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DUAL CONTROL OF THE ARTIFICIAL VENTILATION PROCESS WITH USE OF A FUZZY CONTROLLER IN THE FEEDBACK CIRCUIT

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1. Introduction. Artificial ventilation of the lungs (AV) plays an important role in the system of intensive care of impaired body functions. It is a component of many resuscitation measures and is widely used in anesthesiology and intensive care.

Until recently the level of automation of the AV process has remained insufficient and requires constant accompaniment on the part of highly trained medical personnel (especially in the first stage of the procedure) [5].

One of the objective causes of such a situation is the absence of complete information about the work of the external respiration system (ERS) and absence of the possibility of monitoring all its informatively significant parameters (which can vary during AV).

Autoregulation of AV should take into account the individual activity of the ERS of the organism and fuzziness of the available information [7].

The purpose of the present work was to develop the software and methodology of using fuzzy controllers in controlling the AV process. The description of the AV control processes is based on the theory of fuzzy sets and linguistic approximations of models of the control object [1, 2, 6, 8].

2. Mathematical Model of the Control Object in the AV Loop. The patient's lungs are the control object (CO) during AV. At present Nunn's two-element model (Nunn, 1957*), which consists of element C characterizing the expansibility of the lungs and chest and element R characterizing the resistance of the upper respiratory tracts, is generally accepted. This model does not take into account separately the left and right lungs and the presence of a lag of the air mass and tissues. Nevertheless, the RC circuit describes the property of the CO in the majority of cases with an accuracy sufficient for practice.

The AV system (in addition to CO) includes a pressure generator and respiratory loop with an adjustable choke R_{ch} and inlet K1 and outlet K2 valves. For the CO the regime of operation from a source of the volume gas flow rate serves as the operating regime in the case under consideration

$$\dot{V}(t) = \dot{V}_m.$$

*As in Russian original; this reference not given in Lit. Cited — Publisher.

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As is known, the source of the flow is obtained from the pressure generator P_{gen} and series-connected resistance, which is considerably greater than the load ($R_{ch} >> R$). Switching of the valve with the respiration rate makes it possible to obtain almost rectangular pulses of the flow. The design scheme of the AV loop in the form adopted in electrical engineering is shown in Fig. 1.

The resistance of the respiratory loop (as a first approximation) is connected into the resistance of the choke. The expansibility in this scheme is equivalent to electrical capacitance C, and the pressure difference in it is equivalent to the alveolar pressure $P_A(t)$. According to Kirchhoff's second law, for the inspiratory phase

$$(R_{ch}+R)\cdot\dot{V}_I(t)+\frac{1}{C}\int\dot{V}_I(t)\,dt=P_{gen}.$$

Since $\dot{V}_1(t) = C(dP_A/dt)$

the equation for the inspiratory phase has the form:

$$\tau_1\dot{P}_A(t)\pm P_A(t)=P_{gen}\ \text{where}\ \tau_1=(R_{ch}+R)\cdot C.$$

The solution of this equation $\dot{V}_1(t)=\frac{P_{gen}}{R_{ch}+R}\cdot\exp\left(-\frac{t}{\tau_1}\right)$

or $P_A(t) = P_{gen}(1 - e^{-t/\tau_1})$.

At the end of inspiration $F_{A_0} = P_{gen}(1 - e^{-t_I/\tau_1})$, where T_I is the time of inspiration (T_E is accordingly the time of expiration). The amplitude of the flow (the main quantity being controlled):

$$\dot{V}_m=\frac{P_{gen}}{R_{ch}+R}\approx\frac{P_{gen}}{R_{ch}},$$

since $R_{ch} >> R$.

Analogously, we can obtain the equation for the expiratory phase:

$$\tau_2\cdot\dot{P}_A(t)+P_A(t)=0$$

and its solution in the form

$$\dot{V}_E(t)=-\frac{P_{A_0}}{R}\exp\left(-\frac{t}{\tau_2}\right)$$

or

$$P_A(t)=P_{A_0}\exp\left(-\frac{t}{\tau_2}\right),$$

where $\tau_2 = RC$; $\tau_2 < \tau_1$.

