitude signals need developing, which is also important for many other systems, for example, biology and physics. These are several methods which are presently used to control and eliminate spiral waves and spatiotemporal chaos.[7−15] For example, Sakguchi and Fujimoto [7] suggested a method of eliminating spiral waves by periodic force for the Aliev–Panfilov model. In Ref.[8], the authors used weak spatial perturbations to eliminate spatiotemporal chaos and spiral waves. Suppressing arrhythmias in cardiac ionic models by overdrive pacing was reported in Ref.[13]. Controlling spiral waves and spatiotemporal chaos by a sine wave is shown in Ref.[14]. In Ref.[15], spiral waves and spatiotemporal chaos may be controlled and suppressed by the travelling waves excited by a local perturbation. In this paper, we propose a perturbation scheme to eliminate spiral waves and spatiotemporal chaos. The strategy is as follows: We first record the excited position D of spiral waves or spatiotemporal chaos at an arbitrary time (t_0), then wait for the system at the domain D to enter a recovering state. When the time comes, the pulse is injected into D. Spiral waves and spatiotemporal chaos can be successfully eliminated by the pulse with an appropriate intensive parameter and duration. There are two advantages in the method. Firstly, in some external force methods,

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the core of a spiral wave is usually forced to move toward the boundary and disappears there, while in our scheme, the tip can be quickly eliminated together with the body of spiral wave. Secondly, the pulse perturbation may be very weak and the duration can be very short, so the original systems can be little affected and harmful.

2. The Model

First, we consider the FitzHugh–Nagumo (FHN) model (FitzHugh, 1961).[16,17] The model is generic for excitable systems, and it is applicable to a variety of systems and able to reproduce many qualitative characteristics of electrical impulses along nerve and cardiac fibres, such as the existence of an excitation threshold, relative and absolute refractory periods, and the generation of pulse trains under the action of external currents. The FHN model has been widely used because of its simple two-variable form and generality. The model with a perturbation term is described by the following equations:

$$\frac{\partial u}{\partial t} = \frac{1}{\varepsilon} f(u,v) + \nabla^2 u + \frac{F_{\text{perturb}}}{\varepsilon}, \tag{1}$$

$$\frac{\partial v}{\partial t} = g(u,v), \tag{2}$$

where $f(u,v) = -v - u(u-a)(u-1)$; $g(u,v) = -\gamma v + \beta u - \delta$; u and v describe respectively the membrane voltage (fast variable) and the v-gate (slow variable) in this model; a represents the threshold for excitation; ε represents the excitability; β, γ and δ are parameters that can change the rest state and the dynamics; F_{perturb} is the perturbation pulse. By truncating a travelling wave, a spiral wave can be formed in the absence of the perturbation.

We also consider an activator controller two-variable reaction–diffusion model for the catalytic CO oxidation on Pt(110).[18] Its equation with a perturbation term is as follows:

$$\frac{\partial u}{\partial t} = -\frac{1}{\varepsilon} u(u-1)\left(u - \frac{v+b}{a}\right) + \nabla^2 u + \frac{F_{\text{perturb}}}{\varepsilon}, \tag{3}$$

$$\frac{\partial v}{\partial t} = f(u) - v, \tag{4}$$

where u and v describe the activator (fast) and the inhibitor (slow) variables respectively. For the standard Barkley model, $f(u)$ is taken to be in the continuous form, i.e. $f(u) = u$. If $f(u)$ is discrete, the Bär model can be obtained. In the Bär model, when $0 \le u < \frac{1}{3}$, then $f(u) = 0$; when $\frac{1}{3} \le u \le 1$, then $f(u) = 1 - 6.75u(u-1)^2$; and when $u > 1$ then $f(u) = 1$. In the present paper we take $a = 0.84$ and $b = 0.07$. In the absence of the perturbation, spiral waves can be formed in the standard Barkley model. For the Bär model, spatiotemporal dynamics can be observed by varying the value of ε. In a range of $0.01 < \varepsilon < 0.06$, suitable initial conditions lead to steadily rotational spiral waves. At $\varepsilon = 0.06$, the spiral wave undergoes a transition from steadily rotational to meandering. When $\varepsilon > 0.07$, the spiral wave will break up and the system will quickly fall into a turbulent state. F_{perturb} is the perturbation pulse.

3. Eliminating spiral waves by perturbation pulse

For a travelling or spiral wave, the perturbation stimulation after excited states can cause three possible wave patterns: bidirectional, unidirectional, and decaying (blocked) propagations.[19] The region of blocked propagation is usually called the 'absolute refractory window'. The one of unidirectional propagations, where a pulse responsive to a local disturbance propagates in one direction and is blocked in the other direction, is usually called the 'vulnerable window (VW)'. On the other hand, the excited states will disappear when two wave fonts encounter with each other, because the activator u will jump down from an excited value with the value of the inhibitor v increasing abruptly when one wave front arrives at the recovery regime of the other front. By the above discussion, a method of eliminating the spiral waves and spatiotemporal chaos is offered. The detailed scheme is as follows: At an arbitrary time (t_0), the excited position D of a spiral wave is recorded. When the system at the recorded domain D, of which the shape is spiral, enters a recovering state after t_0, a perturbation pulse is injected into the domain D from t_1 to t_2 (namely, $t_1 < t < t_2$). F_{perturb} can be described as follows:

$$F_{\text{perturb}} = \begin{cases} F_0, & t_1 < t < t_2 \ \text{ and in } \ D, \\ 0, & \text{other.} \end{cases} \tag{5}$$

F_0 is a constant number. F_{perturb} can be defined as a spiral-type perturbation pulse because the shape of the domain D is spiral. With the development of experimental technology, the scheme is operable. Spiral

waves can be quickly eliminated for appropriate values of t_1, t_2 and F_0.

