An Application of the Cellular Automaton Method in Autowave Process Modeling of the Surface Layer of Magnetic Fluid

Natalya Kandaurova[1] Vladimir Chekanov[1] Sergey Mirzakhanov[2]
Andrey Makovsky[2] Yury Kuznetsov[2]

[1] Moscow Technological University (MIREA), Russia
[2] North-Caucasian Federal University, Russia
candaur18@yandex.ru, oranjejam@mail.ru, mirzhn@gmail.com, 8133962@gmail.com, cooper_555@mail.ru

Abstract

The article deals with computer autowave modeling by cellular automaton method. The results are compared with experimental autowave observations flowing in a cell with a magnetic fluid.

1 Introduction

Self-supporting nonlinear waves in active media are called autowaves. Examples of autowave processes are Belousov-Zhabotinsky chemical reaction (B-Z reaction) [1], pulse propagation along nerve fibers and in cardiac muscle [2, 3], population waves. A clear example - the combustion wave in a medium capable of reducing the initial state. The appearance of autowave process is possible only in the active medium which are characterized by the presence of the distributed external energy sources [4]. In the active medium there is not only a connection between the individual elements, but each element is characterized by a complex behavior.

Autowave violations in biological fluids can lead to serious dysfunctions. For example, the occurrence of helical waves in the cardiac muscle leads to life-threatening arrhythmias. To eliminate such arrhythmias is possible by controlling the wave emerged by external influences.

Therefore autowaves play an important role in the functioning of living systems. Learning of their properties is important for understanding many phenomena in the nervous system, the heart, the dynamics of ecological systems.

Autowave processes are under the general laws of self-organization, and their research is of fundamental interest in terms of predicting the behavior of complex systems. Also forecast availability leads to the possibility of predicting and preventing accidents: technological, economic, environmental. Thats why, mathematical modeling of autowave process is an urgent task.

2 Research Methods

Currently, there are two different methods of mathematical modeling of distributed active medium - axiomatic and dynamic. [5, 6, 7] The basis of the axiomatic method consists of J.Von Neumann works, who introduced the concept in the science of "cellular automaton". Cellular automatons got widespread in two-dimensional media dynamic behavior modeling (heat equation model, the wave equation, Navier Stokes equation, diffusion model, and others.).

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Mathematical model of the active medium is based on the properties of the individual elements of the medium - a regular "cell" lattice. Each of them has a finite number of possible states - repose, excitation and refractory [8, 9, 10].

At the moment the element is at a standstill. As a result of external influence or spontaneous, the element moves from a state of rest to a state of excitation that lasts predetermined time. Excitation can be transmitted to neighboring reposed elements. But another factor, that prevents excitation increase, begins to grow and, after the time t_1 it removes the element excitation. Thus, during the time t_2, a new element excitation is impossible. This condition is called refractory. Then the element reverts to the repose state and is ready to receive a new excitation. The variable, responsible for the excitation is called an activator, and the preventing one inhibitor. Mathematically activator and inhibitor behavior is described by similar equations. This ensures the connection between the elements, which together form the medium. Excitation wave moves in the medium without attenuation, while maintaining a constant shape and amplitude. If it passes the dissipation losses are fully compensated at the expense of energy supply. Thus, it is a autowave.

Transitions between states of repose, excitation and refractory are made according to certain rules, typical for element of this type of medium. System status is determined by the values of the variables in each cell, and the evolution of the system - by the rules of cell state changing.

The first axiomatic model of excitable medium was proposed by Wiener and Rosenbluth [5]. Qualitatively, the model reproduced the Wiener-Rosenbluth observed the phenomena in the active medium (the myocardium), but quantitative results were unsatisfactory, so the model was complicated in the works of Leo Rudy [11] Noble [12, 13], Beeler-Reuter [14] and adequate model of myocardial work was constructed in [15].

With the help of the axiomatic approach we can describe switching waves, traveling impulses, leading centers and spiral waves (reverberators) [16]. Using cellular automaton method for modeling is very interesting for researchers nowadays as well [17, 18, 19].

3 Results

Lets look the application of the axiomatic method to the autowave processes occurring in the surface layer of magnetic fluid placed in an electric field [20, 21, 22].

The magnetic fluid (MF) is a colloidal system composed of ferromagnetic particles of nanometer size (e.g. magnetite) which are suspended in the carrier fluid. As the carrier liquid is usually an organic carrier (for example, kerosene) or water. To provide a magnetic fluid aggregate stability in the colloid stabilizing additives are added, so-called surface-active agents (surfactants), which form a protection sheath around the particles and prevent them from sticking together.

The most common type is a magnetic fluid "magnetite in kerosene."

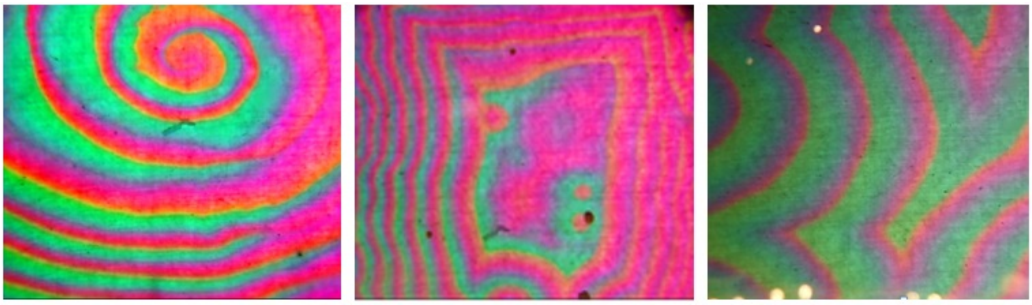

Figure 1: Autowaves in a cell with a magnetic fluid

Cell with magnetic fluid measuring $3 \cdot 5cm$ was placed between two electrodes, one of which is transparent, illuminated with white light and observed an interference pattern on the surface of the magnetic fluid. Under the influence of the electric field of magnetite particles migrate to the electrodes, the magnetite concentration in the electrode layer changes, absorption and refractive indices and the nature of the interference pattern also changes. Reflected light from the surface is painted, the change in concentration is accompanied by a change in the color of the reflected light. At a certain voltage to the electrodes in the surface layer were able to observe autowaves, which are shown in Figure 1 (a, b, c, d). [21].