Thus, for the "Spiron" apparatus [5] and adopted physiological data we have as an example:

$$P_{gen}=5\ \text{kPa};\ R=(2-50)\cdot10^{-3}\ \text{kPa·min/liter}$$
$$R_{ch}=(200-950)\cdot10^{-3}\ \text{kPa·min/liter};\ C=0.1-2.0\ \text{liter/kPa}.$$

This corresponds to the limits of controlling ventilation:

$$\dot{V}_m=15\pm10\ \text{liter/min}$$

The respiration rate (frequency of switching the valves in the scheme in Fig. 1):

$$f=\frac{1}{T_I+T_E}=10-40\ \text{min}^{-1}.$$

In the "Spiron" apparatus the ratio of the time of inspiration and expiration is controlled within limits:

$$T_I:T_E=(1:1.3)-(1:3).$$

If we take a fixed value (1:1.3), then $T_I = 2.6$, $T_E = 3.4$. Thus, as standard values for a healthy male aged 25-35 years we can take:

$$R=R_S=2.84\cdot10^{-3}\ \text{kPa·min/liter},\ C=C_S=2.0\ \text{liter/kPa}.$$

We will take the reference (standard) value of the choke of the AV apparatus

$$R_{ch(s)}=0.330\ \text{kPa·min/liter}.$$

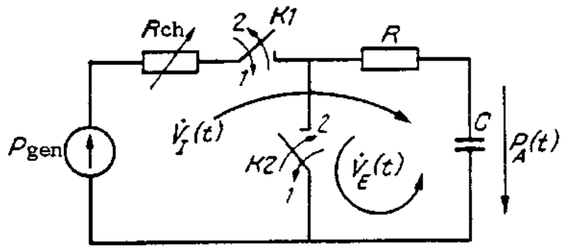

Fig. 1

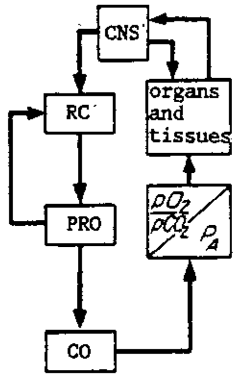

Fig. 2

Fig. 1. Design scheme of the AV loop.

Fig. 2. Block diagram of respiratory chemostat: CO) control object; PRO) partially replaced organ; RC) respiratory center; CNS) central nervous system; P_A) alveolar pressure.

3. Principle of Dual Control of the AV Process. The process of the interaction of the regulating neuroendocrine centers of the patient and the controlling actions of the operator of the AV apparatus realizes dual control [4]. The functions of the operator in the given case are performed by a fuzzy controller simulating the operator's activities on the basis of a rough model of the CO and expert evaluations (see par. 4). The distribution of the control actions between the AV apparatus and system regulating external respiration is the path of dual control.

In connection with the aforesaid we will make several comments. In the system regulating external respiration the respiratory center (RC), which is under the control of the central nervous system (CNS) and other organs and tissues, is what really matters. According to [3], the functional system (in the given case respiration) controls an actuating mechanism which produces in the CO a certain result of the action. In this case, the action of the actuating mechanism (decision making) and final results are controlled over two logic-dynamic feedback loops: the physiological loop of the ERS and loop of the AV apparatus. Mainly the diaphragmatic and abdominal muscles are the actuating mechanism of the ERS [7]. In the case of assisted AV these muscles can be regarded as a "partially replaced organ" (PRO). As the result of the action of ERS in the presence of AV we can limit ourselves to the creation of the necessary profile of the change in the alveolar pressure $P_A(t)$ during inspiration. It largely determines the content in the blood of oxygen (pO_2) and carbon dioxide (pCO_2).

Figure 2 shows a diagram of regulation of external respiration (respiratory chemostat).

During adaptation to AV organs and tissues naturally change their properties. A change in the heart rate (HR) f_h is the clearest example. It was established that the value of the ratio (f_h:f) acceptable for an organism is equal to approximately 4. If we regulate the respiration rate and we record the HR, then as a result we have a noninvasive action.

The diagram of dual control of the AV process taking into account both logic-dynamic loops with the use of the fuzzy controller is shown in Fig. 3.

