ELECTRONICS

UDC 519.67: 519.684 (045)
DOI:10.18372/1990-5548.67.15617

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THE COMPUTER SIMULATION FEATURES IN MODERN BIOTECHNICAL SYSTEMS

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***Abstract*—*The article is devoted to the issues of the features of computer structural modeling of bio- and physiological systems of the human body. It has been established that most of the elements of a living organism and biological processes occurring in them are formalized using integral-differential equations of higher orders, the analytical solution of which is difficult. As modeling components of biotechnical systems and complexes, it is proposed to use circuitry implementation of a wide class of functional solvers based on functional circuits of operational amplifiers, which makes it possible to observe and study the dynamics of parameters of a biological object and bioprocesses in the visual modeling environment in the form of their mathematical models in real time.*

Index Terms—Biotechnical systems; biosignal; computer modeling; structural modeling; functional solver; electrophysiological signal.

I. INTRODUCTION

Problems of man-machine systems – control systems of the "man-machine-environment" type (CS "M-M-E") – were the subject of study of many well-known scientific schools of cybernetics. However, the concept of biotechnical systems does not focus only on humans (it is assumed that any biological objects are included in their structure, not only included in the control systems of technical complexes, but also external objects of study or research carried out using technical systems.

This class also includes all systems for medical and biological purposes, in which a human patient and other types of organisms act as an external object, the state of which is influenced by a biotechnical system (**BTS**) [1], [2], [9], [14].

In Figure 1 shows the possible contours of the interaction of biological objects with the technical complex (**TC**).

Obviously, the main object is a person, therefore, the diagram shows several positions of a person when interacting with the TC:

- **Usr** is a human user, its main functions are to turn on the TC, set the modes and control the operation (for this, the **Usr** has a control panel (**CP**); all other operations of the TC are carried out according to the program included in;
- **Expr** is a human expert who analyzes the quality of the entire system, including not only the work of the TC, but also the behavior of other participants;

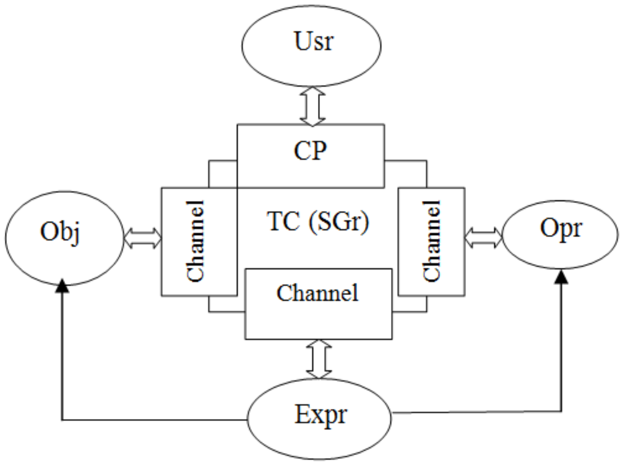

Fig. 1. The position of a person in the structure of the BTS

- **Opr** is a human operator who controls the work of the TC in real time, defining the program of work, choosing the principal operations based on the tasks assigned to the BTS;
- **Obj** is the control object; here a person can be connected as a patient in need of help, but besides him, any / other objects are also possible: for example, technical, biological (single or whole population), economic, informational, etc., that is, such with whom or on which the **Opr** is working;
- **SGr** is a group of jointly working specialists of different specialties: researchers, developers, designers, testers and others, without whose active work no technical means and technologies for their use can appear.

The new medical equipment creation requires the formation of physiologically justified criteria for the construction of equipment that ensure its effective functioning. Determination of the requirements for the choice of parameters and characteristics of the equipment is associated with the study of the processes occurring during the interaction of technical means and a living organism.

Modeling and reproduction of biological objects and bioprocesses in the BTS requires an adequate description of the processes of functioning of the physiological system, which is part of the BTS as a biological link.

The biological objects modeling, as a rule, is carried out by functional and structural identification methods.

Functional identification makes it possible to determine the behavior of the system in the presence of stimuli at its input. To solve this problem, it is necessary to have experimental data on the behavior of the system under various input influences. Functional identification provides for the determination of the transfer function of the system without providing information regarding its internal structure.

Structural identification makes it possible to establish the interaction of individual components of the system in the process of forming reactions. In this case, the configuration of the system is assumed to be known, or an assumption about the class of functional description is made relative to it, and the parameters connecting the system are assumed to be unknown. The identification problem is reduced to finding solutions in the space of the required parameters of the system.

