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ADAPTIVE CONTROL

Logical-Dynamical Controllers for Multiply Connected Technical Objects (on Examples of Gas-turbine Engines)

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Abstract—We propose a design structure and conception for a logical-dynamical controller for separate subsystems of a multiply connected automatic control system for a complex technical object. Basing on the discrete analysis of the movement of the multiply connected control object towards its equilibrium state, we synthesize a double logical algorithm forming a logically corrected signal taking into account the influence of natural cross interfaces inside the object. Using the simulation modeling of the proposed logical-dynamical multiply connected automatic control system for an aviation gas-turbine engine, we confirm the efficiency of the double logical control algorithm authority for a complex technical object functioning under conditions of parametric and functional indefiniteness.

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INTRODUCTION

The development of the contemporary production of an air-plane engine cannot be restricted by the modernization of parts and units for the propulsion itself and the application of new materials and technologies for manufacturing it. It is necessary to improve the structure and algorithms of the control of the propulsion, treating it as a multiply connected dynamical object. This is a hard problem because any modern aviation gas-turbine engine treated as a control object is a multidimensional dynamical system, where interdependent gas-dynamics and heat-physics processes take place (see [1]).

To completely and adequately control such a complicated technical object, we have to develop multiply connected automatic control systems. Each such system is a set of interdependent separate subsystems related between each other via natural cross links in the control object and interacting between each other to obtain their common aim, e.g., the aim to obtain the desired propulsion thrust.

Such control objects are nonlinear, nonstationary, and multiply connected, i.e., there are strong dynamical interfaces between their separate subsystems. Therefore, to investigate an aviation gas-turbine engine, at the very least, its representation by a system of linearized stationary differential equations is used (see [1]). However, such a (linear) mathematical model of a gas-turbine engine is not completely adequate for real processes: it does not take into account the influence of nonlinearities, the environment, the presence of small parameters, etc. Once the investigated system is nonstationary, it leads to changes of thedynamical properties of separate subsystems and cross interfaces, caused by the changes of the operating regimes or external conditions.

Those specific properties of an aviation gas-turbine engine as a multiply connected control object lead to the indefiniteness (both parametrical and structural) of the synthesis and analysis of multiply connected automatic control systems. Apart from sufficient stability resources, the designed multiply connected automatic control system has to efficiently control an aviation gas-turbine engine, taking into account the external conditions and operating regimes. That is why the task of controlling such a technical object (an aviation gas-turbine engine) is extremely hard and design methods adequate to its properties have to be developed.

Nowadays, it is obvious that to efficiently control an aviation gas-turbine engine, taking into account its structural, parametric, and functional properties, requires designing automatic control systems from the class of intellectual systems such that they optimally utilize all accessible resources in any operating regime of the propulsion to achieve the posed aim.

Modern methods and experience in designing intellectual multiply connected automatic control systems for aviation gas-turbine engines originated both in domestic (Central Institute of Aviation Motors, Institute of Control Sciences of Russian Academy of Sciences, Moscow Aviation Institute, Ufa State Aviation Technical University, and others) and foreign scientific schools (see [2–5]). The considered area has been studied extensively; however, no unique design conception for multiply connected automatic control systems taking into account the aim to ensure the required design specifications for various operating regimes exist. This justifies the importance and urgency of the analysis and synthesis problems for intellectual control algorithms for such complicated multidimensional and multiply connected objects.

1. INTELLECTUAL CONTROL ALGORITHMS FOR COMPLEX TECHNICAL OBJECTS

Among intellectual control systems, neural-network, fuzzy-logic, and logic-dynamical control algorithms represent the most interesting directions.

In control sciences, the neural-network and fuzzy-logic approaches are mostly propagated for the cases where there is informational indefiniteness and there are no exact mathematical models. The considered approaches have the following typical advantage: it is possible to create automatic control systems that are quasi-optimal with respect to various criteria, based on a priori known information expressed by a learning sample (for the neural-network approach) or a system of production rules (for the fuzzy-logic approach), and the possibility to realize several control principles and transit from one to another. The most significant disadvantage is as follows: there are no exact verification methods for stability (for attempts to adapt existing approximation approaches, see [6–8]). Also, the design of fuzzy and neural-networks multiply connected automatic control systems requires substantial information about the influence of the environment (not only about the functioning of the control object itself). Finally, it is technically difficult to implement such types of systems.

A class of logic-dynamical control systems that vary the structure and values of their parameters due to the relationships of the internal coordinates, expressed by a logical algorithm, are also quite widely represented (see [9–11]). Thus, controlling an object is based on the parametric and structural changes of control subsystems, which is the simplest case of systems with self-organized structures. Using these logic-dynamical algorithms, we can substantially extend the possibilities to change control processes purposefully, which improves the dynamic and static properties of the control object. A common property of the existing logical algorithms is as follows: they are designed for systems with a single controlled coordinate and, therefore, the structure switches and/or the parameters change subject to the value of the control error and its derivative. Thus, the existing logical-dynamical controllers cannot take into account that modern complex dynamical objects are nonlinear and multiply connected and their parameters are nonstationary. Problems to estimate the stability of such types of systems have also not yet been resolved (see [12]).