Firstly, the FHN model with no-flux boundary is numerically investigated by the split-operator algorithm, with the corresponding parameters being $a = 0.03$, $\gamma = 1.0$, $\beta = 2.0$, $\delta = 0$, and $\varepsilon = 0.005$. With these parameters, the time step and the grid spacing are respectively equal to 0.0025 and 0.1, and the number of space grids is 200×200. A spiral wave can be generated by truncating a travelling wave. Here an excited period is about 139 time units (1 time unit is equal to 1 time step), where 36 time units correspond to the excited states, and 103 time units are occupied by the recovery states. We take arbitrarily $t_0 = 50$ time units, and record the excited position D (where the excited state is judged by $u > 0.5$) of spiral wave. It is easily known that the system in the spiral-type domain D enters the recovering state from 86 to 189 time units within the first excited period after t_0. Here t_1 and t_2 can be selected according to the VW, and the perturbation pulse F_0 is injected into the spiral-type domain D from t_1 to t_2 ($t_1 < t < t_2$). It can be observed that a counter-directional spiral wave can be generated by a spiral-type perturbation pulse and will meet with the original spiral wave, and at last excited states completely disappear. Figure 1 shows a representative eliminating progress of spiral waves by a spiral-type perturbation pulse with $F_0 = 0.192$ and a duration of only 1 time unit, namely the perturbation is injected only at $t = 128$ time units. It is easily

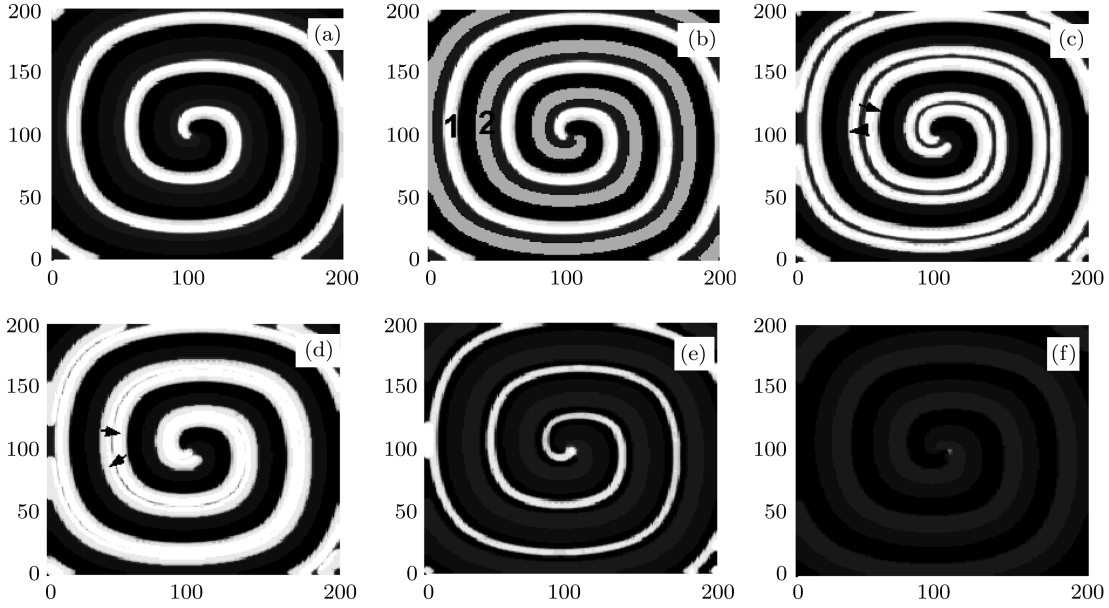


Fig.1. The elimination of the spiral wave in the FHN system, with $t_1 = 127$ time units, $t_2 = 129$ time units, and $F_0 = 0.192$. (a) $t = 127$ time units, the spiral wave before the perturbation is injected. (b) the spiral wave at $t = 127$ time units is marked by '1', and the recorded spiral-type domain D at $t_0 = 50$ time units is described by '2'. The perturbation is injected at 128 time units. (c) $t = 139$ time units, an anti-spiral wave is excited at the recovery position of the original spiral wave by the perturbation. (d) $t = 146$ time units, the original spiral wave begins to meet with the anti-spiral wave. (e) $t = 169$ time units, the excited states start to diminish gradually. (f) $t = 193$ time units, the spiral wave is completely eliminated.

found that a counter-directional spiral wave, which propagates toward the core, appears at the spatial position of being in the recovery states, and soon will encounter with the original spiral wave. On the basis of the characters of excited waves, as a result of the encounter, the excited states will disappear. In the progress, the tip of spiral wave can be quickly eliminated at its original position and together with the body, so the elimination can be achieved only within 66 time units after the perturbation has been injected, which is less than an excited period. It is also very important for practical applications. Figures 2(a) and 2(b) give the optional ranges of F_0 and t_1 under different injection durations of the perturbation, in which spiral waves can be successfully eliminated. For the amplitude F_0 at which the spiral waves can be cleared up, a minimum value ($F_{0\,\min}$) can be observed. Figure 2(c) shows the selectable values of t_1 and t_2 for eliminating spiral waves when $F_0 = 0.064$. In order to make a success of elimination, t_2 should be taken from

the vulnerable window, while t_1 from the vulnerable or absolute refractory window. Figure 2(d) shows the relation between $F_{0\,\min}$ and $t_2 - t_1$, which can be accurately fitted to the second order exponential decay.

