The Excitability by Both Electric and Concentrative Perturbation in CSTR

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Excitability is one of the basic and fundamental mechanisms utilized for signal transmission in living organisms. With reference to the condition by Marek and the condition by Schneider, we found a condition in which excitability with similar shapes can appear by chemical and electric perturbation. Our condition is constructed with 3 chemical channels and 1 electric channel, and can be used as a condition for a chemical spiking neuron and as a unit of a chemical spiking neural network.

Key Words : Chemical excitability, Chemical spiking neural network

Introduction

Excitability is one of the basic and fundamental mechanisms utilized for signal transmission in living organisms because it allows then to react adequately to external stimuli. Examples include biochemistry of sensory perception, neural and muscular activity, metabolic regulation, etc. In addition, excitabilities occur in chemical, biochemical, and physical systems under special conditions.[1] An excitability is an ability to amplify a superthreshold pulse. When a steady-state system is subject to a small-size perturbation, it may decrease. However, when it is larger than a threshold, it can be significantly amplified. This action allows the system to distinguish noise and to respond to the signal.[1-3]

The Belouzsov-Zhabotinskii (BZ) reaction is now the most thoroughly studied oscillating and excitable chemical system.[1-3] The mechanism of the BZ reaction including about 20 chemical species was proposed by Field, Koros, and Noyes in 1972,[4] and is now generally accepted. The simple model Oregonator which has only three species[5] and another version with seven species[6] were developed later. These models were shown to reproduce qualitatively the bistability, excitability, and oscillations observed in experiments with the BZ reaction. Bar-Eli and Noyes[7] have further simplified the Oregonator to a two-variable system and studied its dynamical properties including excitability. Ruoff and Noyes[8] presented a four-variable model which expands the basic properties of the Oregonator. Thus, having well–established the kinetics of the BZ reaction, observations obtained in different experimental configurations can be compared with the results of theoretical considerations or simulation studies.[1,2,9] Marek performed a series of experiment and also compared the experimental results with simulations of the Oregonator.[9,10] This condition was known broad excitability range, and thus the excitability can be found by us.

The subject of the present work is excitability of a chemical system that is able to perform logic functions, to learn and to recognize dynamical patterns, or to perform artificial neural network activities. Chemical learning and recognition devices, or artificial neurons, can be composed of chemical systems (such as a continuous-flow stirred tank reactor (CSTR) or a batch reactor). In previous studies we described theoretically that an excitable chemical system can be an artificial neuron, which can be combined to form an artificial neural network.[11] All reactors were run in excitable states of BZ reaction. When each reactor is coupled with any of the other reactors, the network is structurally similar to an electric neural network and a mathematical neural network. It is a chemical spiking neuron network (CSNN) on the basis of the formulation of a spiking neural network (SNN)[12-14] that was introduced by Maass. The SNN is composed of spiking neurons based on the temporal coding of analog information by using the timing of an action potential. The information processing in the SNN can be described briefly as follows: First, analog information is encoded by using the firing time of action potentials; that is, presynaptic neurons produce action potentials with a time advance in proportion to the size of input variables. Then a postsynaptic neuron receives the weighted sum of the post synaptic potentials (PSPs) and fires as soon as the sum of the PSPs crosses over the threshold of the postsynaptic neuron. Because information is represented and processed by using the time differences between spikes, a SNN has important advantages over classical neural networks, based on the firing-rate encoding and computing, in its computing power and biological reality.[11] In classical neural networks, the velocity of signal transmittance is later than that of biological system.

In this work we find a condition to be a neuron of CSNN. In this condition, CSTR is excited by an electric or chemical perturbation. The condition by Marek[9,10] was firstly used in this work. It shows the excitability by Ag^+ perturbation and is encountered by numerical simulations with the Oregonator-based model of the BZ reaction. Though the experiment utilizes in various flow rate and electric current conditions, an excitability by electric perturbation could not be found. As a replacement, the condition suggested by Schneider[15,16] is adopted as an experimental condition for an excitable chemical system in a CSTR. In the condition by Schneider, the bifurcation point, or so-called SNIPER (saddle node infinite period bifurcation) point, is the crossing point between the stable state, unstable state, and oscillation state.

The condition can show stability or oscillation, depending on electric current. Because the excitability region is near the bifurcation point between the stable state and oscillation state, we attempted to find a condition in which the CSTR is excited by electric or chemical perturbation. That is, a condition where both chemical and electric perturbation methods result in chemical excitabilities of similar shapes.