The gas mixture passes through the intake 1 into pressure generator 2. The gas through adjustable choke 4 is directed into the respiratory loop, passes inspiration valve 3 and T-branch of the patient 5, and enters the lungs (CO). Expiration is realized through expiration valve 8 and outlet of the gas 9 into the atmosphere. The resistance of the choke 4 is regulated by actuating mechanism AM-1, which is used as a stepper motor. Valves 3 and 8 are controlled by actuating mechanism AM-2 (electronic circuit). The latter sets the respiration rate f as a function of HR f_h and the inspiration/expiration ratio (T_I:T_E). The compensatory reactions of the respiratory chemostat and organism as a whole are taken into account by this.

In the general case, in the future it is proposed to use an additional fuzzy controller FC1, which should be connected between the HR transducer and fuzzy controller FC. Here we will limit ourselves just to methodological comments.

The physiological mechanism of the interaction of the described logic-dynamic loops (feedback channels) of the ERS and AV realizes the negative reactions of a natural organism to the action of the AV apparatus. In this case, homeostasis of a natural organism by the feedback channels of the ERS effects adaptation of the organism to the control actions of the AV apparatus through setting informative parameters of the type (f_h:f). In this case, the discrete states (f_h:f) in the ERS channels correspond to the current continuous states in the AV channel. Thus, during AV the ratio f_h:f can be maintained in a given range up to 2 (3) h with an insignificant change in the parameters of other vitally important subsystems of the organism.* As a result, the principle of complementarity is realized during interaction of the two antagonistic mechanisms of control of ERS and AV.

A description of the logic-dynamic feedback channels interacting according to the principle of complementarity leads to the need to use various nonclassical logics [2]. Thus, the fuzzy controller (FC in Fig. 3) in the feedback channel is considered in a class of linguistic approximations on the basis of classical fuzzy logic (see par. 4), and the logic behavior of the second ERS channel realizing the negative reaction of the natural organism obeys the laws of material implication of fuzzy quantum logic. As a formalized description of classical logic we have the partially ordered set of events of the type $A \leq B$, and for quantum logic [2, 10] we have $A \leq B'$, where the prime mark is the complement (in the particular case strong negation). As a result, for the first feedback channel the law of logical conclusion has a form of the type $A \leqslant B \Rightarrow A \to B = \neg A \vee B$ where $\vee$ is disjunction, $\neg$ is equation, $\to$ is implication; for the second channel $A \leqslant B' \Rightarrow A \to B' = \neg A \vee (A \wedge B)$, where $\wedge$ is conjunction. Thus the compensatory reactions of the respiratory chemostat (second feedback channel) are described in the general case within the frameworks of fuzzy quantum logic.† According to [9-11, 15, 16, 19, 20], material implication of quantum logic is characterized by the most rigorous logical conclusion in the class of fuzzy logics and is more informative and less sensitive to variations of the initial data in comparison with the classical variants.

In the proposed scheme of dual control of the AV process we will confine ourselves to one FC producing a control signal u and for an AM-1 with a fixed state of the second feedback channel (i.e., for a given ratio f_h:f) in order to illustrate only the operating principle of the FC in the AV apparatus. An electrical model-standard (RC circuit) supplied by a current pulse generator (CPG), which in turn is regulated with respect to the pulse repetition rate and on-off ratio from AM-2, is provided for in the diagram in Fig. 3.

The transducer converts the capacitor voltage u_c into a forward signal g delivered to the adder. A signal of the quantity being regulated x from the alveolar pressure P_A transducer goes to this same adder with an opposite sign. After the adder the error ε with respect to the value of $P_A(t)$ is sent to the FC. It is necessary to note that the standard device can have also a purely program realization in the form of a mathematical model. The presence of an interchangeable standard makes it possible to take into account the expert "norm" for various groups of patients.

4. Fuzzy Regulators (Controller). In a general form the law of regulation is described as the mapping ϕ_m of a set of inputs F into a set of control actions V, i.e., $\phi_m: F \to V$.

In the given case the input quantity is $\varepsilon(t)$, the error with respect to the alveolar pressure $P_A(t)$, and the control action is u, which pertains to the stepper motor controlling the value of the resistance of the adjustable choke. However, information on the error $\varepsilon(t)$ is not sufficient for making decisions and therefore it is necessary to calculate the derivative of the error $\dot{\varepsilon}(t)$.