II. Problem Statement

The most costly in relation to the use of the resources of the human body seems to be the work of a human operator (**Opr**), since he has full responsibility for the implementation of the task and the quality of work of the BPS as a whole largely depends on his condition and knowledge.

But he can control these TC using effectors' modalities (mainly of a mechanical type), and perceive information using sensory modalities through three carriers of information – optical images in the visible spectrum, acoustic signals and tactile touches.

Consequently, the connection of such means to a person is possible only when using special converters of the physical forms of the information carrier into one of the sensory and effectors' modalities (Fig. 2).

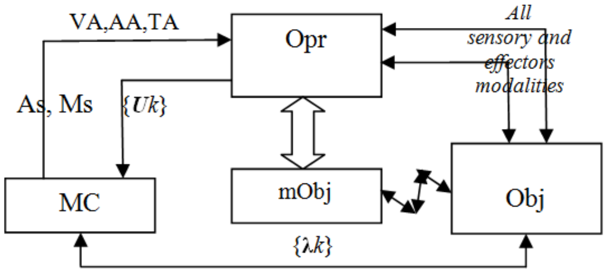

Fig. 2. Scheme the object information analysis: VA, AA, TA are visual, auditory and tactile analyzers; As is the acoustic signals; Ms are motor skills; MC are means of cognition (information retrieval); mObj is the object model; commands $\{Uk\}$; means of information retrieval $\{\lambda k\}$.

The current stage in the development of medicine in the field of electrophysiology is characterized by the widespread use of digital recording tools with built-in algorithms for automatic processing and analysis of electrophysiological signals (**EPS**).

To test such devices, to assess the quality of the EPS processing algorithms, as well as for the purpose of training special personnel, it is advisable to use artificially created EPS that repeat the shape of real signals. They can have given amplitude-time parameters (form-factors) and are able to simulate a wide range of normal and pathological conditions of a person [3], [4].

III. Analysis of Recent Research and Publications

The analysis of the special scientific and technical literature on the state of modern means of reproducing the EPS shows that the specialized generators and simulators used have limited functionality and, as a rule, form separate fragments and signal pulses.

Therefore, the urgent task is to develop a system of hardware and software playback of EPS for testing medical diagnostic devices, assessing the quality of algorithms implemented in them and creating expert systems with a wide database [10] – [12], [14], [15], [17], [18].

From the point of view of an integrated approach, the functional state is determined through a set of physiological indicators and a complex of behavioral manifestations that accompany various aspects of human activity and the behavior of the organism with the external environment and reflects the state of the "organized" whole.

According to this logic, the functional state is an integral complex of the available characteristics of those qualities and properties. From the standpoint of the systems approach, the functional state is the result of the dynamic interaction of the human body, which directly or indirectly determine its activity [3], [4].

The functional state change is a change from one set of reactions to another, and all these reactions are interconnected and provide more or less adequate behavior of the organism in the environment.

The most widely used indicators of the functional state in the framework of an integrated approach are the following:

- the cardiovascular system indicators (heart rate, heart rate variability, blood pressure, etc.);
- the muscular system state indicators (electromyography);
- the brain indicators (EEG, evoked potentials of the brain);
- skin resistance;
- psychophysiological indicators (memory, attention, sensorimotor reactions, etc.).

The set of these indicators is determined in each specific case separately and can be changed and supplemented arbitrarily.

The maximum possible set of physiological indicators used to assess the human condition is shown in Fig. 3.

The functional state of the body (FSB) of a person is determined in the process of research and is described by a complex of medical and biological indicators: physical, biological and psychological.

Research method is a method of obtaining target information based on a qualitative or quantitative relationship between the property of a biosystem and the measured parameters that characterize this property.

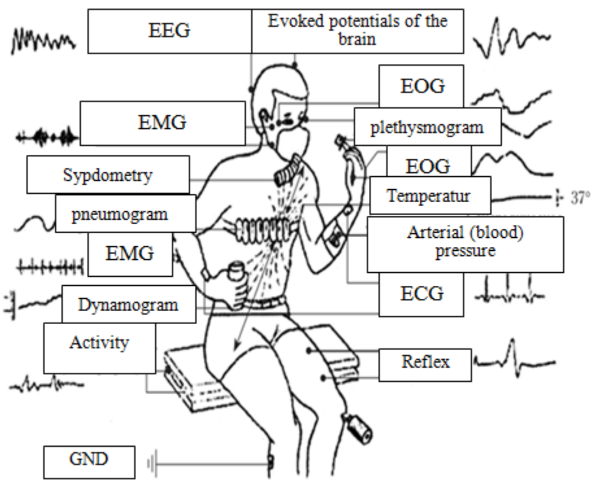

Fig. 3. Physiological methods used in the study of the functional state of a person

To implement the research method, a number of conditions must be met:

- quantitative or qualitative description of the relationship of a biomedical indicator with a measured physical parameter;
- measurement alignment algorithm;
- availability of technical means for conducting research;
- availability of an algorithm and means of processing the received information.