Experimental Section

First, the well-known condition to show excitability by chemical perturbation was experimented. In the condition by Marek, three reactant feed streams into the CSTR of 7 mL volume are delivered by peristaltic pumps at the same rate via three channels, where channel I delivers 0.006 M $Ce(SO_4)_2 \cdot 4H_2O$, 0.41 M H_2SO_4, and 0.1 M malonic acid; channel II, 0.3 M $NaBrO_3$; and channel III, 0.01 M NaBr. The outflow is pumped off at the top of the CSTR. A teflon-coated magnetic stirrer operates at 700 rpm. The redox potentials in CSTR are measured by a Pt/Ag/AgCl redox electrode, and digitally monitored at 100 Hz and averaged over 1 second. The excitability by chemical perturbation is observed. However, the excitability by an electrical perturbation is not shown though various flow rates and electrical perturbation methods are experimented.

We found a condition in which there is a possibility for excitability by electric perturbation. In the condition by Schneider, channel I delivers 0.42 M $NaBrO_3$; channel II, 0.0015 M $Ce_2(SO_4)_3$ and 0.9 M malonic acid; and channel III, 1.125 M H_2SO_4. The flow rate is fixed at 0.1 mL/min with stirring at 700 rpm. Owing to variations in the sensitivities of the redox electrodes, the normalized redox potentials are presented in arbitrary units. The electric current is controlled by output board (National Instruments) (Figure 1).

When currents higher than 1.3 mA are applied to the Pt working electrode, the BZ oscillations change into a stable steady state. Generally, the excitability region is in the stable state near the bifurcation point. Therefore, this region was scanned. When the current is dropped to a small amount negatively from basic currents of 1.4 mA, excitability is observed. When basic currents of 1.4 mA are applied and the 0.1 M Ag^+ ion is injected by a syringe, the excitability of similar shape is also observed.

To ensure the possibility of coupling, a sawtooth-shaped perturbation is used because it is similar to the spike of excitability of precoupling CSTR. In the same condition (reactants and basic current), the possibility of excitability by electric perturbation of sawtooth shape was tested.

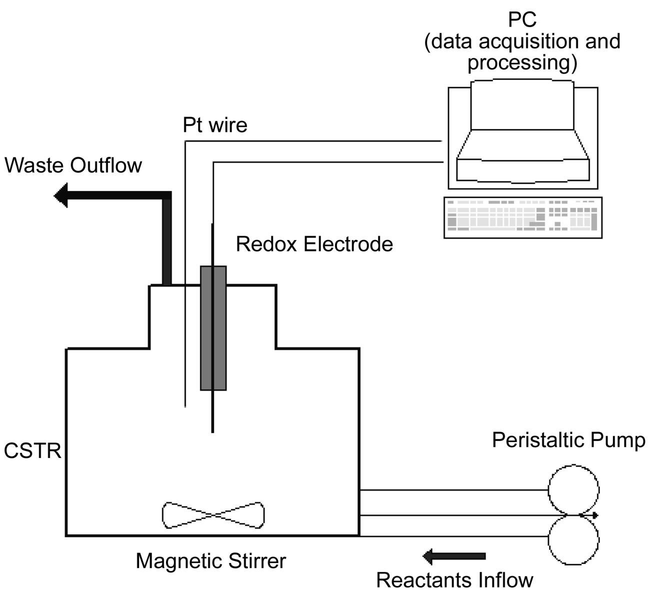

Figure 1. Schema of CSTR.

Results

When low currents (0.2 mA) are applied to the Pt working electrode, the CSTR shows an oscillation state (Fig. 2). Figure 3 shows that when currents from 0.1 mA to 1.3 mA are applied to the Pt working electrode, the period of the BZ oscillations becomes longer. The vertical axis is redox potential (arbitrary unit) and the horizontal axis is time(s). When high currents (1.3 mA) are applied to the Pt working electrode, CSTR shows a stable state (Fig. 4).

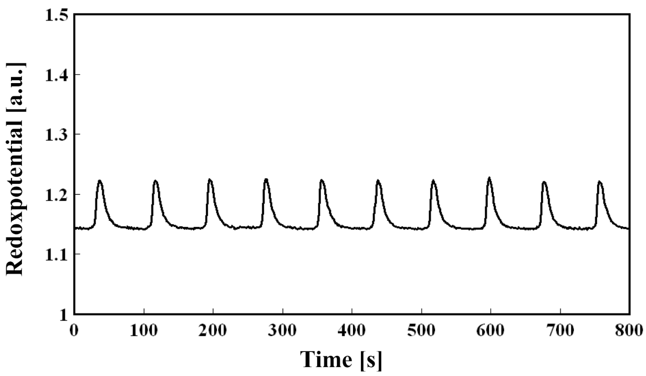

Figure 2. Oscillation phenomena on the low current (0.2 mA) [channel I : 0.42 M $NaBrO_3$; channel II, 1.5×10^{-3} M $Ce_2(SO_4)_3$ and 0.9 M malonic acid; channel III, 1.125 M H_2SO_4; flow rate : 0.1 mL/min; room temperature].