In view of the fact that the model of the control object is rather rough and information about individual parameters of the CO is fuzzy, the unknown regulator is realized in a class

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*The authors thank G. S. Leskin for a useful discussion of the problems touched upon.
†For quantum systems problems of fuzzy quantum logic were examined by G. Cattaneo, Fuzzy Sets and Systems, 9, No. 2, 179-198 (1983).

of linguistic approximations of fuzzy representations [1, 2, 6, 8, 12-14, 17] of the type: "if ε is equal to ε_n and $\dot{\varepsilon}$ is equal to $\dot{\varepsilon}_n$, then u is equal to u_n, otherwise..." (n = 1, 2, 3, ...).

The idea of the method of regulating the AV apparatus consists in the automatic selection of the value of the gas flow $\dot{V}_m(u)$ such that the error ε is minimum. Thus reference is to the creation in the lung of an optimal change in the alveolar pressure during the inspiratory phase under the given conditions.

On the basis of the selected model of the CO and standard model we can write:

$$x(t) = P_{gen}(1 - e^{-t/\tau_1});\ g(t) = P_{gen}(1 - e^{-t/\tau_S});$$

where $\tau_S = (R_{ch(S)} + R_S)\cdot C_S$.

By definition the error is equal to $\varepsilon(t) = x(t) - g(t)$.

Hence we obtain $\varepsilon(t) = P_{gen}(e^{-t/\tau_S} - e^{-t/\tau_1})$;

$$\dot{\varepsilon}(t) = P_{gen}\left(\frac{e^{-t/\tau_1}}{\tau_1} - \frac{e^{-t/\tau_S}}{\tau_S}\right).$$

In the FC the input signal $\varepsilon(t)$ is distributed over two channels and is differentiated in one of them. The value of the error ε and its derivative $\dot{\varepsilon}$ determine the control action u. Prior to this the signals are subjected to additional treatment:

The signal $\varepsilon(t)$ is integrated during the time of inspiration

$$\bar{\varepsilon} = \frac{1}{T_I}\int_0^{T_I} \varepsilon(t)\,dt$$

and subsequently certain values of the error are used;

the derivative of the error is taken only for time = 0, when it is maximum (for the given organization of the AV process), i.e., $\dot{\varepsilon}(0)$. It is natural that this is not the only possible solution of the discretization problem:

For generalizing the calculations, both signals are normalized with respect to their maximum values expected under operating conditions

$$\bar{\varepsilon}_N = \frac{\bar{\varepsilon}}{\bar{\varepsilon}_{max}};\quad \dot{\varepsilon}_N(0) = \frac{\dot{\varepsilon}(0)}{\dot{\varepsilon}_{max}(0)}.$$

Substituting the values of $\varepsilon(t)$ and $\dot{\varepsilon}(t)$ obtained, we have

$$\bar{\varepsilon}_N = \frac{P_{gen}}{\bar{\varepsilon}_{max}\cdot T_I}\cdot[\tau_S(1 - e^{-T_I/\tau_S}) - \tau_1(1 - e^{-T_I/\tau_1})];$$

$$\dot{\varepsilon}_N(0) = \frac{P_{gen}}{\dot{\varepsilon}(0)_{max}}\cdot\left(\frac{\tau_S - \tau_1}{\tau_S\cdot\tau_1}\right).$$

For the set of values $\pm\bar{\varepsilon}_N$ and $\dot{\varepsilon}_N(0)$ we can introduce the membership functions (MFs) and linguistic variables (LVs), as is customary in the theory of fuzzy sets [1, 2, 6]. The MFs for $\bar{\varepsilon}_N$ and $\dot{\varepsilon}_N(0)$ reflect the qualitative expert evaluation of the physiological significance of these quantities for the patient.

Figure 4 shows the form of the selected MFs for the normalized positive error, its derivative, and control action.

Curve 1 is intended for a set of values of $\bar{\varepsilon}_N$ and corresponds to the function

$$\mu(\bar{\varepsilon}_N) = \bar{\varepsilon}_N^2\cdot\exp[k_1(1 - \bar{\varepsilon}_N)],\ \text{where}\ k_1 = 2.$$

Curve 2 is selected for a set of values of $\dot{\varepsilon}_N(0)$ and differs from the preceding expression by the value of the parameter:

$$\mu[\dot{\varepsilon}_N(0)] = \dot{\varepsilon}_N^2(0)\cdot\exp\{k_2[1 - \dot{\varepsilon}_N(0)]\},\ \text{where}\ k_2 = 0.3.$$

Straight line 3 corresponds to a set of values of Δu expressed in terms of the angles of rotation of the stepper motor (AM-1).