The essence of the research method:

- the physical phenomenon or process used;
- measured physical parameter;
- biological processes characterized by this parameter;
- medical significance of the method;
- quantitative or qualitative ratios for examples of the significance of the ratio for diagnostic examples that have found wide application in clinical practice.

The implementation of the research method is a biotechnical system (apparatus), i.e., a set of biological and technical elements that perform the target function of determining biomedical parameters (signal form-factors).

Existing diagnostic complexes and systems mainly analyze the electrocardiogram (ECG), blood pressure (BP), rheogram (RG), photoplethysmogram of the pulse wave (PW), phonocardiosignal (PCS) and a number of other physiological parameters, as well as their Fourier and wavelet spectra [3], [4].

The main purpose of this article is to substantiate the use of methods and methods of computer hardware (circuitry) reproduction of test signals (idealized form factors) of EFS of a complex form, which make it possible to automate diagnostic processes, biomedical research, as well as testing medical diagnostic devices for training medical and technical directions specialists.

IV. THE COMPUTER MODELING TECHNIQUE FEATURES

There are various approaches to the construction of artificial electrophysiological signals (EPS), but despite the large number of studies carried out, questions remain that require additional study. These include the task of developing special test signals that most accurately reflect the amplitude-time parameters of real signals of complex shape.

This is especially true for ECG signals, since they have a complex shape for analysis with the maximum number of informative areas and are the most common among all EPS [4] – [8].

Computer modeling is a means of solving problems of analysis or synthesis of a complex system (including a medical one) based on its computer model.

The essence of computer modeling is to obtain quantitative and qualitative results based on the use of its computer model. Qualitative conclusions obtained as a result of the analysis make it possible to determine previously unknown features of the system, its structure, dynamics of development, stability, integrity.

Quantitative indicators are predictive of the future or an explanation of the past values of the variables that characterize the system.

Information in systems is transmitted in the form of signals that manifest the movement of a substance: mechanical movement, propagation of electric current, heat, sound, nerve signal by fibers, etc.

Signals are characterized by the direction of action – any system can be interpreted by a set of simpler links – where the previous link is a sensor for the next signal receiver. Therefore, the sensors and signal receivers in the system are physically connected with each other by communication channels, by which the signals transmit information.

When modeling the systems of a living organism, two approaches are possible.

Firstly, the study of the characteristics of individual systems (subsystems) and the mathematical description of the organism as a whole. Here, models of systems are obtained based on physical laws and hypotheses about their functioning.

Secondly, certain general concepts are used to analyze the whole organism. Get data models that do not require or use any hypotheses about physical processes – mathematical statistics models.

To study the vital activity of an integral organism, the method of studying its individual isolated systems (subsystems) is used. In this case, the influence of other systems on the physically selected system (subsystem) is either ignored or taken into account with an approximation.

When creating a model of biological or physiological systems, it is necessary to take into account both the absence of regulators with rigid fixation of regulated parameters in the latter, and the absence of absolutely constant functions in the body. An organism with rigidly fixed parameters would remain viable for a limited time, but would lose the ability to survive – the problem of adaptability (adaptation).

It is known that processes in bio- and physiological systems are mathematically formalized, as a rule, by nonlinear differential (integral-differential) equations. Finding exact analytical solutions is associated with significant difficulties (depending on the order of the equations). Therefore, in mathematical modeling of bioprocesses and biological objects, as a rule, the qualitative theory of differential equations is used.

The essence of the latter is manifested in obtaining qualitative characteristics of the behavior of the system in dynamics: stable and unstable stationary states, transitions, oscillatory modes, critical states, etc. The most significant characteristic of a stationary state is its stability - the ability of the system to return to the primary stationary state (equilibrium) after the cessation of the influence of external excitations. In a qualitative analysis, the phase portrait of the system is reconstructed and conclusions are drawn about its stability [5–8].

As a rule, the mathematical description of a biological (physiological) system has the form of a differential equation:

$$\sum_{i=0}^{n} b_i y^{(i)} = \sum_{j=0}^{m} a_j x^{(j)} \Leftrightarrow \begin{cases} \dfrac{dx}{dt} = a_{11}x + a_{12}y, \\ \dfrac{dy}{dt} = a_{21}x + a_{22}y, \end{cases} \quad (1)$$

where a_j, b_i, a_{11}, a_{12}, a_{21}, a_{22} are constant coefficients.