This justifies the urgency of the theoretical and practical problem to synthesize logical control algorithms taking into account the structural and parametric properties of a multiply connected object to achieve the required control quality.

2. TWO-CHANNEL LOGICAL-DYNAMICAL CONTROLLERS

This problem has resulted in the necessity to construct a logical-dynamical control system that flexibly changes its structure and parameters subject to the behavior of a multiply connected automatic control system of a complex dynamical object as a whole in order to obtain the global functioning aim. To solve this problem, it is proposed to synthesize a two-channel logical-dynamical controller analyzing the current state and dynamics of the movement of a multiply connected automatic control system, based on a systemic method of its decomposition into the separate subsystems and multidimensional elements linking them (see [13]). Using this approach to describing the system, we can analyze multiply connected systems of any dimension and estimate the influence of the separate subsystems and links between them taking into account their structure on the control quality and stability, while preserving the property of the coordinates of the investigated system to be “physical” at all design stages (see [14]).

In [15], the following necessary condition of the efficient control of a multiply connected automatic control system for a complex dynamical object under parametric variations of separate subsystems of a multiply connected control object is established. Thus, the design conception of the proposed logical-dynamical multiply connected automatic control system is to integrate the linear controllers and two-channel logical corrector analyzing both the character of the movement of the separate subsystems and the influence of the cross interfaces on their dynamics, with the aim of improving the quality control for a multiply connected object under off-design regimes.

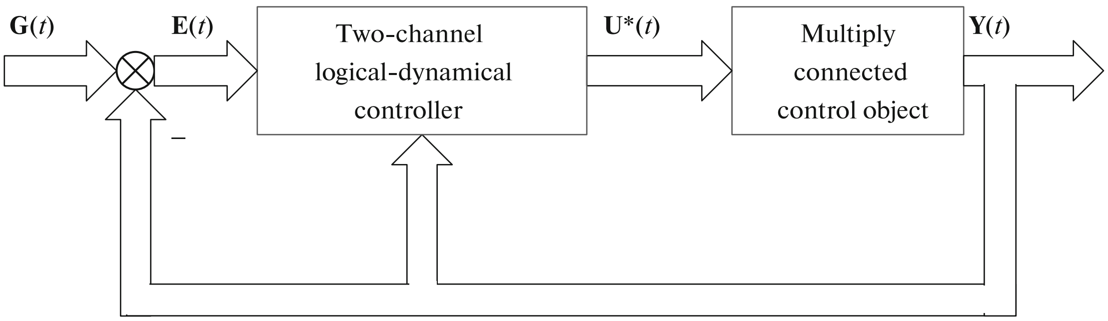

Fig. 1. Structural scheme of logical-dynamical multiply connected automatic control system of complex dynamical object.

The structural scheme of a multiply connected automatic control system with a two-channel logical-dynamical controller, implementing the proposed design conception, is presented in Fig. 1, where $\mathbf{G}(t)$, $\mathbf{Y}(t)$ is the vector of the given and controlled coordinates, $\mathbf{E}(t)$ is the vector of the control errors, and $\mathbf{U}^*(t)$ is the vector of the logically corrected control signals.

The conception of the proposed double logical control is as follows: we form a logically corrected control signal for any separate subsystem, coming from the integration of the main logical correcting control algorithm for its own separate subsystem and an additional coordinating logical algorithm, taking into account the influence of cross interfaces.

The structural scheme of a two-channel logical-dynamical controller implementing the proposed control conception is presented in Fig. 2, where the following notation is used for any ith ($i = \overline{1,n}$) separate subsystem: $\varepsilon_i(t)$ and $\dot{\varepsilon}_i(t)$ are its control error and its derivative, $\varepsilon_i^*(t)$ is the corrected control error, $y_i(t)$ and $y_j(t)$ are its own and not its own ($j = \overline{1,n}$, $j \neq i$) output coordinates, $\dot{y}_i(t)$ and $\dot{y}_j(t)$ are the derivative of its own and not its own output coordinates, $\overline{y}_i(t)$ is the coordinating signal, and $u_i(t)$, $\overline{u}_i(t)$, and $u_i^*(t)$ are its own, coordinating, and logically corrected control signals. Note that an additional linear controller is introduced to preserve the property of the separate subsystem to be astatic.

To stabilize the movement dynamics of the separate subsystem, the main logical algorithm forms the corrected error $\varepsilon_i^*(t)$ according to the following logic:

$$\varepsilon_i^*(t) = \begin{cases} \varepsilon_i(t) & \text{for} \quad (\varepsilon_i(t)\dot{\varepsilon}_i(t) \le 0) \wedge [\varepsilon_i(t)(K_{\mathrm{L}}\varepsilon_i(t) + T_{\mathrm{L}}\dot{\varepsilon}_i(t)) \ge 0], \\ \varepsilon_i(t) + T_{\mathrm{L}}\dot{\varepsilon}_i(t) & \text{for} \quad (\varepsilon_i(t)\dot{\varepsilon}_i(t) \le 0) \wedge [\varepsilon_i(t)(K_{\mathrm{L}}\varepsilon_i(t) + T_{\mathrm{L}}\dot{\varepsilon}_i(t)) < 0], \\ K_{\mathrm{L}}\varepsilon_i(t) + T_{\mathrm{L}}\dot{\varepsilon}_i(t) & \text{for} \quad \varepsilon_i(t)\dot{\varepsilon}_i(t) > 0, \end{cases}$$

where K_{L} and T_{L} are parameters of the logical algorithm, tuned subject to the external conditions and operating regimes of the multiply connected control object.