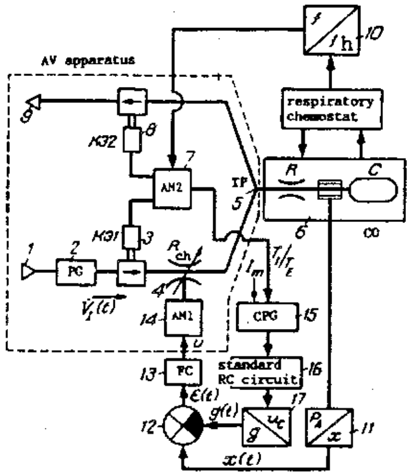

Fig. 3. Block diagram of dual control of the AV process: 1) air intake; 2) pressure generator; 3) electromagnetic inspiration valve; 4) regulating choke; 5) T-branch of patient; 6) control object (lungs); 7) actuating mechanism of valves and current pulse generator; 8) expiration valve (electromagnetic); 9) air outlet; 10) heart rate-to-respiration rate transducer; 11) P_A-to-controlled quantity transducer; 12) adder; 13) fuzzy controller; 14) actuating mechanism (stepper motor); 15) current pulse generator; 16) standard RC circuit; 17) u_c-to-forward action transducer.

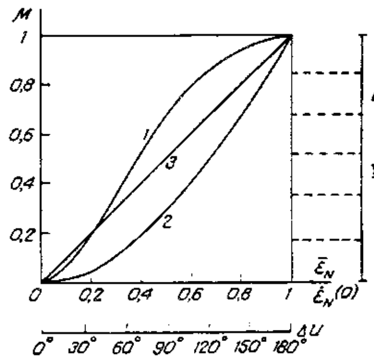

Fig. 4. Graphs of the membership functions: 1) normalized error $\mu(\bar{\varepsilon}_N)$; 2) normalized rate of variation of the error $\mu(\dot{\varepsilon}_N)$; 3) control signal $\mu(\Delta u)$.

For the normalized membership function the values of the argument and function itself are included in the interval [0, 1].

The value "1" corresponds to the condition of maximum mismatch with the health "standard" and the value of "0" means complete coincidence with it. The final form of the MF is established after experimental refinement of the system.

We will introduce the linguistic variables for the MFs in the form of term-sets of MFs of the normalized error, its derivative, and control action. For all three variables we equally denote the intervals (see Fig. 4): L – large, AV – above average, A – average, BA – below average, S – small, Z – close to zero.

In this case, the intervals are taken equal, which corresponds to the usual psychological setting.

$\mu(\dot{\varepsilon}_N)$ \ $\mu(\bar{\varepsilon}_N)$	L	AV	A	BA	S	Z
L	(L)					
AV	(L)					
A	L	(A)				
BA	L	AV				
S	AV	AV	(BA)	(BA)	(S)	(Z)
Z	(A)	A	A	BA	S	Z
	$\mu(\Delta u)$					

Fig. 5. Table of linguistic rules (TLR).

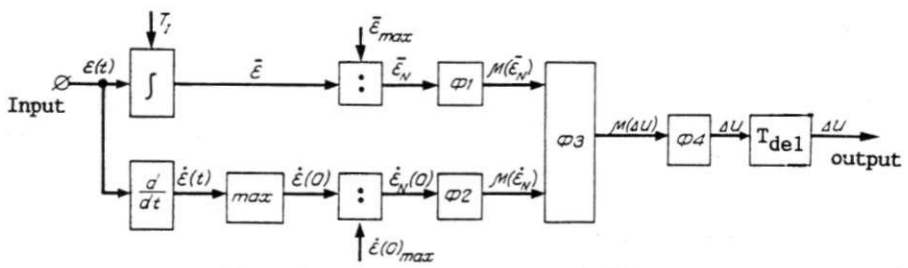

Fig. 6. Block diagram of FC.