The solution to such a system of differential equations is to find the changing functions $x(t)$, $y(t)$.

Structural modeling based on such differential equations (system) involves the interpretation of operations on phase variables and their functions by special functional solvers – integrators, differentiators, adders and multipliers, which are quite fully described in the theory of automation and control.

Figure 4 shows the principle of drawing up a structural diagram of the solution of the system of differential equations (1) taking into account the initial conditions.

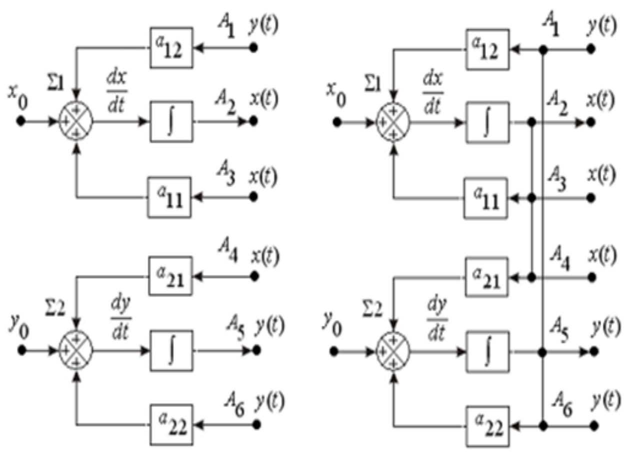

Fig. 4. Blocks of functional solvers: (a) is the open system; (b) is the closed

For example, consider the implementation of a function (process) of the form:

$$a_2x'' - b_2y'' - b_0y + a_0x = c,$$

or in canonical form:

$$y = -\frac{b_2}{b_0} y'' + \frac{a_2}{b_0} x'' + a_0 x - c.$$

To explicate the chosen technique of computer structural modeling of a bioprocess, consider a second-order differential equation with constant coefficients:

$$6y = x'' - 2y'' + 3x - 8.$$

Let us express the equation in terms of the output signal y with arbitrary constant coefficients:

$$y = \frac{1}{6} x'' - \frac{1}{3} y'' + \frac{1}{2} x - \frac{4}{3}.$$

The block diagram of the functional solver is shown in Fig. 5.

According to the block diagram (Fig. 5), the electrical circuit of the decisive part is implemented schematically, as the basic element of the circuit we use an operational amplifier (as a functional elementary solver).

A differentiating amplifier – a differentiator (not to be confused with a differential) – is obtained from an inverting amplifier when switched on instead of a resistor R_{in} of a capacitor C_{in}.

The expression for the output voltage of each of the differentiators has the form:

$$U_{out} = -RC \frac{dU_{in}}{dt}. \quad (2)$$

The fact is that in mathematics they usually work with dimensionless functions. Here, the input and output functions are voltages, and to match the dimensions of both sides of (2), the proportionality coefficient $\tau = RC$ appears in it, which has the dimension of time.

The derivation time constant for the circuit on DA2.1 is chosen equal to 1 (for matching), and, thus, the equality: $\tau = R_{in}C_{in} = R_1C_1 = 1$.

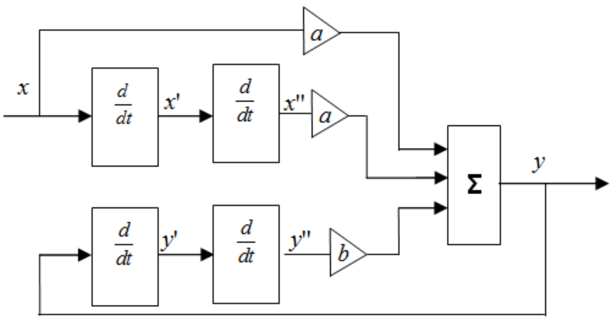

Fig. 5. Block diagram of the decision circuit

Based on the above expression and having set the resistance value $R_{fb} = R_1$, the capacitance of the capacitor C_{in} is calculated

$$C_{in} = 1 / R_{fb}.$$

To obtain the second derivative of the signal X, the circuit includes two differentiators implemented on the elements R_1, C_1, DA1.1 (first stage) and R_2, C_2, DA1.2 (second stage) (Fig. 6).

We apply the same circuit solution for the Y signal, where the circuit is implemented on the elements R_3, C_3, DA2.1 (first stage) and R_4, C_4, DA2.2 (second stage) (Fig. 6).

