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Dynamical responses in a new neuron model subjected to electromagnetic induction and phase noise

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HIGHLIGHTS

- New neuron model is presented with electromagnetic induction being considered.
- Magnetic flux is used to describe the effect of electromagnetic induction.
- Memristor is used to realize feedback and coupling between membrane potential and electromagnetic field.
- Double coherence resonance is detected and multiple modes in electrical activities are observed.

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ABSTRACT

Complex electrical activities in neuron can induce time-varying electromagnetic field and the effect of various electromagnetic inductions should be considered in dealing with electrical activities of neuron. Based on an improved neuron model, the effect of electromagnetic induction is described by using magnetic flux, and the modulation of magnetic flux on membrane potential is realized by using memristor coupling. Furthermore, additive phase noise is imposed on the neuron to detect the dynamical response of neuron and phase transition in modes. The dynamical properties of electrical activities are detected and discussed, and double coherence resonance behavior is observed, respectively. Furthermore, multiple modes of electrical activities can be observed in the sampled time series for membrane potential of the neuron model.

1. Introduction

The neurodynamics [1–9] on biological system has been paid much attention since the breakthrough on electrical activities of isolate neuron model in 1950s. The Hodgkin–Huxley neuron model is thought as a reliable neuron model because the effect of ion channels can be described. Indeed, some simplified neuron models can also be helpful to understand the dynamical properties of neuron, for example, the mathematical Hindmarsh–Rose neuron model [2] is effective to reproduce main properties of neuronal activities and can be available for bifurcation analysis. Readers can find detailed description for other neuron models in Ref. [4], as mentioned in Ref. [3], reliable neuron circuits can be set up to detect the response of neuron to external stimuli. Based on most of the neuron models, stochastic resonance [10–16] can be found by applying appropriate noise and periodical forcing on the isolate neuron and even neuronal network [17–19]. Stochastic resonance and coherence resonance on neuron and neuronal network can induce distinct regularity in sampled time series for membrane

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potential, and spatial regular distribution [20–24] under applying optimal intensity of different kinds of noise, such as Gaussian white noise [24], Lévy noise [14] and channel noise [23]. For stochastic resonance, external periodical forcing or intrinsic autaptic driving are important for generating continuous pulses or wave fronts like pacemaker [13,25] in presence of noise. As a result, bifurcation parameters [26,27] such as time delay and conductance for ion channels can be adjusted to enhance coherence and also induce decoherence of network [28].

By now, dynamical analysis and synchronization transition has been extensively discussed on many neuron models, and it is confirmed that the external forcing current and bifurcation parameters can change the modes of electrical activities [29–35]. In fact, some realistic factors should be considered by dealing with these neuron models. For example, autapse, a specific synapse connected to the body of neuron via a close loop. As reported in Refs. [34–36], autapse plays important biological function in regulating the electrical activities of neuron and network. In the case of neuronal network [37,38], autapse driving can regulate the collective behaviors of neurons like a pacemaker and even generate regular spatial patterns such as spiral waves or continuous pulses. Furthermore, the effect of electromagnetic induction in neuron should be considered during the changing of concentration of ions in the cell. According to the physical law of electromagnetic induction, time-varying electromagnetic field can be induced when different ion currents across the channels embedded into the membrane, and magnetic flux across the membrane is also changed. As a result, Lv et al. [39,40] suggested that magnetic flux across the membrane can be used to describe the effect of electromagnetic induction, and it is confirmed that electromagnetic radiation can also be imposed the model to investigate the transition of electrical activities in neuron. However, these results presented in Refs. [39,40] have been carried out on the Hindmarsh–Rose and the effect of noise and ion channels is out of consideration. Besides the Lévy noise in Ref. [14], it is interesting to investigate the response of the improved biological neuron model driven by phase noise [41–44]. Readers can explore the previous review [45] and references therein for neurodynamics. In this paper, the effect of electromagnetic induction is considered on the Hodgkin–Huxley neuron model, and then phase noise is considered to detect the possible emergence of stochastic resonance, and the emergence of multiple modes in electrical activities.

2. Model description

Magnetic flux φ is used to describe the effect of electromagnetic induction, and the dynamical equations developed from the original Hodgkin–Huxley neuron model are described as follows

$$\begin{cases} C_m \dfrac{dV}{dt} = -(I_K + I_{Na} + I_L + AC_m \cos \omega t) + I_{ext} + k\rho(\varphi)(V + V_e); \\ \dfrac{dy}{dt} = \alpha_y(V)(1-y) - \beta_y(V)y; \quad (y = m, h, n) \\ \dfrac{d\varphi}{dt} = k_1 V - k_2 \varphi; \\ \dfrac{dQ}{dt} = \omega_1 + \sqrt{2D}\xi(t) \end{cases} \tag{1}$$

$$\begin{cases} \rho(\varphi) = (\alpha + 3\beta\varphi^2); \qquad V_e = A \sin \omega t/\omega; \qquad I_{ext} = A_1 \sin(Q(t)); \\ I_K = 36n^4(V + V_e + 12); \qquad \alpha_n = 0.01\dfrac{10 - V}{\exp[(10 - v)/10] - 1}, \qquad \beta_n = 0.125 \exp[-V/80]; \\ I_{Na} = 120n^3 h(V + V_e - 115); \qquad \alpha_m = 0.1\dfrac{25 - V}{\exp[(25 - V)/10] - 1}, \qquad \beta_m = 4 \exp[-V/18] \\ I_L = 0.3(V + V_e - 10.6); \qquad \alpha_h = 0.07 \exp[-V/20], \qquad \beta_h = \dfrac{1}{\exp[(30 - V)/10] + 1} \end{cases} \tag{2}$$

where the variable V, φ represents the membrane potential and magnetic flux across the membrane, respectively. V_e is the additive induction membrane induced by external electric stimuli, C_m, m, n, h is the membrane capacitance, and the gate variable for channels, the function $\rho(\varphi)$ is the conductance developed from memristor and used for memory associated with magnetic field. A, A_1, ω is the amplitude and angular frequency for external forcing currents, $\xi(t)$ is Gaussian white noise, ω_1 is the angular frequency of phase noise $Q(t)$ [41–44]. For detailed description about the parameters α, β, k, k_1, k_2, readers can find in Ref. [40]. The schematic diagram for the neuronal circuit is plotted in Fig. 1.

3. Numerical results and discussion

In this section, the fourth order Runge–Kutta algorithm is used for dynamical equations, time step $h = 0.01$, the initial values for the variables are selected as $V_0 = -64.999801$ mV, $m_0 = 0.052938$, $h_0 = 0.5916$, $n_0 = 0.317726$, $\varphi_0 = 1$, the parameters are set as $\alpha = \beta = 0.1$, $k_1 = 0.1$, $k_2 = 1$, $A = 2.5$ μA/cm^2, the membrane capacitance is set as $C_m = 1$ μF/cm^2. At first, the dependence of magnetic flux on the membrane potential is investigated without additive