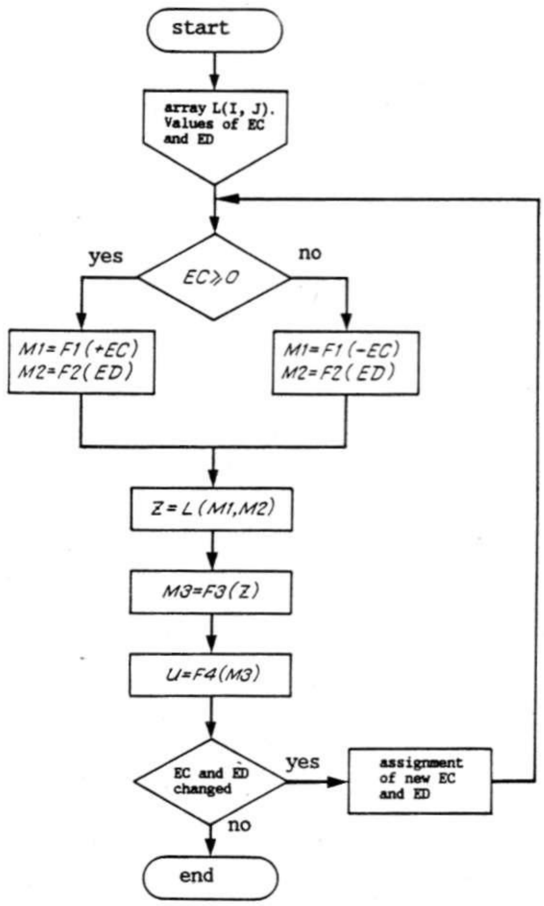

Fig. 7. Block diagram of program for processing the information of the FC.

The number of LVs can be expanded up to 120 positions of the stepper motor, but for illustrating the method we can limit ourselves to six variables.

Then we compile a table of linguistic rules (TLR) for a product of the form:

$$\text{if } \bar{\varepsilon}_N = \bar{\varepsilon}_{N_i}\left[\mu\left(\bar{\varepsilon}^*_{N_i}\right) \to \text{«AV»}\right] \text{ and } \dot{\varepsilon}_N(0) = \dot{\varepsilon}_{N_i}\left[\mu\left(\dot{\varepsilon}^*_{N_i}\right) \to \text{«Z»}\right], \text{ then } \mu(\Delta u^*) = \text{«A» } [\mu(\Delta u) \to \Delta u], \text{ otherwise . . .» etc.}$$

The LVs are denoted by asterisks, and "AV," "Z," and "A" are examples of terms. Furthermore, it is implied that a change from the LVs to the control action in the codes of the stepper motor (AM-1) is accomplished also by means of the MFs of the form shown in Fig. 4.

The selected discrete step $\Delta u = 30°$ and the code message are determined by the type of selected motor. In turn, the relation of Δu to the value of the resistance of the choke R_{ch} can be obtained in the following way.

It is obvious that neglecting the load resistance, we can write $\tau_s = R_{ch(s)} \cdot C_s$; $\tau_1 = R_{ch}(\tau_1) \cdot C_1$.

Hence $R_{ch}(\tau_1) = (\tau_1 \cdot C_s / \tau_s \cdot C_1) R_{ch(s)}$.

Subtracting $R_{ch(s)}$ from both sides, we obtain

$$\Delta R_{ch}(\tau_1) = R_{ch(s)} - R_{ch}(\tau_1) = \left(1 - \frac{\tau_1 C_s}{\tau_s C_1}\right) \cdot R_{ch(s)}$$

It is also known that along with an increase of τ_1 also C_1 increases. If we consider this relation in the first approximation to be linear $C_1 = a + b\tau_1$, then we arrive at the formula

$$\Delta R_{ch}(\tau_1) = R_{ch(s)} \cdot \left[1 - \frac{\tau_1 C_s}{\tau_s (a + b\tau_1)}\right].$$

Knowing the limits of variation of τ_1, we easily determine the parameters a and b. The values of $R_{ch(s)}$, C_s, and τ_s are known.