The synthesis of the specified correcting algorithm is based on the heuristic discrete analysis of the movement dynamics of the separate subsystem towards its equilibrium state via signals of the control error $\varepsilon_i(t)$ and its derivative $\dot{\varepsilon}_i(t)$ (see [16]).

Consider the main aspects of the logical correction. If a separate subsystem moves off its equilibrium state, i.e., the absolute value of the control error increases (see (t_0, t_1) and (t_3, t_4) in Fig. 3), then the logical algorithm takes the decision to slow the system's movement, taking into account the current state of the control error $K_{\mathrm{L}}\varepsilon_i(t)$ and the dynamics of its variation $T_{\mathrm{L}}\dot{\varepsilon}_i(t)$. However, if a separate subsystem approaches its equilibrium state, i.e., the absolute value of the control error decreases (see (t_1, t_3) and (t_4, t_6) in Fig. 3), its movement dynamics are counted additionally. If a separate subsystem is far from its equilibrium state (see (t_1, t_2) and (t_4, t_5) in Fig. 3), then the correcting algorithm does not produce any correcting action. If a separate subsystem is close to its equilibrium state (see (t_2, t_3), (t_5, t_6) in Fig. 3), then the logical control algorithm takes the decision to slow the system's movement dynamics, taking into account its dynamics $T_{\mathrm{L}}\dot{\varepsilon}_i(t)$. The graph in Fig. 3 displays the formation of the logical correcting error $\varepsilon_i^*(t)$ under the assumption that its own control error is $\varepsilon_i(t) = \sin(\omega t)$, its derivative is $\dot{\varepsilon}_i(t) = \omega\cos(\omega t)$, $\omega = 1\ \mathrm{s}^{-1}$, $K_{\mathrm{L}} = 1$, and $T_{\mathrm{L}} = 1$ s.

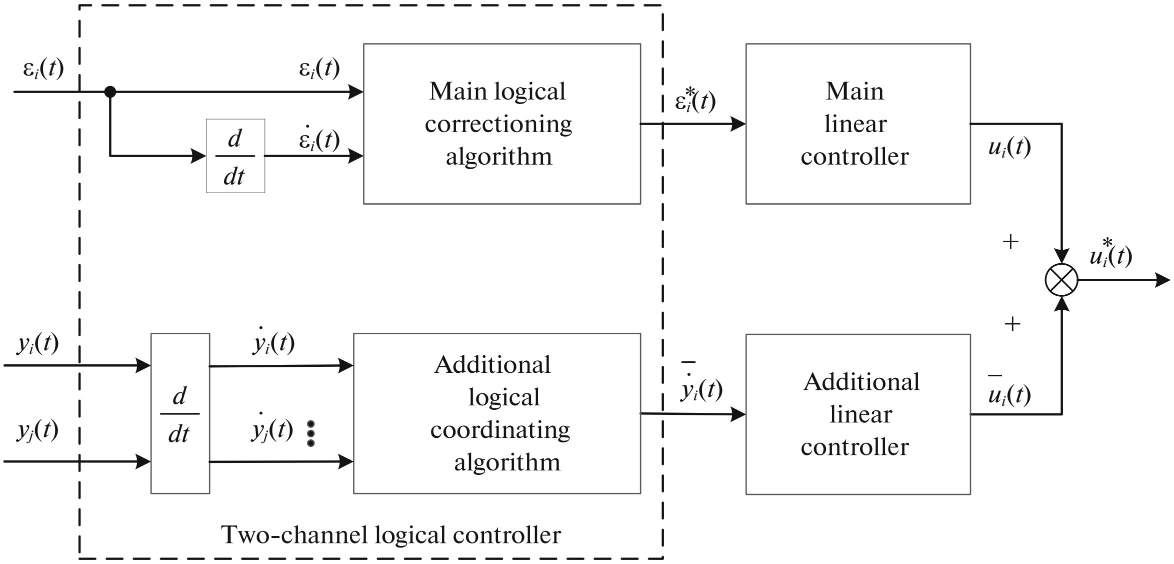

Fig. 2. Structural scheme of two-channel logical-dynamical controller in *i*th separate subsystem.