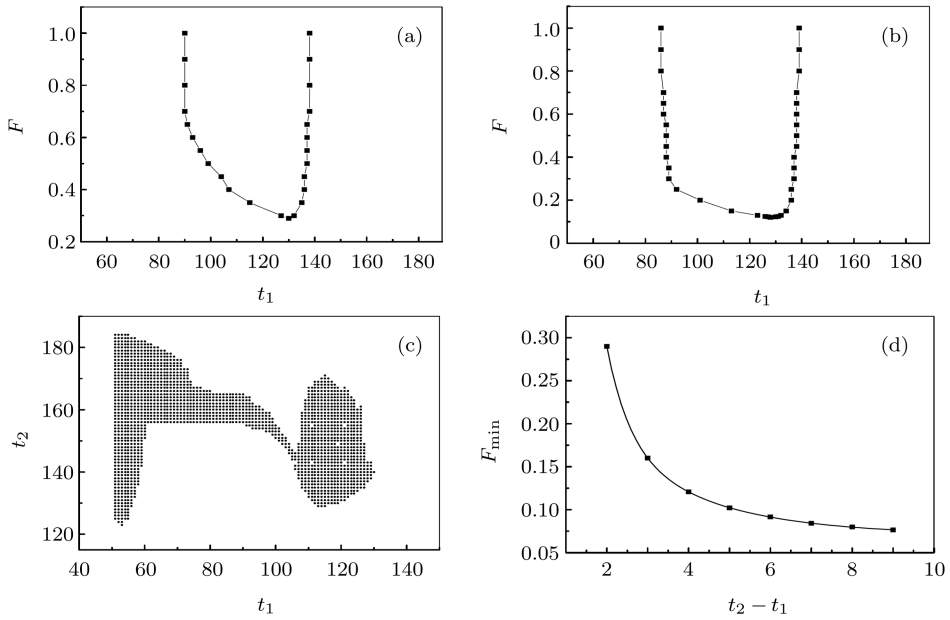


Fig.2. The optional ranges of F_0 and t_1 to eliminate spiral waves under the different injected durations of the perturbation. (a) $t_1 < t < t_1 + 2$, namely the perturbation is injected into the spiral-type recorded domain D only at $t_1 + 1$. Here, the minimum value of F_0 to remove completely spiral waves, $F_{0\min}$, is 0.232, and the corresponding value of t_1 is equal to 130 unit times. (b) $t_1 < t < t_1 + 4$, here, the minimum value of F_0 to remove completely spiral waves, $F_{0\,\min}$, is 0.0966, and the corresponding value of t_1 is equal to 128 unit times. In (a) and (b), F_0 and t_1 are taken from the domain enclosed by the curves and on the curves, so that spiral waves can be eliminated. (c) the selectable domains of t_1 and t_2 (shown by black dots) in which the spiral waves are completely eliminated when $F_0 = 0.064$. (d) the durations of the perturbation $t_2 - t_2$ vs the optional minimum amplitude $F_{0\,\min}$, the numerical results are depicted by the dots, and the fitting to the second order exponential decay is described by the line. The fitting function $F_{0\,\min} = (0.24053\mathrm{e}^{-\frac{t_2-t_1}{2.45696}} + 4.11292\mathrm{e}^{-\frac{t_2-t_1}{0.55653}} + 0.07033) \times 0.8$, where the relation between F_0 and F (used in the Figures) is given by $F_0 = 0.8 \times F$.

It is easily seen that the relation should follow the exponential decay, which shows that $F_{0\,\min}$ may be very small if the standing duration of the perturbation is very long. It is important for practical applications that spiral waves are eliminated by a weak perturbation pulse. We also notice that the scheme can be in effect within an arbitrary excitation period after t_0. The null lines of $f(u, v)$ and $g(u, v)$, phase trajectories of u and v (from 51 to 191 time units) and intersectional positions of the null lines for the different values of F_0 are pictured in Fig.3. The times corresponding, respectively, to 53, 90, 130, 138 time units are marked

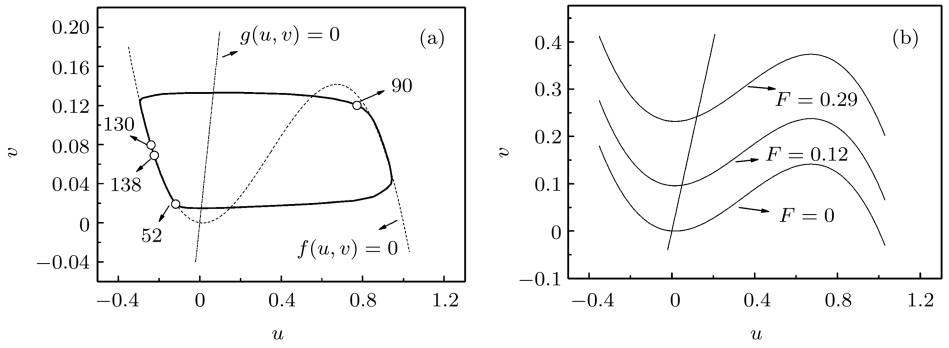


Fig.3. The null lines of the functions $f(u, v)$ and $g(u, v)$ and the phase orbits of u and v panel. (a) is for the null lines of $f(u, v)$ and $g(u, v)$ and the phase chart between 51 and 191 time units when $F = 0$, and panel (b) is for the null lines under different values of F_0. Here the relation between F_0 and F (used in the Figures) is given by $F_0 = 0.8 \times F$.

in Fig.3(a). It is easily observed that the null u-lines will move an increment of F_0 up. Figure 4 shows how the wave is excited by a perturbation pulse. If the pulse is injected in the controllable time range (shown in Figs.4(a) and 4(b)), D can be excited, otherwise it is not excited.