The rest of the stages of differentiators are similar, therefore the elements $R_1 = R_2 = R_3 = R_4$, and the capacitors $C_1 = C_2 = C_3 = C_4$.

However, it must be borne in mind that the considered nodes based on the op-amp do not change the waveform of the signal supplied to the input. A distinctive feature of the differentiator is a significant change (in the general case) in the shape of the input voltage. For example, when a sawtooth voltage is applied to the input of the differentiator, the output voltage will be rectangular, $u_{in} = \pm kt$, where k is a constant coefficient, and the time derivative $u'_{out} = k$.

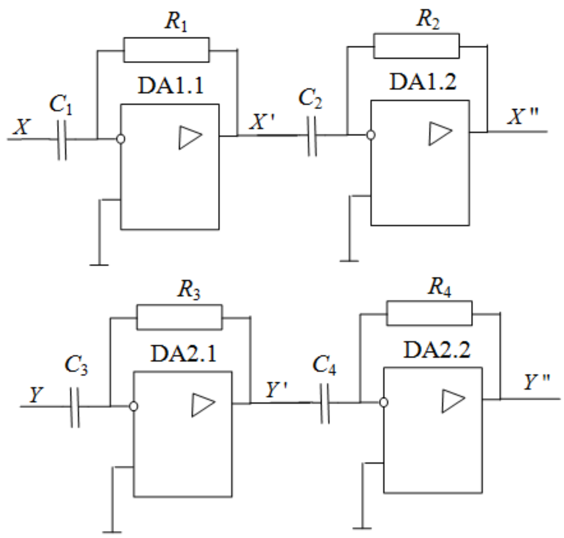

Fig. 6. Scheme of differentiators

Further, in accordance with Fig. 5, it is necessary to design a summation circuit to form the output signal. Again, we are looking for the final stage of the block diagram of the functional solver in the class of functional circuits on the operational amplifier (OA).

Based on the inverting amplifier, it is possible to build a summing amplifier, the output voltage of which is determined by the expression:

$$u_{out} = (k_1 u_{in1} + k_2 u_{in2} + k_3 u_{in3} + \ldots + k_n u_{inn}) = \sum_{i=1}^{n} k_i u_{ini}.$$

The scheme of such an amplifier is shown in Fig. 7. Input voltages (Fig. 7) u_{11}, u_{12}, ..., u_{1n} are supplied to n inputs of the device.

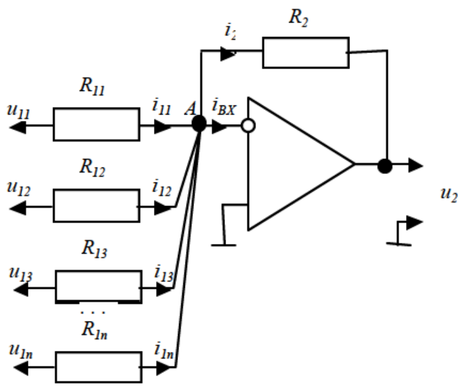

Fig. 7. Signal combiner circuit

At point A, the currents i_{11}, i_{12}, ..., i_{1n} from these voltages are summed up, so the current through the resistor $R_2 = R_{fb}$ is $i_2 = i_{11} + i_{12} + i_{1n}$, and taking into account that

$$i_{in\,i} = \frac{u_{in\,i}}{R_{in\,i}} \text{ and } u_{out} = -i_2 R_2 = -i_2 R_{fb},$$

you can calculate the weighting factors at the input of the adder (see Fig. 7):

$$k_i = \frac{R_2}{R_{in\,i}} = \frac{R_{fb}}{R_{in\,i}}.$$

The adder circuit consists of resistors $R_5 - R_{11}$, op-amp DA3.1 and is shown in Fig. 8, which implements our final expression:

$$y = \frac{1}{6}x'' - \frac{1}{2}x - \frac{1}{3}y'' - \frac{4}{3}.$$

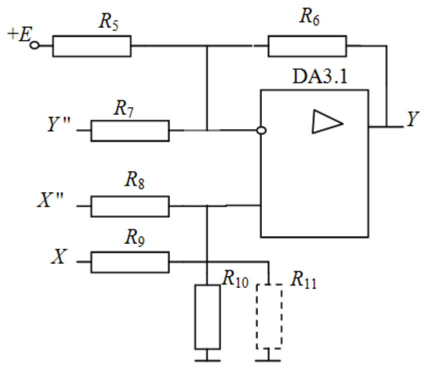

Fig. 8. Summation-subtraction scheme

An analysis of the equation indicates that there are no gains in the balance circuit $\frac{1}{6} + \frac{1}{2} \neq \frac{1}{3} + \frac{4}{3}$ and the need to provide it with a resistor R_{11}, which is added to the non-inverting part of the op-amp. So that it does not affect the result of the sum, the resulting input is grounded. To calculate the circuit elements, they are set by the values of the resistances of the resistors R_6 and R_{10}.