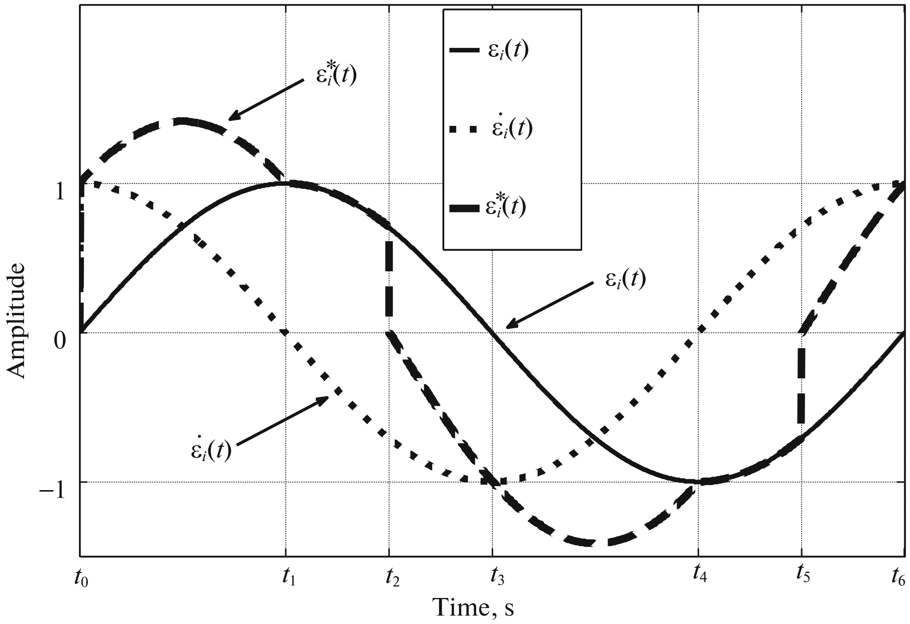

Fig. 3. Formation graph for logical correcting error $\varepsilon_i^*(t)$.

In [16], the influence of the logical correction parameters K_L and T_L on the control quality for separate subsystems is analyzed. The results of the investigation show that it is possible to select the quasi-optimal values of the logical parameters such that the correcting logical algorithm is able to reduce the oscillation transitional process in separate subsystems to an aperiodic form, using the efficient damping of the system's movement dynamics.

To coordinate the movement dynamics of the separate subsystem and the movement dynamics of the remaining separate subsystems, an additional logical algorithm forms a coordinating signal $\bar{\dot y}_i(t)$ according to the following logic:

$$\bar{\dot y}_i(t)=\begin{cases}0 & \text{for}\quad (\dot y_i(t)\dot y_j(t)\ge 0)\wedge[\dot y_i(t)(\dot y_i(t)-\dot y_j(t))\le 0],\\ -\alpha_L\dot y(t) & \text{or}\quad (\dot y_i(t)\dot y_j(t)\ge 0)\wedge[\dot y_i(t)(\dot y_i(t)-\dot y_j(t))> 0],\\ \alpha_L\dot y(t) & \text{or}\quad \dot y_i(t)\dot y_j(t)<0,\end{cases}$$

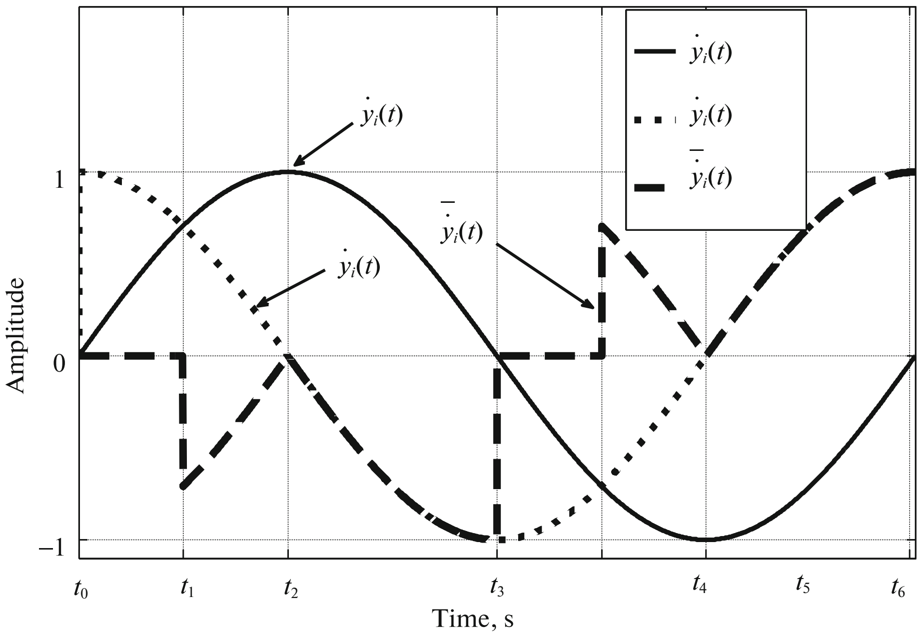

Fig. 4. Formation graph for logical coordinating signal $\bar{y}_i(t)$.

where $\dot{y}(t)$ is the dynamics of the "leading" *j*th separate subsystems, i.e.,

$$\dot{y}(t) = \max\{\dot{y}_j(t)\}, \quad j = \overline{1, n},\ j \neq i,$$

and α_L is a parameter of the logical algorithm tuned subject to the external conditions and operation regimes of a multiply connected control object.

To synthesize the above coordinating algorithm, we use the comparative discrete analysis of the movement dynamics of the separate subsystem $\dot{y}_i(t)$ with the movement dynamics of the leader $\dot{y}(t)$ among the other separate subsystems (see [17]).

