A MODEL OF A NEURON WITH OSCILLATORY ACTIVITY BELOW THE EXCITATION THRESHOLD *

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We propose a dynamic model of a neuron with spontaneous periodic oscillations below the excitation threshold. Such neurons, in particular, play an important role in the problem of coordination of motions by the brain specifying the universal rhythm of muscular contractions. The model is constructed on the basis of the known model dynamic systems and is described by a system of fourth-order differential equations. A good qualitative agreement between the model dynamics and experimental data for the actual neurons is obtained.

1. INTRODUCTION

One of the problems intensively studied by specialists in neurophysiology in recent years is the study of mechanisms of coordination of motions effected by the nervous system of people and animals. It turns out that any motion is sequential in a certain (kinematic) sense rather than continuous, i.e., has a characteristic time scale determined by a frequency of \( \sim 10 \) Hz. As physiologists claim, this time scale means that the nervous system controls the muscle contraction each \( \sim 100 \) msec or less frequently. In the coordination of motions, this specifies a universal rhythm, which does not change from species to species and from type to type [1, 2, 3].

The latest studies[4] performed by specialists in neurophysiology show that the most important role in the problem of coordination of motions by the nervous system is played by the so-called inferior olives, i.e., the groups of neurons located in the brain stem (see Fig. 1). These neurons create the above-mentioned universal rhythm (10 Hz) on the basis of which any muscular contraction occurs. The characteristic feature of such neurons is the presence of spontaneous oscillations that are close to harmonic oscillations (with frequency \( \sim 10 \) Hz) and take place below the neuron excitation threshold [2, 3]. These oscillations, which have a sufficiently large amplitude with respect to noise but do not initiate the action and excitation potential of the neuron, are called subthreshold oscillations. However, excitation of the olive neurons can occur due to either external action on the given neuron or random fluctuations and also has its special features.

The understanding and study of the mechanisms of functioning of complex neuron systems such as, for example, the inferior olives using the methods of nonlinear dynamics require, first of all, the construction of an adequate model of the ensemble unit, i.e., individual neuron. Such a model must meet at least two main requirements. First, it must reflect the results of an actual neurophysiological experiment, i.e., reproduce, at least qualitatively, the main dynamic regimes of an actual neuron. Second, it must be relatively simple to make it possible to study the dynamics of a neuron ensemble.

In this paper, we propose a model for the olive neuron, i.e., a neuron with oscillatory activity below the excitation threshold. In the first part of the paper, we present a short review of some known and widely used models of neurons. In the second part of the paper we describe the main idea and the general view of

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the model on the basis of the known model systems. In the third part the modeling results are compared with the experimental data on the dynamics of olive neurons. In the conclusion, we present a short discussion of the results obtained.

2. NEURON MODELS

We know of various types of neurons that differ from one another by both their physiological structure and functional features. As a result, there exist a great number of different models reflecting the characteristic regimes of behavior of a neuron of one type or another (see, for example, [5]).

One of the most universal features of actual neurons is their ability to generate an excitation pulse (action potential). The classical model of a neuron describing, in particular, the emergence of the action potential is the Hodgkin-Huxley model [6, 7] based on the results of actual neurophysiological experiments with a giant axon of a squid. The model deals in detail with the dynamics of ion currents through the cell membrane. However, in view of the great number of dynamic variables and parameters, its study with the help of nonlinear dynamics and use as a unit of the neuron ensemble seems to be difficult. A simpler model (two dynamic variables) that reflects (qualitatively) the main features of the dynamics of the potential of the cell membrane is the Fitz Hugh–Nagumo (FHN) model [8, 9], which has also become classical for describing the propagation of the excitation pulse along the nerve fiber. From the dynamical viewpoint, the FHN model is a relaxation-type system.

As is obvious from experiments, oscillatory activity of special form is a feature that is rather typical of neurons from different regions of the nervous system. These oscillations have explicit fast and slow time scales (spike-burst behavior) and can be chaotic. One of the most popular models of neurons of this type is the Hindmarsh–Rose model [10], which has three independent variables, some of which describe (qualitatively) the dynamics of slow ion currents, while others describe the dynamics of fast ion currents.

In the study of the collective behavior of large neuron ensembles, in particular, the synchronization and self-organization processes, simple phase oscillators are often used as an ensemble unit (see, for example, [11]).