The values of the corresponding weighting coefficients (transmissions) of the arguments of the input function are given in the equation and are defined as:

$$k_1 = \frac{R_6}{R_5} + E = \frac{4}{3}, \quad k_2 = \frac{R_6}{R_7} = \frac{1}{3},$$

$$k_3 = \frac{R_{10}}{R_8} = \frac{1}{6}, \quad k_4 = \frac{R_{10}}{R_9} = \frac{1}{2}.$$

To balance the balance of the adder, the balance resistance R_{11} is calculated from the condition of equality of the coefficients:

$$k_1 + k_2 = k_3 + k_4 + k_5,$$

$$k_5 = k_1 + k_2 - k_3 - k_4 = \frac{4}{3} + \frac{1}{3} - \frac{1}{6} - \frac{1}{2} = 1,$$

$$k_5 = \frac{R_{10}}{R_{11}} = 1, \quad R_{11} = \frac{R_{10}}{k_5}.$$

As an example of computer (structural) modeling in the BTS, one can cite the circuitry implementation of the simplest models of biological processes:

a) the simplest **model of the formation of white blood cells** has the form:

$$\frac{dx}{dt} = -\gamma x + \beta x(t - \tau),$$

where x is the concentration of white cells in the blood (per 1 kg of body weight); γ is the rate of decay of white cells, 1/h; β is the rate of inflow of new white cells, 1/h; τ is the delay in the influx of new white cells, h (here the delay is calculated as $\tau = \sqrt{LC}$, where L, C are the inductances and capacitance of the elements of the delayed link).

At the Fig. 9 shows a block diagram of a functional solver on an op-amp in the visual design environment *ElWorkbench* and an oscillogram of the process itself.

b) The **simplest model of the cardiovascular system** (is Roston's model, built on the basis of Frank's "elastic reservoir" concept).

The differential equation approximating the blood flow from the left ventricle to the aorta (systole) and from the aorta to peripheral vessels (diastole) has the form:

$$C\frac{dP}{dt} + \frac{P}{R} = Q(t),$$

where C is the elasticity of the walls of the aortic chamber; P is the pressure in the aortic chamber; R is the hydraulic resistance of the peripheral vascular system; $Q(t)$ are impulses of blood flow from the left ventricle to the aortic chamber.

In the model, the left ventricle is taken as a source of blood impulses, and the aorta is a chamber with elastic elastic walls, while it is assumed that the outflow of blood from the aorta occurs with a delay τ, which depends on the elasticity of the aortic walls, blood viscosity, vascular water resistance, etc.
For modeling, the model is converted into a form convenient for structural computer modeling:

$$\frac{dP}{dt}=k_1Q(t)-k_2P(t-\tau)\Rightarrow p(t-\tau)=-\frac{1}{k_2}p''(t)+\frac{k_1}{k_2}Q(t),$$

where k_1, k_2 are weight coefficients, are set in the process of solving, for modeling it is taken: the frequency of blood pulsations is f = 1...1,5 Hz, the integration constant is $0.01\,/\,f \le T_i = RC \le 0.1f$, and the delay value is chosen empirically $0.1f \le \tau \le 0.9f$.

Figure 10 shows a block diagram of a functional solver on an op-amp in the visual design environment *ElWorkbench* and an oscillogram of the behavior of the cardiosystem itself in dynamics.