Consider the main aspects of the logical coordination. If the output coordinates of the separate subsystem and the leader vary in the opposite directions (see (t_2, t_3) and (t_5, t_6) in Fig. 4), then the separate subsystems act against each other and the proposed logical algorithm forms a positive feedback $+\alpha_L\dot{y}(t)$ with respect to the movement dynamics of the leader. If the output coordinates of the compared subsystems vary in the same direction (see (t_0, t_2) and (t_3, t_5) in Fig. 4), then an additional comparative analysis of the movement dynamics of the separate subsystems is required. If the separate subsystem is ahead the leader among the other separate subsystems (see (t_1, t_2) and (t_4, t_5) in Fig. 4), the proposed logical algorithm forms a negative feedback $-\alpha_L\dot{y}(t)$ with respect to the movement dynamics of the leader. No logical interface is formed otherwise (see (t_0, t_1) and (t_3, t_4) in Fig. 4).

Figure 4 displays the graph of the formation of the logical coordinating signal $\bar{\dot{y}}_i(t)$ under the assumption that the movement dynamics of the separate subsystem are $\dot{y}_i(t) = \sin(\omega t)$, the movement dynamics of the leader among the other separate subsystems are $\dot{y}(t) = \cos(\omega t)$, $\omega = 1\ \mathrm{s}^{-1}$, and $\alpha_L = 1$.

In [17], the influence of the parameter α_l on the quality of the logical coordination for separate subsystems is analyzed. The results of the investigation show that it is possible to select a quasi-optimal value of the logical parameter such that the coordinating logical algorithm is able to compensate the destabilizing influence of the cross interfaces by introducing logical stabilizing interfaces.

Below, we show that the proposed double logical-dynamical algorithm treated as a part of a multiply connected automatic control system for a gas-turbine engine is efficient for various flight conditions and off-design operating regimes for separate subsystems.

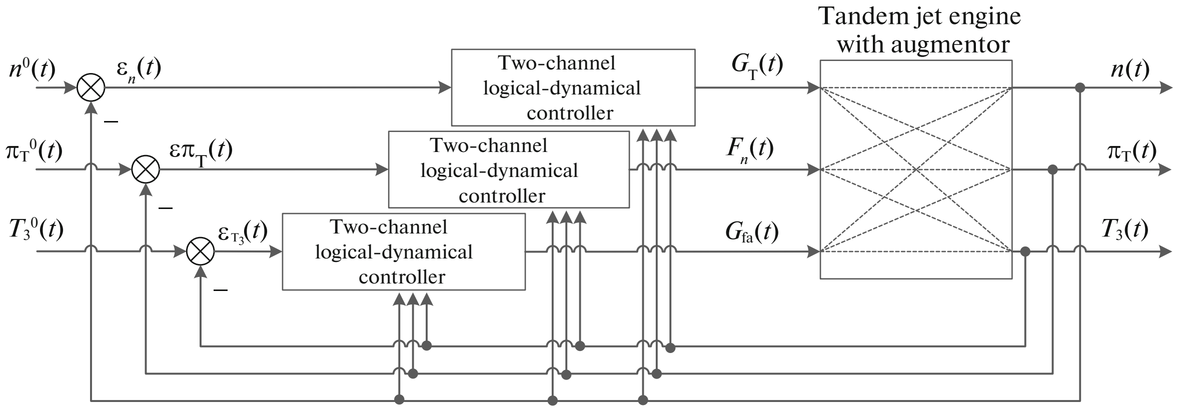

Fig. 5. Structural scheme of logical-dynamical multiply connected automatic control system of tandem jet engine with augmentor.

3. MULTIPLY CONNECTED AUTOMATIC CONTROL SYSTEM FOR GAS-TURBINE ENGINES: MOVEMENT ANALYSIS FOR VARIOUS FLIGHT CONDITIONS

To estimate the efficiency of the proposed logical-dynamical control system, we take the linearized mathematical model of a real tandem jet engine with an augmentor as an example. The structural scheme of the investigated multiply connected automatic control system with two-channel logical controllers in separate subsystems for a jet engine with an augmentor is displayed in Fig. 5. The functioning process of that control system is described by the following functional parameters of the tandem jet engine with an augmentor: the rotation frequency of the vorticity of the turbocompressor (denoted by n), the power of the pressure loss in the turbine (denoted by π_T), and the gas temperature in front of the turbine (denoted by T_3). The fuel consumption in the main burner can (denoted by G_T), the cross-section area of the reactive nozzle (denoted by F_n), and the fuel consumption in the augmentor (denoted by G_{fa}) are treated as control actions.

Assuming that a jet engine with an augmentor is investigated under workbench conditions, i.e., the flight height H and the flight velocity M are zero, and taking into account the inertia of the automatic pilots of separate subsystems with the time constant $T_{ap} = 0.4$ s, we describe the engine by the matrix transfer function

$$\mathbf{W}_{oy}(s) = \frac{1}{(0.4s+1)(0.6s+1)}\begin{bmatrix} 0.5 & 0.6 & -0.15 \\ 0.25(0.25s+1) & 0.6(0.4s+1) & -0.1(0.35s+1) \\ 0.8(0.38s+1) & -0.68(0.19s+1) & 0.13(0.23s+1) \end{bmatrix}.$$

Here $\mathbf{W}_{oy}(s)$ is the matrix transfer function of the control object.