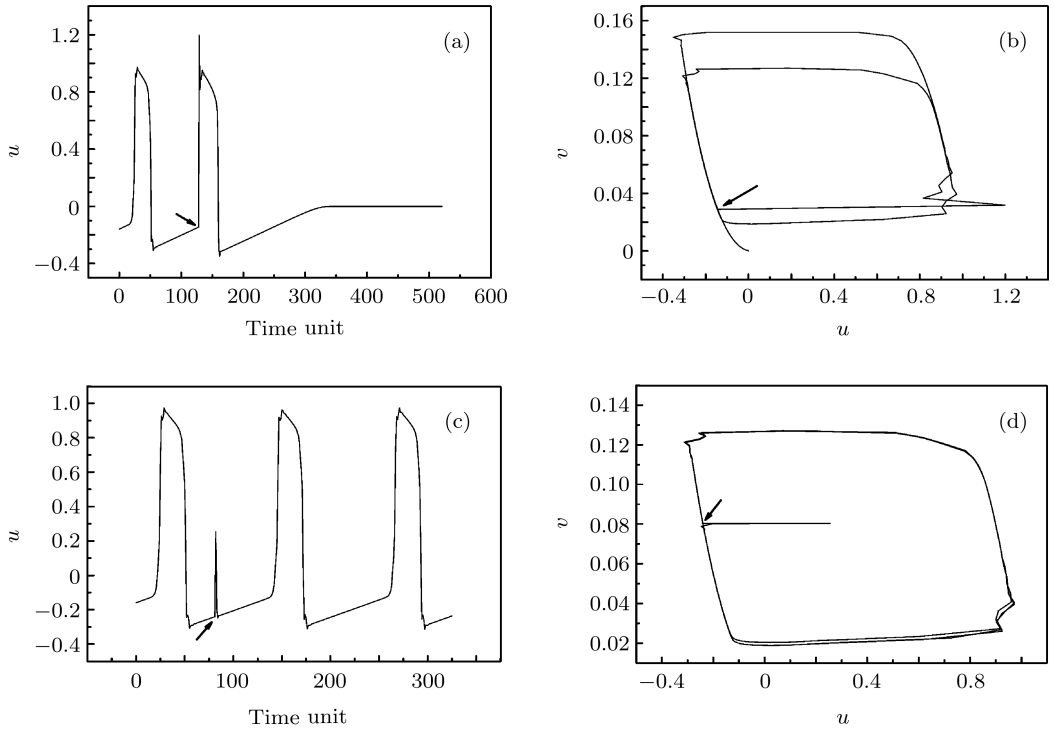


Fig.4. The plots of u vs time and u vs v at a certain point for the different times when the pulses with a very specific spatiotemporal configuration are injected into the system. In panels (a) and (b) the pulse is injected to a certain point in the 'bidirectional window' or the part of 'vulnerable window', and the point can be excited. In panels (c) and (d) the pulse is injected to a certain point in the 'absolute refractory window', and the point cannot be excited. The pulse lasts 1 time unit, and it is injected at the time marked by the arrows.

In order to prove the universality of the scheme, the Barkley model is also considered. In the numerical simulation, the number of space grids is 202×202, and no-flux boundary is used. The semi-implicit form for local dynamics and the five-point finite-difference Laplacian formula for the diffusion are adopted. The spiral-type domain D is recorded at $t_0 = 60$ time units and the perturbation F_0 is injected when $t = 81$ time units. Figure 5 exhibits the progress of eliminating spiral waves with $F_0 = 0.3$. Spiral waves can be completely cleared up within 59 time units.

Here we offer also a simple experimental design for eliminating spiral waves by the scheme. The experiment should be carried out in the light-sensitive Belousov–Zhabotinsky (BZ) reaction which is extensively studied due to the easiness of many operations, such as the effect of spatiotemporal structured noise[20] and the local coupling of the bilayer.[21] The experimental details can be obtained from Refs.[20–22]. In many light-sensitive BZ reactions, the external spatiotemporal noise and perturbation are usually introduced by the light, which is projected through a transparency imprinted with a pattern. Considering the above argument, the pattern of the transparency should be imprinted according to the recorded spiral pattern by a video camera at t_0 (The corresponding technology can be found in Ref.[21]). For a controllable time and duration, the light is injected into the Petri disc through the transparency with the spiral pattern, and a counter-directional wave should be excited by adjusting the intensity of the light. The two variable Oregonator model is usually adapted to the light-sensitive media. Our scheme is successful for the Oregonator model as shown in Fig.6.

