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Identifying time delay-induced multiple synchronous behaviours in inhibitory coupled bursting neurons with nonlinear dynamics of single neuron

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Abstract

Time delay-induced multiple synchronous behaviors are simulated in inhibitory coupled bursting neurons when time delay is larger than the period of the bursting, which can be well interpreted with dynamics of single neuron combined with inhibitory coupling current. The bursting pattern of uncoupled neuron can change to multiple different firing patterns when receiving negative stimulus at suitable phase to form the multiple patterns of synchronous bursting appearing at different time delay. The synchronization is dependent on the stable characteristics of the quiescent state corresponding to the stable node of the fast subsystem, wherein long lasting inhibitory coupling current is conductive to achieve synchronization. This is the reason that inhibitory coupling current modulated by time delay can induce multiple synchronous behaviors.

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Keywords: Synchronization; Inhibitory coupling; Bursting; Bifurcation; Time delay

1. Introduction

Synchronization is ubiquitous in nature, and studied in many fields such as mechanics, physics and biology[1]. In neuroscience, synchronization appeared in many brain regions including hippocampus, thalamus and neocortex[2,3], and is related to many functions such as learning, memory and locomotion[3]. The synchronous behaviors of the nervous system are dependent on both coupling of the synapse and intrinsic cellular properties of the neuron[2,4].

Inhibitory coupling plays important roles in the central pattern generation to generate motor rhythms or in the central nervous system to maintain the balance between excitatory and inhibitory couplings. It was believed that the reciprocal inhibitory coupling always induces anti-phase synchronization in some previous investigations[5,6]. Some theoretical and biological experimental studies found that slow inhibitory synapse can induce synchronization[6–9]. Time delay is inherent in the nervous system due to the finite propagation speed of information and time lapses in synapse[10]. Time delay can induce multiple synchronizations when time delay is within multiple of the intrinsic period

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of individual neuron [11] or within one period of individual neuron [12,13]. Despite these investigations, the dynamics of inhibitory coupled neurons remained unclear, for example, how to identify the spatiotemporal behaviors of network with the dynamics of single neuron combined with the inhibitory coupling current.

Two or three reciprocally inhibitory coupled neurons, for example, the pyloric network of lobster [8], can generate motor rhythms related to digestive function and can exhibit in-phase bursting synchronization as time constant of synapse becomes long. The bursting pattern of an isolated neuron is resulted from the competition between fast and slow currents and exhibits alternation between fast spikes and slow quiescent state. The complex dynamics of bursting pattern can be acquired with fast/slow variable dissection method [4,14,15]. In the inhibitory coupled bursting neurons, as time delay becomes long, a slow time scale is introduced and will interact with the time scales of the bursting pattern. In the present paper, time delay-induced multiple synchronous behaviours are well interpreted with nonlinear dynamics of single neuron and inhibitory coupling current applied at different phase modulated by different time delay. The nonlinear dynamics includes different responses of bursting pattern at different phase stimulated by the negative current and the stable characteristics of the quiescent state of the bursting pattern, which are acquired with fast-slow variable dissection method.

The rest of the paper is organized as follows. Section 2 gives the theoretical models and methods. The results are presented in section 3. The conclusion is provided in section 4.

2. Models and methods

The reduced leech heart model [14–16] is widely used as a bursting neuron model and is given by:

$$C\dot{V} = -[\overline{g}_{Na} f(-150, 0.0305,)h_{Na}(V - E_{Na}) - \overline{g}_{K2} m_{K2}^2 (V - E_{K2}) + g_L(V - E_L) + I_{app}], \quad (1)$$

$$\dot{h}_{Na} = [f(500, 0.0325, V) - h_{Na}]/\tau_{Na}, \quad (2)$$

$$\dot{m}_{K2} = [f(-83, 0.018 + V_{K2}^{shift}, V) - m_{K2}]/\tau_{K2}. \quad (3)$$

Where V is membrane potential; m_{K2} and h_{Na} are the gating variables describing the activation of potassium current and inactivation of sodium current, respectively; C is the membrane capacitance; $\overline{g}_{Na}$, $\overline{g}_{K2}$ and g_L are the conductance of sodium current, potassium current and leaky current, respectively; E_{Na}, E_{K2} and E_L are the reversal potential of sodium current, potassium current and leaky current, respectively; τ_{K2} and τ_{Na} are the time constants of activation of potassium current and inactivation of sodium current, respectively; $f(x, y, z) = 1/(1 + exp\{x(y + z)\})$ is a Boltzmann function describing kinetics of the currents. V_{K2}^{shift} is the shift of the membrane potential of half-activation of potassium current from its canonical value. In the present paper, $\tau_{Na} = 0.0405$ s, $\tau_{K2} = 0.9$ s, and other parameter values are $C = 0.5$ nF, $\overline{g}_{K2} = 30$ nS, $\overline{g}_{Na} = 200$ nS, $g_L = 8$ nS, $E_{K2} = -0.07$ V, $E_{Na} = 0.045$ V, $E_L = -0.046$ V, $I_{app} = 0.001$ mA and $V_{K2}^{shift} = -0.01$.

The fast threshold modulatory synapse [5] is employed in the present paper and described as follows:

$$I^{syn} = -g_s(V_{pos}(t) - E_s)\Gamma(V_{pre}(t - \tau)). \quad (4)$$

Where g_s and E_s are the coupling strength and reversal potential of synapse, respectively. To ensure the coupling is inhibitory, $E_s = -0.0625$ V is chosen. V_{pre} and V_{pos} are the presynaptic and postsynaptic potentials, respectively. $\Gamma(x) = 1/(1 + exp(-1000(x - \Theta_{syn})))$, where Θ_{syn} is the threshold of synapse and $\Theta_{syn} = -0.03$ V. τ is time delay.

The model of three reciprocal coupled neurons by inhibitory synapse is described as follows:

$$C\dot{V}_i = -[\overline{g}_{Na} f(-150, 0.0305,)h_i(V_i - E_{Na}) - \overline{g}_{K2} m_i^2 (V_i - E_{K2}) + g_L(V_i - E_L) + I_{app} + I_i^{syn}], \quad (5)$$

$$\dot{h}_i = [f(500, 0.0325, V_i) - h_i]/\tau_{Na}, \quad (6)$$

$$\dot{m}_i = [f(-83, 0.018 + V_{K2}^{shift}, V_i) - m_i]/\tau_{K2}. \quad (7)$$

Where $I_i^{syn} = -(V_i(t) - E_s)\sum_{j=1(j\neq i)}^{3} g_{ij}\Gamma(V_j(t - \tau))$, $g_{12} = g_{23} = g_{31} = g_1$ and $g_{21} = g_{32} = g_{13} = g_2$.

A similar function S_{ij} is used to describe the synchronous degree of the network and is given by:

$$S_{ij} = \frac{\langle (V_i - V_j)^2 \rangle}{[\langle V_i^2 \rangle \langle V_j^2 \rangle]^{1/2}} \quad (8)$$