The main multidimensional linear collector (see Fig. 2) ensuring both the required control quality and the necessary speed of a multiply connected automatic control system under the workbench regime has the following parameters:

$$\mathbf{W}_{con}(s) = \frac{0.6s+1}{(0.05s+1)s}\begin{bmatrix} 1.4 & 0 & 0 \\ 0 & 2.5 & 0 \\ 0 & 0 & 9 \end{bmatrix},$$

where $\mathbf{W}_{con}(s)$ is the matrix transfer function of the linear controller.

According to the structure of the two-channel logical-dynamical controller (Fig. 2), an additional linear controller inside each ith separate subsystem, preserving the property to be astatic, is described by the following transfer function:

$$R_i(s) = \frac{1}{s}, \quad i = 1, 2, 3.$$

The values of the parameters K_L, T_L, and α_L of the proposed two-channel logical corrector for the given regime are presented in Table1.

Table 1. Parameters of logical corrector of multiply connected automatic control system of tandem jet engine with augmentor

Separate control subsystem	T_L, s	K_L	α_L
Rotation frequency of vorticity of turbocompressor, n	0.6	1	0.2
Power of pressure loss in turbine, π_T	0.5	2	0.35
Gas temperature in front of turbine, T_3	0.8	4	0.3

In Fig. 6, the graphs of the transitional processes $\mathbf{Y}(t)$ for the output coordinate are displayed for each separate subsystem of the investigated logical-dynamical control system for a tandem jet engine with an augmentor under the workbench regime. The simulation results imply the following conclusion: both the logical-dynamical and linear controllers of the separate subsystems provide the required functioning quality for the investigated multiply connected automatic control system under the design regime.

Let us estimate the efficiency of the double logical control algorithm for an aircraft jet engine with an augmentor functioning in a broad range of flight heights and flight velocities of the aircraft.

At the point P_1 corresponding to the flight condition $H = 7$ km and $M = 1$, a multiply connected control subject is described by the following matrix transfer function:

$$\mathbf{W}_{oy}(s) = \frac{1}{(0.4s+1)(0.79s+1)}\begin{bmatrix} 0.65 & 0.6 & -0.19 \\ 0.32(0.33s+1) & 0.6(0.52s+1) & -0.13(0.46s+1) \\ 1.05(0.5s+1) & -0.69(0.25s+1) & 0.17(0.3s+1) \end{bmatrix}.$$

From the simulation modeling results (see Figs. 7a, 7b), we can conclude that even small variations of the parameters of the separate subsystems and cross interfaces between them lead to a substantial overcorrection in the investigated linear multiply connected automatic control system for a jet engine with an augmentor (see Fig. 7a). Using the proposed logical algorithms, a multiply connected automatic control system ensures the required control quality for a tandem jet engine with augmentor (see Fig. 7b).

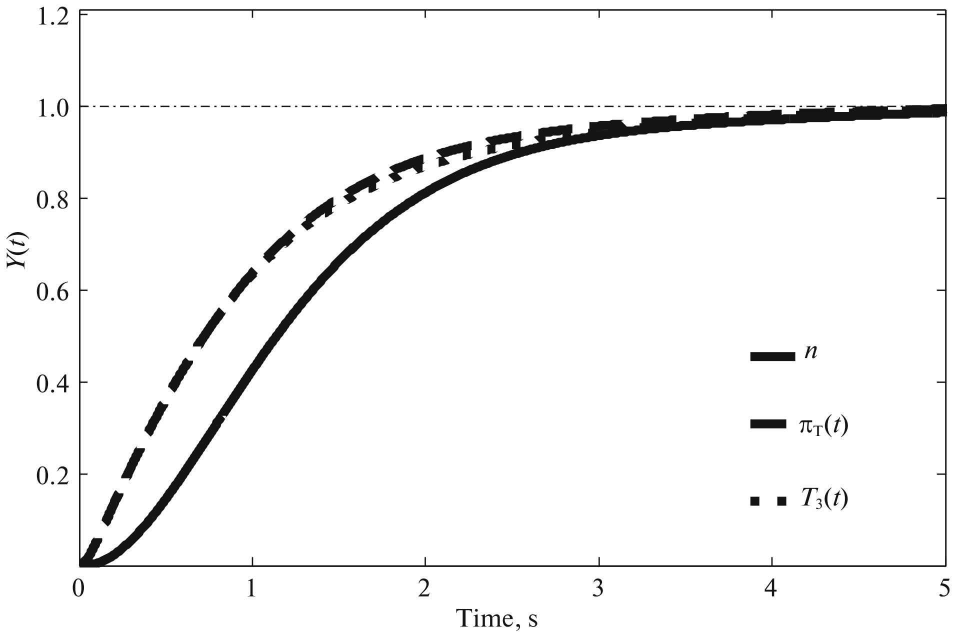

Fig. 6. Investigated logical-dynamical multiply connected automatic control system of tandem jet engine with augmentor: graph of transitional processes at calculated point.