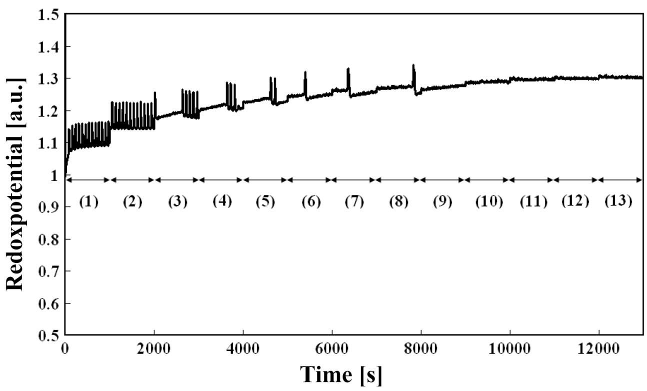

Figure 3. Change of phenomena as a function of base current (1) 0.1 mA (2) 0.2 mA (3) 0.3 mA (4) 0.4 mA (5) 0.5 mA (6) 0.6 mA (7) 0.7 mA (8) 0.8 mA (9) 0.9 mA (10) 1.0 mA (11) 1.1 mA (12) 1.2 mA (13) 1.3 mA [same condition as figure 2].

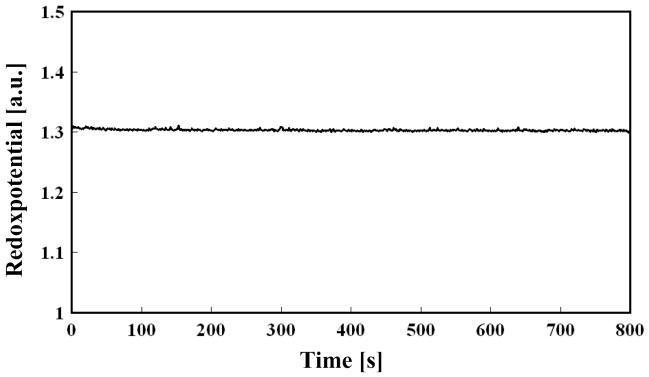

Figure 4. Stability phenomena on the low current (1.3 mA) [same condition as figure 2].

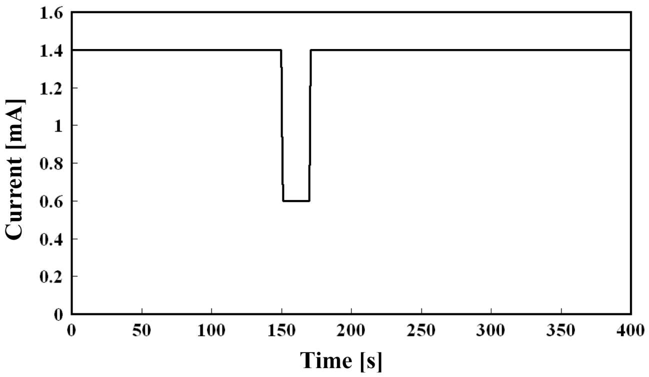

Figure 5. Electric perturbation method (1.4 mA base current, −0.8 mA 10 sec perturbation) [same condition as figure 2].

Figure 5 shows the electric perturbation method. A continuous base current of 1.4 mA is applied and for 10 seconds the current is dropped to 0.6 mA, resulting in a perturbation current of −0.8 mA. This perturbation method makes the excitability (Fig. 6).

We also studied the phenomena of concentrative perturbation with the same condition. Figure 7 shows the phenomena by Ag^+ perturbation with a syringe. A continuous 1.4 mA base current is supplied and 0.1 mL of 0.01 M Ag^+ is instantly injected by a syringe. This experiment shows a

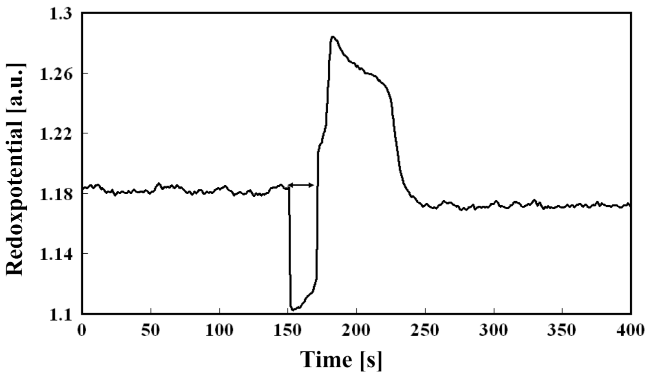

Figure 6. Excitability by electric perturbation (1.4 mA base current, −0.8 mA 10 sec perturbation in arrow range) [same condition as figure 2].