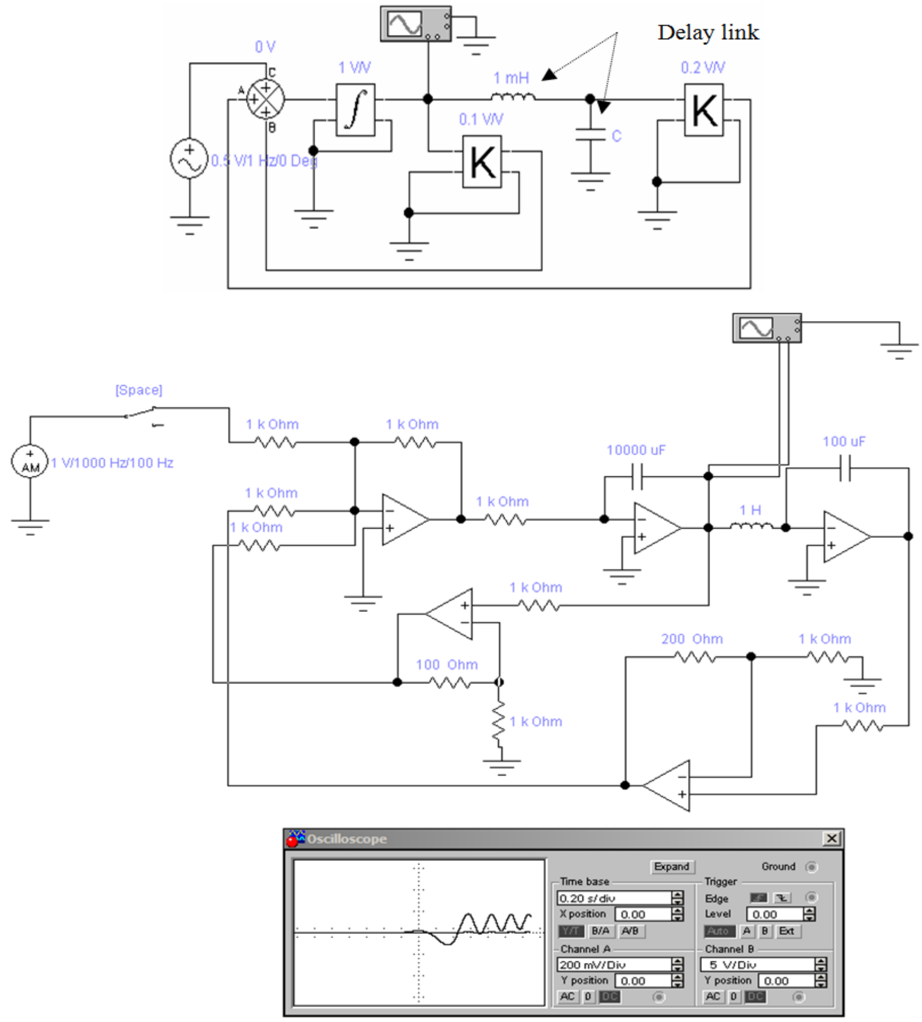

Fig. 9. Computer model of the process of formation of white blood cells

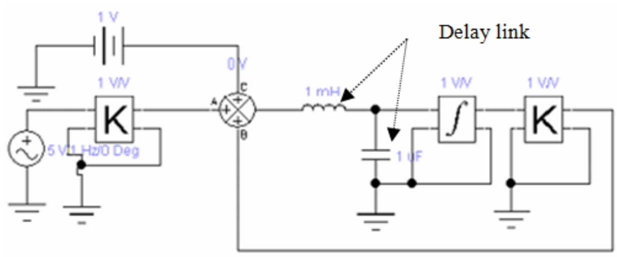

Fig. 10. Computer model of the pulsations behavior in dynamics in the visual design environment *ElWorkbench* and an signals oscillograms