Thus, assigning the values of τ_1, we can calculate $\bar{\varepsilon}_N$, $\dot{\varepsilon}_N(0)$, and $\Delta R_{ch}(\tau_1)$, and consequently also Δu. As a particular example for compiling the TLR we will use the values τ_{1min} = 1.2 sec, T_I = 2.6 sec, C_{1min} = 0.1 liter/kPa. By means of the values selected earlier and the expressions obtained we calculate $\Delta R_{ch}(\tau_1)$ = 0.130 kPa min/liter (it corresponds to Δu = 180°); τ_s = 40 sec; a = 0.040; b = 0.049; ε_{max} = 3.1 kPa; $\dot{\varepsilon}_{max}(0)$ = 5.43 kPa/sec. A series of discrete values of τ_1 from 1.2 to 6 sec was taken. As a result, the TLR was obtained for the positive error (Fig. 5). The calculated values are indicated without parentheses and those obtained by extrapolation are in parentheses. The cells corresponding to unrealizable regimes for the given values and forms of the input pulses of the gas flow are hatched.

The use of MFs and the TLR corresponds to the operation

$$\bigvee_{i=1}^{n} \mu\left(\bar{\varepsilon}_{Ni}\right) \wedge \mu\left(\dot{\varepsilon}_{Ni}\right) \wedge R\left[\bar{\varepsilon}_{Ni}, \dot{\varepsilon}_{Ni}(0), \Delta u_i\right] = \mu(\Delta u),$$

where R is a fuzzy ratio.

Figure 6 shows a block diagram of the fuzzy controller. The input signal of the error $\varepsilon(t)$ goes simultaneously to the integrator and differentiator. After the latter the maximum value of the variable coinciding with the initial value is sampled. Then the signals of the error and its derivative are normalized and go to the functional converters Φ_1 and Φ_2. Here after conversion by means of the MFs and LVs we obtain the error and its derivative in a linguistic form. After this they go to converter Φ_3. In the internal memory of converter Φ_3 are stored the decision rules collected in the TLR and selection of the control action $\mu(\Delta u)$ also in a linguistic form is carried out. After reverse conversion in Φ_4 and a delay for entry into the expiratory phase T_E, the control signal Δu through the stepper motor and adjustable choke issues the values of the volume rate of the gas flow V_m compensating the error.

5. Software of Fuzzy Controller. A progressive development of the idea of dual control is its realization in the form of a microprocessor system. This is preceded by the development of a program of the functioning of at least the converters Φ_1-Φ_4. The parameters of the set of standards, selection of the MFs, and procedures for the TLR should be refined