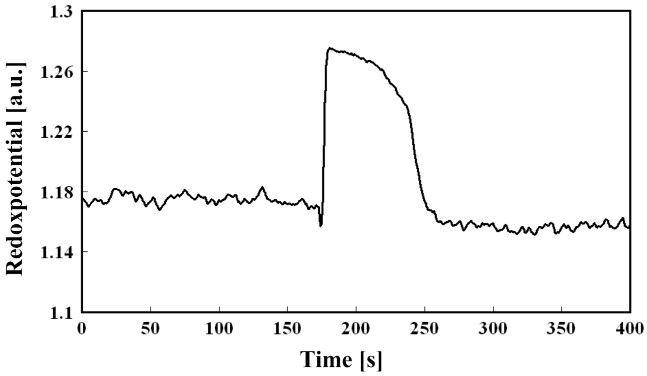

Figure 7. Excitability by concentrative perturbation (0.01 M Ag^+ 0.1 mL) [same condition as figure 2].

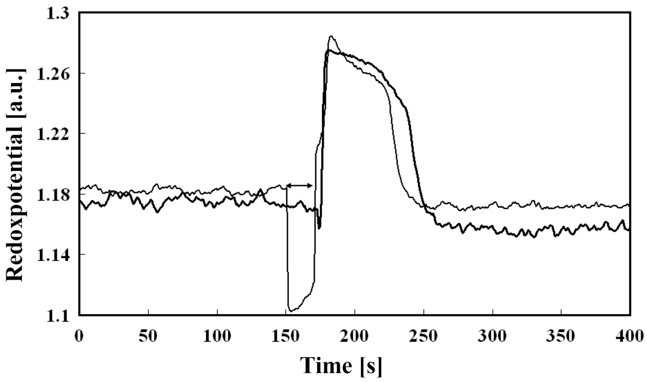

Figure 8. Comparison of excitability by electric perturbation (thin) and concentrative perturbation (thick) [same condition as figure 2].

good excitable phenomenon. In addition, the excitability shapes by the two perturbation methods are similar (Fig. 8). The electric perturbation method makes low the voltage of the redox electrode on the perturbation, because the voltage of perturbation affects the redox electrode. It is natural that different perturbations make different reactions. We consider it remarkable that the spike shapes of the redox electrode are very similar after the perturbation.

Sawtooth perturbation is studied because the shape of

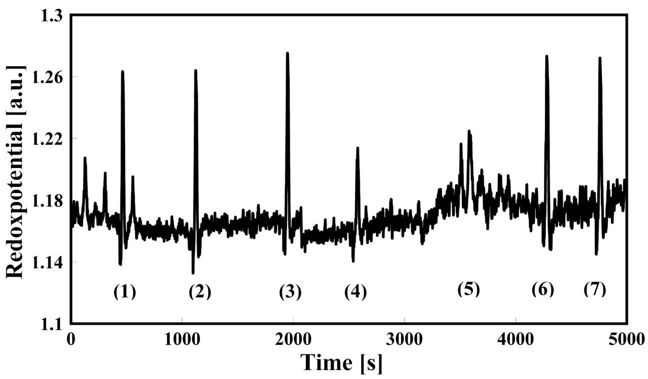

Figure 9. Excitability by sawtooth perturbation (1) −0.5 mA perturbation (2) −0.4 mA perturbation (3) −0.3 mA perturbation (4) −0.2 mA perturbation (5) −0.1 mA perturbation (6) −0.5 mA perturbation (7) −0.6 mA perturbation [same condition as figure 2].

coupling is sawtooth. Sawtooth perturbations make excitability. In Figure 9, when –0.1 mA perturbation is applied, excitability is not shown. When –0.2 mA perturbation is applied, excitability is shown but the peak is small. From –0.3 mA, excitability clearly appears. Therefore, our condition can be used in electric coupling.

Conclusion

In this work we have found a condition to be a neuron of CSNN. It is shown that our condition can be used as a condition for a chemical spiking neuron and as a unit of a CSNN. The condition has two excitation mechanisms : electric perturbation and chemical perturbation. The phenomena of the different perturbations are similar. Regardless of the excitation mechanism, the reactions can be coupled, and therefore compose a CSNN. If couplings between chemical systems for the CSNN are accomplished, the CSNN can process information. If the couplings are accomplished by using chemical perturbation, CSNN is wholly chemical. But if the couplings are accomplished by using electric perturbation, it is controlled easier.

In our condition, a small electric current is continuously applied in our CSTR. In biological systems, a small electric current is also continuously applied. Therefore, the electric current channel is simulating a real phenomenon. We believe that this work is a base for CSNN experiments, and hope that it gives some direction for further understanding of information processing in biological systems.

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