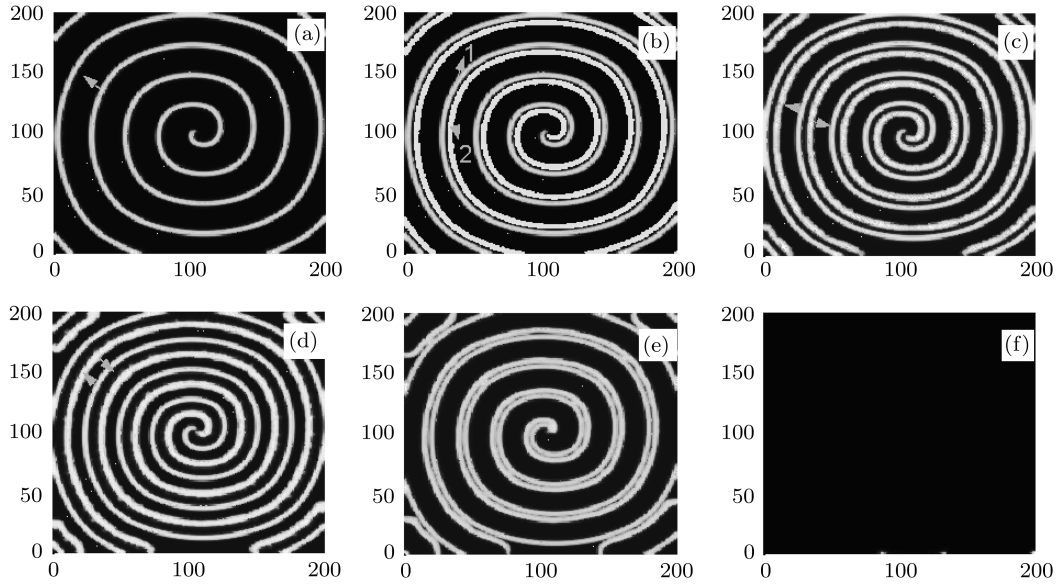


Fig.5. The elimination of spiral waves in the standard Barkley model by a spiral-type perturbation pulse, with $F_0 = 0.3$. (a) $t = 80$ time units, a spiral wave before the perturbation is introduced. (b) The spiral wave at $t = 80$ time units is marked by '1', and the recorded spiral-type domain D at $t = 60$ time units is described by '2'. The perturbation is injected at 81 time units. (c) $t = 86$ time units, an anti-spiral wave is generated. (d) $t = 92$ time units, the anti-spiral wave begins to meet with the original spiral wave. (e) $t = 104$ time units, the excited domain is gradually diminishing. (f) $t = 140$ time units, the spiral wave is completely eliminated.

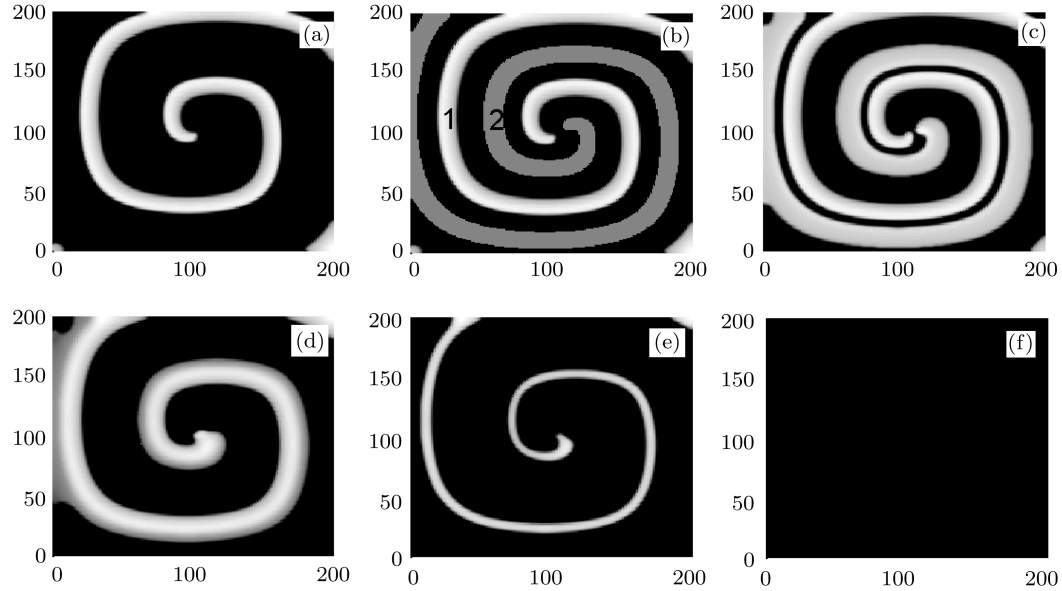


Fig.6. The elimination of the spiral wave in the two-variable Oregonator model[20] which describes the light-sensitive Belousov–Zhabotinsky reaction, with the corresponding parameters being $f = 1$, $\phi = 0.035$, $q = 0.0015$, $\varepsilon = 0.003$, $D_u = 1$, $D_v = 0$, $t_1 = 1900$ time units (one time unit is equal to 0.0003), $t_2 = 1920$ time units, and $t_0 = 50$ time units when the injected configuration is recorded. (a) $t = 1900$ time units, the spiral wave before the perturbation is injected. (b) The spiral wave at $t = 1900$ time units is marked by '1', and the recorded spiral-type domain D at $t_0 = 50$ time units is described by '2'. The perturbation is injected at 1901 time units. (c) $t = 2200$ time units, a counter-spiral wave is excited at the recovery positions of the original spiral wave by the pulse. (d) $t = 2582$ time units, the original spiral wave begins to meet with the anti-spiral wave and the excited states start to diminish gradually. (e) $t = 2903$ time units. $t = 3250$ time units, the spiral wave is completely eliminated.

4. Eliminating spatiotemporal chaos by perturbation pulse

Repetitive breakup of spiral wave can lead to spatiotemporal chaos, which can be believed to be composed of many undeveloped spiral waves. It is possible to eliminate spatiotemporal chaos by the above scheme. The Bär model is selected, and let $\varepsilon = 0.08$, spontaneous breakup of spiral wave into spatiotemporal chaos can happen at this parameter. The number of space grids is 202×202, and no-flux boundary is used. The semi-implicit form for local dynamics and the five-point finite-difference Laplacian formula for the diffusion are adopted. Excited domain D of spatiotemporal chaos at $t_0 = 60$ time units is recorded, then perturbation pulse is injected into the domain D with appropriate values of F_0, t_1 and t_2. Here the excited states are judged by $u > 0.5$. Figure 7 shows the progress of eliminating spatiotemporal chaos when $F_0 = 0.5$, $t_1 = 71$ time units, and $t_2 = 74$ time units. It is easily observed that counter-directional waves can