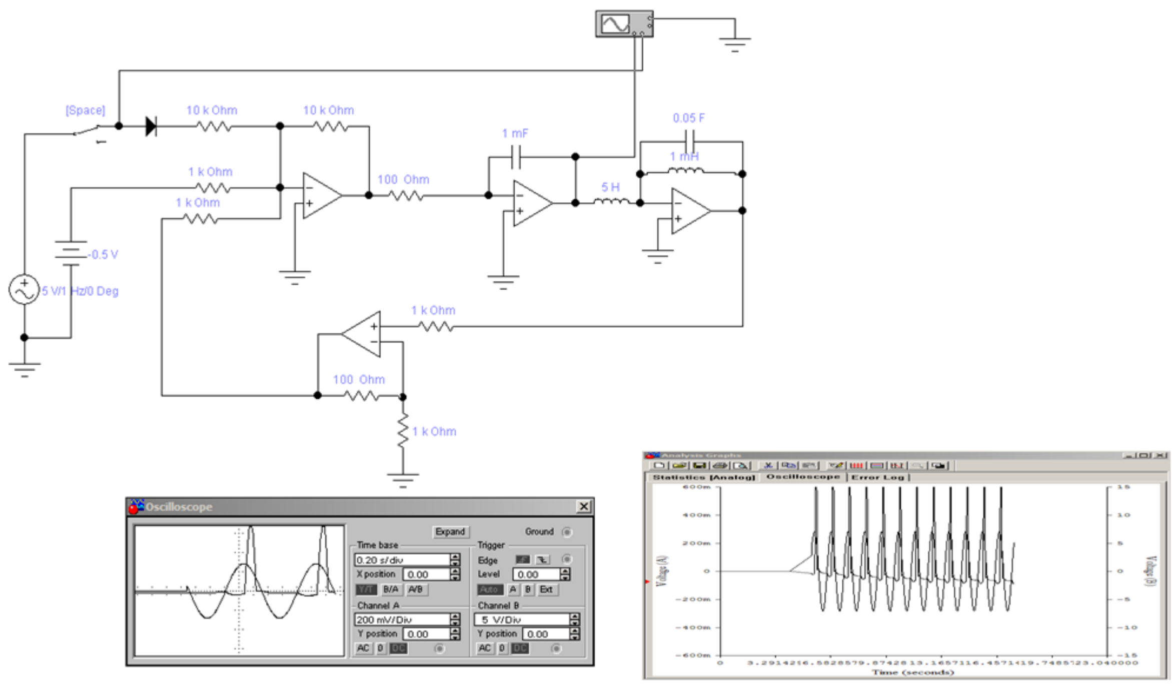

Fig. 10. Ending. (See also p. 90)

V. CONCLUSIONS

The process of development and improvement of biotechnical systems and their widespread use in medical diagnostic practice gives reason to believe about the automation of decision-making and medical diagnosis, and with the development of telemedicine – about remote examination and observation in general.

It should be noted the emergence of a wide range (class) of software developments (CAD) for the design and creation of effective medical diagnostic systems and complexes – the direction of development and implementation of biotechnical systems in everyday practice.

With the development of expert systems and automated systems and diagnostic complexes, the problem arises of high-quality and correct special algorithmic, mathematical and software support for specialized medical diagnostic systems and complexes, especially with the widespread introduction of microprocessor control of medical complexes and processing of biomedical information (biosignals).

Structural computer modeling of biological and physiological processes is based on the proven and well-known apparatus of automatic control systems, which makes it possible to study a wide class of dynamic systems described by high-order integral-differential equations, while using the real-time scale.

Due to a wide choice of circuitry implementation of functional solvers on an op-amp (in addition, you can consider the method of calculating signal converters on exponential, logarithmic and integrating functional solvers), mathematical formalization of biological and physiological objects and processes occurring in them, as well as structural interpretation of body systems (organs) is possible. with the ability to observe the reaction at any stage (step) of the signal (information) transformation.

The inclusion of the block of computer structural modeling in the composition of modern biotechnical systems and complexes will increase the flexibility and versatility of the latter in conducting research, which is useful both for the special staff of the diagnostic unit and for teachers, graduate students and student scientific and technical partnerships to improve their professional level.

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Received January 21, 2021.

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К. О. Безвершнюк, О. Б. Іванець, О. В. Мельников. Особливості комп'ютерного моделювання в сучасних біотехнічних системах

Статтю присвячено питанням особливостей комп’ютерного структурного моделювання біо- і фізіологічних систем організму людини. Встановлено, що більшість елементів живого організму і біологічних процесів, що протікають в них, формалізуються за допомогою інтегро-диференціальних рівнянь вищих порядків, аналітичне рішення яких утруднено. В якості моделюючих складових біотехнічних систем і комплексів пропонується використовувати схемотехнічну реалізацію широкого класу функціональних розв’язувачів на базі функціональних схем операційних підсилювачів що дозволяє проводити в середовищі візуального моделювання спостереження та дослідження динаміки параметрів біооб’єкту і біопроцесів у вигляді їх математичних моделей в масштабі реального часу.

Ключові слова: біотехнічні системи; біосигнал; комп’ютерне моделювання; структурне моделювання; функціональний розв’язувач; електрофізіологічний сигнал.

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К. А. Безвершнюк, О. Б. Іванец, О. В. Мельников. Особенности компьютерного моделирования в современных биотехнических системах

Статья посвящена вопросам особенностей компьютерного структурного моделирования био- и физиологических систем организма человека. Установлено, что большинство элементов живого организма и биологических процессов, протекающих в них, формализуются с помощью интегро-дифференциальных уравнений высших порядков, аналитическое решение которых затруднено. В качестве моделирующих составляющих биотехнических систем и комплексов предлагается использовать схемотехнические реализацию широкого класса функциональных решателей на базе функциональных схем операционных усилителей что позволяет проводить в среде визуального моделирования наблюдения и исследования динамики параметров биообъекта и биопроцессов в виде их математических моделей в масштабе реального времени.

Ключевые слова: биотехнические системы; биосигнал; компьютерное моделирование; структурное моделирование; функциональный решатель; электрофизиологический сигнал.

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