The described near-electrode layer of an electrochemical cell with a magnetic fluid is an active two-component medium and can have three specific states: repose, excitation and refractory. Also observed process has the properties of excitable medium as: 1) the existence of a threshold excitation launch mechanism (autowaves appear when the voltage on the electrodes of the critical value), and 2) the ability to maintain the distribution of pulses.

For computer simulation of the observed autowave process we applied a generalized model of Wiener-Rosenbluth and used the algorithm proposed in [23].

We divide the surface of the cells with magnetic fluid on a two-dimensional grid, each cell of which describes a certain region of space and has the coordinates i and j.

Each cell element is in one of three states: repose, excitation and refractory. Cells in the same state do not differ from each other in any way. In the absence of external force each grid is at repose.

As a result of the impact when the activator value reaches the threshold, the element goes into an excited state, gaining the ability to excite the neighboring cells. After a while the element switches to the state of the refractory, in which it can not be excited. Then the element goes itself back to its original state of repose, gaining the ability to move in an excited state again.

Let the state of each element be described by phase $y^t_{(i,j)}$ and the concentration of activator $q^t_{(i,j)}$, where t is the discrete moment of time.

If the item is at repose, it will be assumed that $y^t_{(i,j)} = 0$. If the concentration of the activator $q^t_{(i,j)}$, reaches a threshold Q_{cr}, the element is excited and goes into 1. In the next step element automatically switches to state 2, then - in state 3, while being excited, and so on until it reaches the condition r -Refractory. After $s(s > r)$ steps after the excitation element is returned to a state of repose.

We write the rule cellular automaton:

$$y^{t+1}_{i,j} = \begin{cases} y^t_{i,j} + 1, & \text{if } 0 < y^t_{i,j} < s, \\ 0, & \text{if } y^t_{i,j} = s, \\ 0, & \text{if } y^t_{i,j} = 0, q^t_{i,j} < Q_{cr}, \\ 1, & \text{if } y^t_{i,j} = 0, q^t_{i,j} \geq Q_{cr} \end{cases} \tag{1}$$

We assume that the transition from a state of excitation in the repose state the activator concentration becomes 0. In the presence of a neighboring cell is in an excited state, it is increased by 1. If l nearest neighbors are excited, then at the appropriate step to the previous value of the activator concentration is added the number of excited neighbors: $q^{t+1}_{(i,j)} = q^t_{(i,j)} + l$.

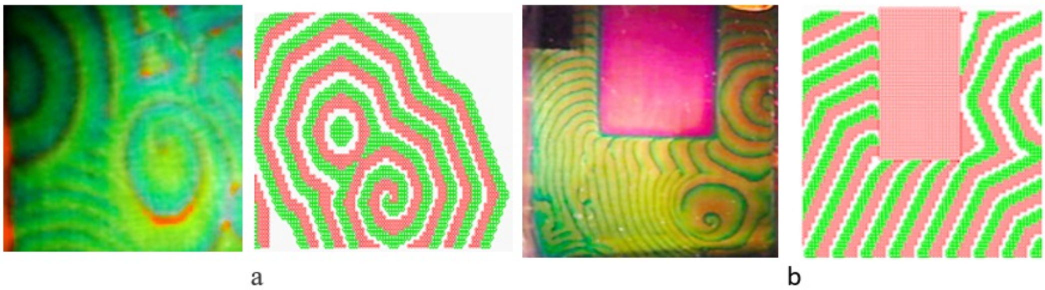

Figure 2: Comparison of the results of natural experiment and computer autowave modeling: a - a leading center (pacemaker) and a spiral wave (reverberator), b - rounding a barrier

You can restrict account of the eight neighboring cells. To create a Autowave modeling program we form the time cycle, which calculates the medium elements phase at subsequent time moments and the concentration of the activator. Also it erases the previous distribution of the excited elements and constructs a new one. The algorithm used hereinafter was proposed by R.V.Mayer and implemented by us with the parameters of the medium s = 15; r = 8; h = 6. These parameters affect the structure and construction of the interaction of waves, both among themselves and with the barrier. They were obtained by comparing the results of the implementation of the computer program and the picture being rendered in full-scale experiment. The program added a module that allows you to simulate the bending of barriers. The result obtained after the computer program is shown in Figure 2, it is consistent with full-scale experiments (see Figure 1).

4 Discussion of the Results

In this paper we used a cellular automaton that models autowave process in active medium - magnetic fluid. The experiments with the model show its equality to empirical data. Application of cellular automaton appears particularly promising when researching the excitation dissemination processes in the active medium in the presence of multiple excitation centers, as well as the existence of objects embedded in medium watched and preventing the spread of excitation (modeling of barrier rounding).

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