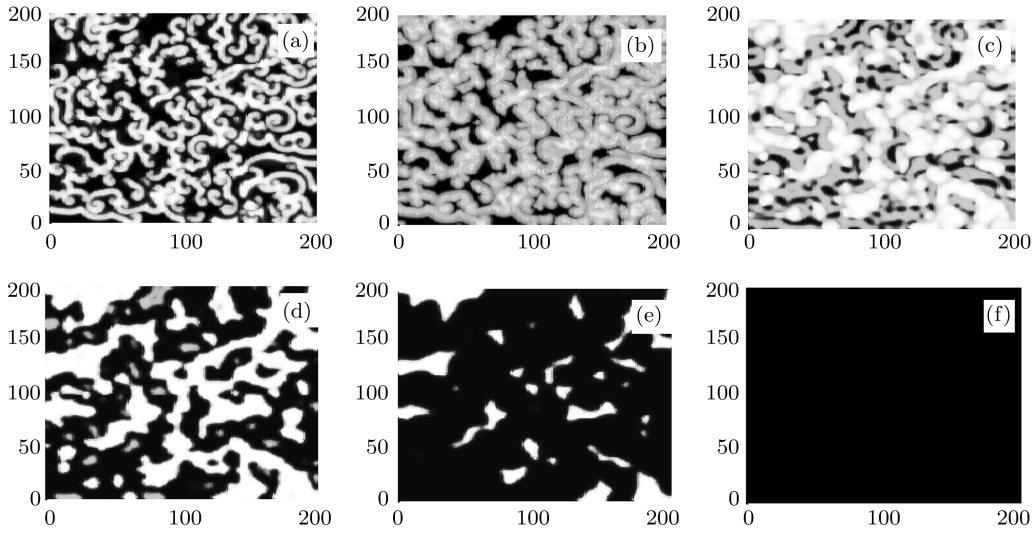


Fig.7. The elimination of spatiotemporal chaos in the Bär model by the pulse perturbation method, where t_1 =71 time units, $t_2 = 74$ time units, and $F_0 = 0.5$. (a) The spatiotemporal chaos before the perturbation is introduced. (b) The pulse perturbation has been injected. (c) 21 time units after the pulse perturbation, counter-directional waves appear. (d) 31 time units after the pulse perturbation, counter-directional waves begin to encounter with the original wave. (e) 51 time units after the pulse perturbation, the excited waves are gradually disappearing. (f) 121 time units after the pulse perturbation, the spatiotemporal chaos is completely eliminated.

be excited by the perturbation, and soon will meet with the original wave. Intersectional positions of the excited and unexcited states in Fig.7(c) are all in the wave back, so the excited domain will gradually diminish and finally disappear. The selectable values of t_1 and t_2 used to clear up spatiotemporal chaos are not consecutive due to different developments of many undeveloped spiral waves in spatiotemporal chaos, which is different from the case of eliminating spiral waves. The appropriate values of t_1 and t_2 in a range from 60 to 80 time units, in which the spatiotemporal chaos are eliminated, are presented in Fig.8 when $F_0 = 0.5$. It can be seen that $t_1 < 77$ time units is needed to eliminate the spatiotemporal chaos when $F_0 = 0.5$. Generally, the numbers of the optional values of t_1 and t_2 will diminish with the value of F_0 lessening.

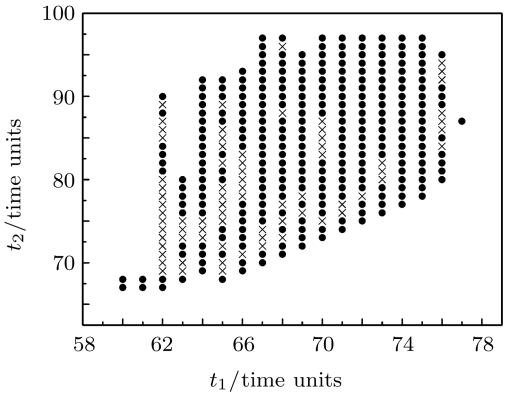


Fig.8. The optional values of t_1 and t_2 in which the spatiotemporal chaos is eliminated between 60 and 80 time units when $F_0 = 0.5$. Solid circle dots correspond to the values of t_1 and t_2 in which the spatiotemporal chaos is eliminated. Fork dots represent the time values that cannot be used to eliminate spatiotemporal chaos.

For some values of t_1 and t_2, spatiotemporal chaos cannot be completely eliminated via a perturbation pulse, but a majority of spiral tips can be cleared up and only a few tips are retained. Before the residual tips develop into spatiotemporal chaos, if excited domain D' is recorded and another perturbation pulse is injected into D', the spatiotemporal chaos can be completely eliminated. Sometimes, more tips are retained after the first perturbation, and there are still a few residual tips via the second perturbation, then more than two pulses are needed. Figure 9 shows the progress of eliminating the spatiotemporal chaos by two perturbation pulses when $F_0 = 0.5$. With the value of F_0 lessening, the success of a perturbation pulse can become impossible for a weak perturbation, but two or more perturbation pulses may be successful for small values of F_0. Figure 10 give the progress of eliminating the spatiotemporal chaos by two perturbation pulses for a lower perturbation amplitude (F_0) of 0.1875. For a longer duration of $t_2 - t_1$, the perturbation may be weaker. Figure 11 shows the eliminating process with F_0 being 0.06.