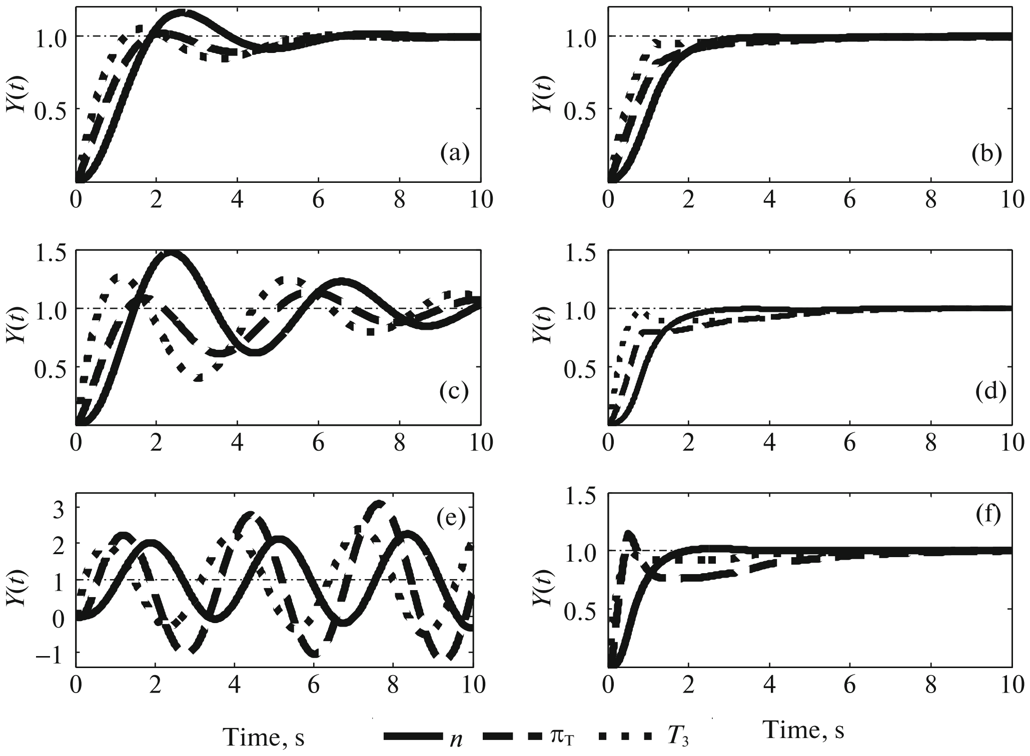

Fig. 7. Graphs **Y**(t) of transitional processes at investigated points of multiply connected automatic control system of jet engine with augmentor: (a, c, e) for case of linear controllers; (b, d, f) for case of logical-dynamical controllers.

At the point P_2 corresponding to the flight condition $H = 22$ km and $M = 2.5$, a multiply connected control object is described by the following matrix transfer function:

$$\mathbf{W}_{\text{oy}}(s) = \frac{1}{(0.4s+1)(1.41s+1)}\begin{bmatrix} 0.9 & 0.78 & -0.27 \\ 0.34(0.59s+1) & 0.6(0.94s+1) & -0.14(0.82s+1) \\ 1.88(0.89s+1) & -1.15(0.33s+1) & 0.3(0.54s+1) \end{bmatrix}.$$

From the simulation modeling results (see Figs. 7c, 7d), we can conclude that a linear multiply connected automatic control system approaches the boundary of its stability due to the more substantial variation of the parameters of a jet engine with an augmentor (see Fig. 7c). However, a logical-dynamical multiply connected automatic control system preserves an acceptable level of control quality for a jet engine with an augmentor and prevents any overcorrection in the separate subsystems (see Fig. 7d).

At the point P_3 corresponding to the flight condition $H = 17$ km and $M = 1.3$, a multiply connected control object is described by the following matrix transfer function:

$$\mathbf{W}_{\text{oy}}(s) = \frac{1}{(0.4s+1)(2.62s+1)}\begin{bmatrix} 2.18 & 0.6 & -0.65 \\ 1.09(1.09s+1) & 0.6(1.75s+1) & -0.43(1.53s+1) \\ 3.5(1.66s+1) & -0.68(0.83s+1) & 0.57(s+1) \end{bmatrix}.$$

From the simulation modeling results (see Figs. 7e, 7f), we can conclude that the substantial parametric variations of a jet engine with an augmentor, treated as a multiply connected control object, lead to the instability of the linear multiply connected automatic control system (see Fig. 7e). However, the proposed logical-dynamical controller prevents any instability of the multiply connected automatic control system, preserving the appropriate control quality for a tandem jet engine with an augmentor, while for a number of separate subsystems, overcorrections of the output coordinates are observed close to the equilibrium state (see Fig. 7f).