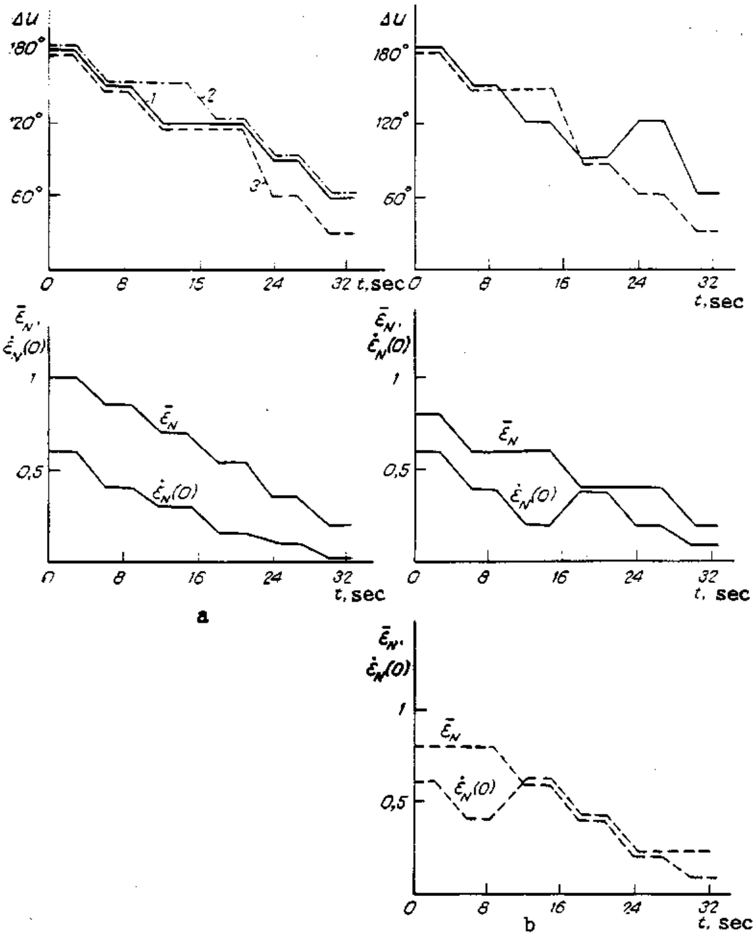

Fig. 8. Results of modeling the operation of the FC: a) sensitivity of control to a change in the parameters of the selected membership function (graph 1 corresponds to $k_1 = 2$, $k_2 = 0.3$; graph 2 corresponds to $k_1 = 2$, $k_2 = 1$; graph 3 corresponds to $k_1 = 1.5$, $k_2 = 0.3$); b) sensitivity of control to a change in the trajectory of the process ($k_1 = 2$, $k_2 = 0.3$).

during its debugging by means of a personal computer [2, 8, 18, 21]. In connection with this, we will give an example of such a program for a fuzzy controller (Fig. 7) realized on a personal computer of the type IBM PC-XT.

The program begins with assignment of the TLR in the form of a two-dimensional integer array L(I, J). Then the normalized error $\bar{\varepsilon}_N$ = EC and its derivative $\dot{\varepsilon}_N(0)$ = ED are entered.

After selecting the sign of the error EC, the values of EC and ED are converted by appropriate membership functions F_1 and F_2 to linguistic variables M1 and M2. After logical processing, in which each linguistic variable M1 and M2 is associated with an index of the array L(I, J) and the value of the quantity Z = L(M1, M2) is determined, the result is issued in the form of a linguistic variable M3 = F3(Z). Then by reverse conversion by the membership function F4 the linguistic variable M3 is converted to a control signal u. The result of the action is assessed from the viewpoint of possible changes in EC and ED. In the case of the presence of these changes, new values of EC and ED are assigned and the process is repeated.

Calculation of the functions F1-F4 in the program can be carried out by means of analytical formulas or by resorting to subprograms determining F1-F4 in a tabular form.

The parameters indicated above are refined during debugging of the program on the model and biological object.

Figure 8 gives the results of modeling the operation of the controller in time. The horizontal segments of the graphs correspond to the time of inspiration (≈2.6 sec) and the slope segments to the time of expiration (≈3.4 sec). In those cases when the variables $\bar{\varepsilon}_N$, $\varepsilon_N(0)$, Δu do not change, the horizontal segment also corresponds to expiration.

Figure 8a shows the data of the change in the positions of the controller Δu (upper graph) for the case when the error and rate of change of the error develop according to the laws represented respectively on the lower graphs. In linguistic variables such a change $\bar{\varepsilon}_N/\dot{\varepsilon}_N(0)$ can be described as L/A → L/BA → AV/S → A/Z → BA/Z → S/Z. It is seen in Fig. 8a that the position of the controller depends on the approximation of the membership functions $\mu(\bar{\varepsilon}_N)$ and $\mu(\dot{\varepsilon}_N)$. On the graph of the function $\Delta u(t)$ (Fig. 8a) the solid line corresponds to the case $k_1 = 2$, $k_2 = 0.3$, the dot-dashed line to $k_1 = 2$, $k_2 = 1$, and the dashed line to $k_1 = 1.5$, $k_2 = 0.3$.

Figure 8b gives the results of modeling the operation of the controller for two possible cases of the temporal variation of the error and its derivative (solid and dashed line). The changes in the errors and its derivative are shown on the middle and lower graphs for two trajectories. In linguistic variables these two cases of development of $\bar{\varepsilon}_N/\dot{\varepsilon}_N(0)$ can be written in the form: AV/A → A/BA → A/S → BA/BA → BA/S → S/Z (solid line); AV/A → AV/BA → A/A → BA/BA → S/S → Z/S (dashed line). The corresponding graphs of the position of the controller $\Delta u(t)$ are shown at the top of Fig. 8b.

The software and hardware realization of the FC under consideration is effected on microprocessor modules of type [18, 21].

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