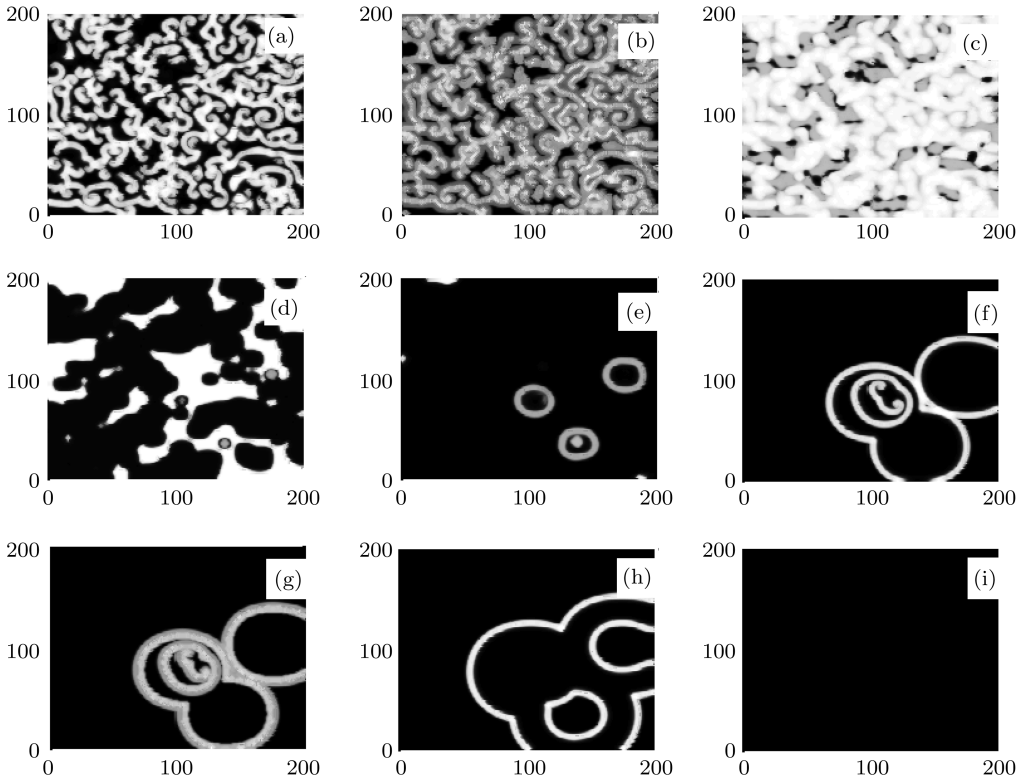
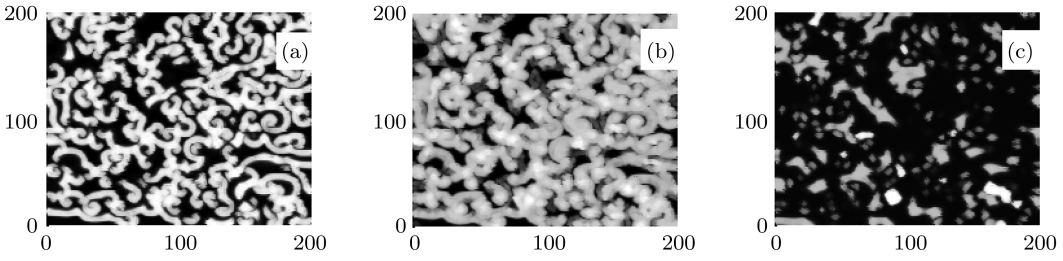


Fig.9. The elimination of spatiotemporal chaos in the Bär model by two perturbation pulses, with $F_0 = 0.5$. The first excited domain D is recorded at $t_0 = 60$ time units, and the first pulse perturbation is injected into the domain D between $t_1 = 71$ and $t_2 = 76$ time units. The second excited domain D' is recorded at $t'_0 = 273$ time units, and the second pulse perturbation is injected into the domain D' between $t'_1 = 285$ and $t'_2 = 288$ time units. (a) $t =$ 71 time units, the spatiotemporal chaos before the perturbation is introduced. (b) $t = 75$ time units, the first pulse perturbation is injected into the domain D, counter-directional waves start to be formed. (c) $t = 97$ time units after the first pulse perturbation. (d) $t = 137$ time units, the counter-directional waves encounter with the original wave. (e) 197 time units. (f) $t = 285$ time units, a majority of the tips are removed, but a few of the tips are retained. (g) $t = 288$ time units, the second pulse perturbations are injected into the domain D'. (h) $t = 330$ time units, the tips are entirely removed. (i) $t = 730$ time units, the spatiotemporal chaos is completely eliminated.



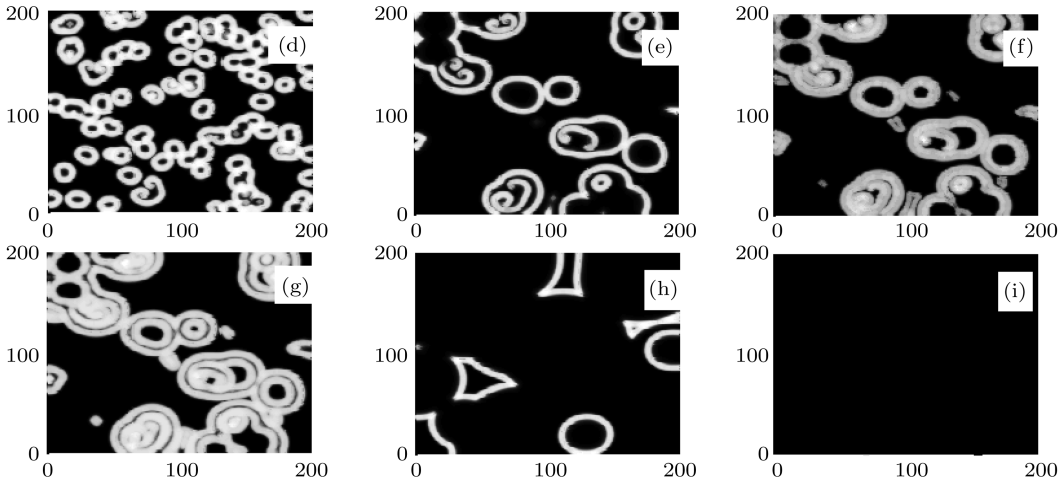


Fig.10. The elimination of spatiotemporal chaos in the Bär model by two perturbation pulses with F_0 having a smaller values (0.1875). The first excited domain D is recorded at $t_0 = 60$ time units, and the first pulse perturbation is injected into the domain D from $t_1 = 71$ to $t_2 = 74$ time units. The second excited domain D' is recorded at $t'_0 = 200$ time units, and the second pulse perturbation is injected into the domain D' from $t'_1 = 212$ to $t'_2 = 216$ time units. (a) $t = 71$ time units, the spatiotemporal chaos before the perturbation is introduced. (b) $t = 75$ time units, the first pulse perturbation is injected into the domain D, counter-directional waves start to be formed. (c) $t = 100$ time units. (d) $t = 133$ time units. (e) $t = 212$ time units, a majority of the tips are removed, but a few of the tips are retained. (f) $t = 216$ time units, the second pulse perturbation is injected into the domain D'. (g) $t = 226$ time units. (h) $t = 316$ time units, the tips are entirely removed. (i) $t = 1039$ time units, the spatiotemporal chaos is completely eliminated.

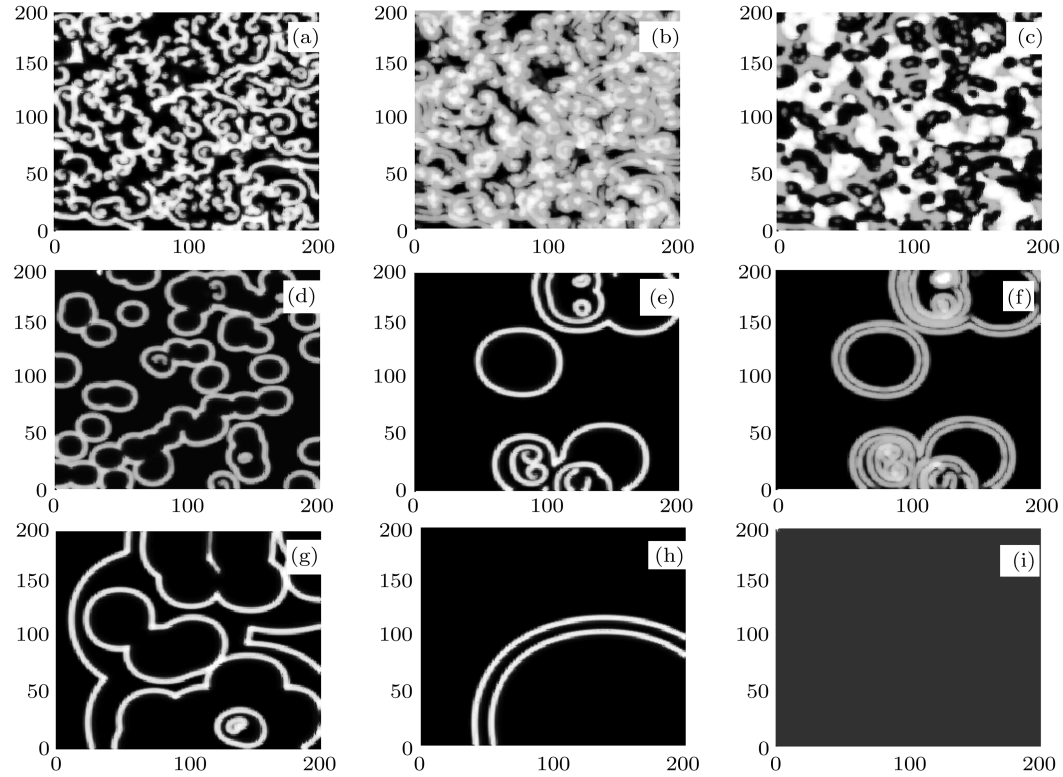


Fig.11. The elimination of spatiotemporal chaos in the Bär model by two perturbation pulses with F_0 having a smaller value (0.06) and with a longer pulse duration. The first excited domain D is recorded at $t_0 = 60$ time units, and the first pulse perturbation is injected into the domain D from $t_1 = 66$ to $t_2 = 80$ time units. The second excited domain D' is recorded at $t'_0 = 260$ time units, and the second pulse perturbation is injected into the domain D' from $t'_1 = 267$ to $t'_2 = 281$ time units. (a) $t = 66$ time units, the spatiotemporal chaos before the perturbation is introduced. (b) $t = 80$ time units, the first pulse perturbation is injected into the domain D, counter-directional waves start to be formed. (c) $t = 99$ time units. (d) $t = 122$ time units. (e) $t = 267$ time units, a majority of the tips are removed, but a few of the tips are retained. (f) $t = 281$ time units, the second pulse perturbation is injected into the domain D'. (g) $t = 404$ time units. (h) $t = 706$ time units, the tips are entirely removed. (i) $t = 1226$ time units, the spatiotemporal chaos is completely eliminated.

5. Conclusion and discussion

Spiral wave and spatiotemporal chaos after spontaneous breakup are harmful to many real systems, so it is very important to know how to eliminate them. In order not to destroy the original system, weak signals and quickly eliminating progress are needed. This paper offers a scheme of eliminating the spiral waves and spatiotemporal chaos by the perturbation pulse. In this scheme, the tips can be simultaneously cleared up with the body of spiral waves, which is difficult to implement in some external force methods, so the elimination of spiral waves and spatiotemporal chaos are generally very speedy. Moreover, the needed perturbation pulse may also be very weak. These are all important for practical applications.

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