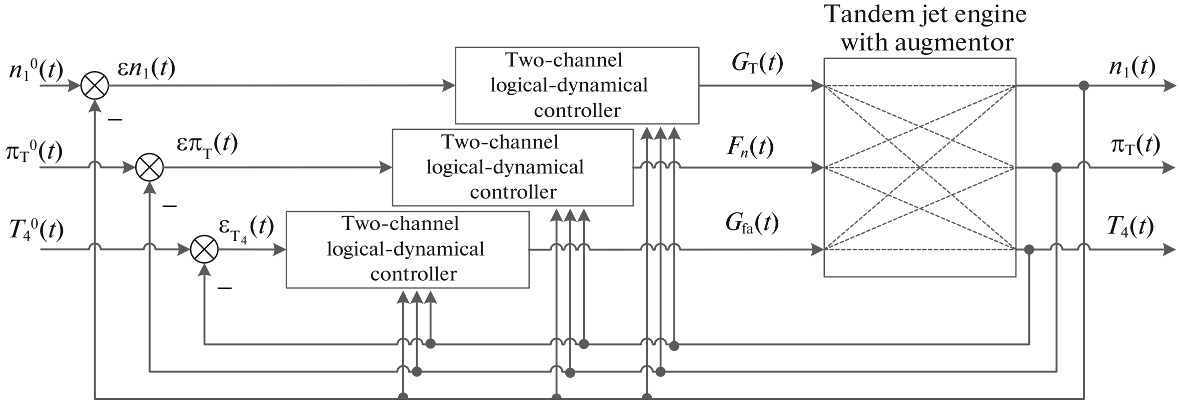

Fig. 8. Structural scheme of logical-dynamical multiply connected automatic control system of two-shaft jet engine with augmentor.

The simulation modeling results show that, by adding the proposed logical corrector to the control loop, we stabilize and coordinate the dynamics of all the separate subsystems under the parametric variations of a multiply connected control object, which increases the efficiency of controlling a gas-turbine engine functioning in a broad range of flight heights and flight velocities of the aircraft.

4. LOGICAL-DYNAMICAL MULTIPLY CONNECTED AUTOMATIC CONTROL SYSTEMS FOR GAS-TURBINE ENGINES: MOVEMENT ANALYSIS FOR OFF-DESIGN OPERATING CONDITIONS FOR SEPARATE SUBSYSTEMS

We estimate the efficiency of the proposed logical-dynamical control system for off-design operating conditions for separate subsystems, taking the linearized mathematical model of a real tandem jet engine with an augmentor.

The structural scheme of the investigated multiply connected automatic control system with two-channel logical controllers in separate subsystems for a tandem jet engine with an augmentor is displayed in Fig. 8. The functioning of the multiply connected automatic control system is described by the following parameters of a tandem jet engine with an augmentor: the rotation frequency of the vorticity of the low-pressure turbocompressor (n_1), the power of the pressure loss at the turbine (π_T), and the gas temperature behind the turbine (T_4). The same actions as in the above example, i.e., the fuel consumption in the main burner can (denoted by G_T), the cross-section area of the reactive nozzle (denoted by F_n), and the fuel consumption in the augmentor (denoted by G_{fa}), are treated as control actions.

Assuming that a jet engine with an augmentor is investigated under workbench conditions, i.e., the flight height H and the flight velocity M are zero, and taking into account the inertia of the automatic pilots of the separate subsystems with the time constant $T_{ap} = 0.15$ s, we describe the engine by the matrix transfer function

$$\mathbf{W}_{oy}(s) = \frac{1}{(0.15s+1)\left(0.15s^2+0.85s+1\right)}$$
$$\times \begin{bmatrix} 0.8(0.4s+1) & 1.6(0.45s+1) & -0.85(0.25s+1) \\ 0.26\left(0.2s^2+0.7s+1\right) & 1.25\left(0.25s^2+0.8s+1\right) & -0.5\left(0.18s^2+0.7s+1\right) \\ 0.4\left(0.3s^2+1.2s+1\right) & -0.75\left(0.2s^2+0.35s+1\right) & 0.35\left(0.25s^2+0.4s+1\right) \end{bmatrix},$$

where $\mathbf{W}_{oy}(s)$ is the matrix transfer function of the control object.

Table 2. Parameters of logical corrector of multiply connected automatic control system of two-shaft jet engine with augmentor

Separate control subsystem	T_L, s	K_L	α_L
Rotation frequency of vorticity of turbocompressor, n	1.2	2	0.25
Power of pressure loss in turbine, π_T	1.6	3	0.75
Gas temperature behind turbine, T_4	1.8	2.5	0.5

The main multidimensional linear collector (see Fig. 2) ensuring both the required control quality and the necessary speed of a multiply connected automatic control system under the workbench regime has the following parameters:

$$\mathbf{W}_{\text{con}}(s) = \begin{bmatrix} \dfrac{1.6(0.6s+1)}{(s+1)s} & 0 & 0 \\ 0 & \dfrac{2.25(s+1)}{(0.8+1)s} & 0 \\ 0 & 0 & \dfrac{4.75(s+1)}{(0.8s+1)s} \end{bmatrix},$$

where $\mathbf{W}_{\text{con}}(s)$ is the matrix transfer function of the linear controller.

According to the structure of the two-channel logical-dynamical controller (Fig. 2), an additional linear controller inside each ith separate subsystem, preserving the astatic property, is described by the following transfer function:

$$R_i(s) = \frac{1}{s}, \quad i = 1, 2, 3.$$

The values of the parameters K_L, T_L, and α_L of the proposed two-channel logical corrector for the given regime are presented in Table 2.

In Fig. 9, the graphs of the transitional processes $\mathbf{Y}(t)$ for the output coordinate are displayed for each separate subsystem of the investigated logical-dynamical control system for a tandem jet engine with an

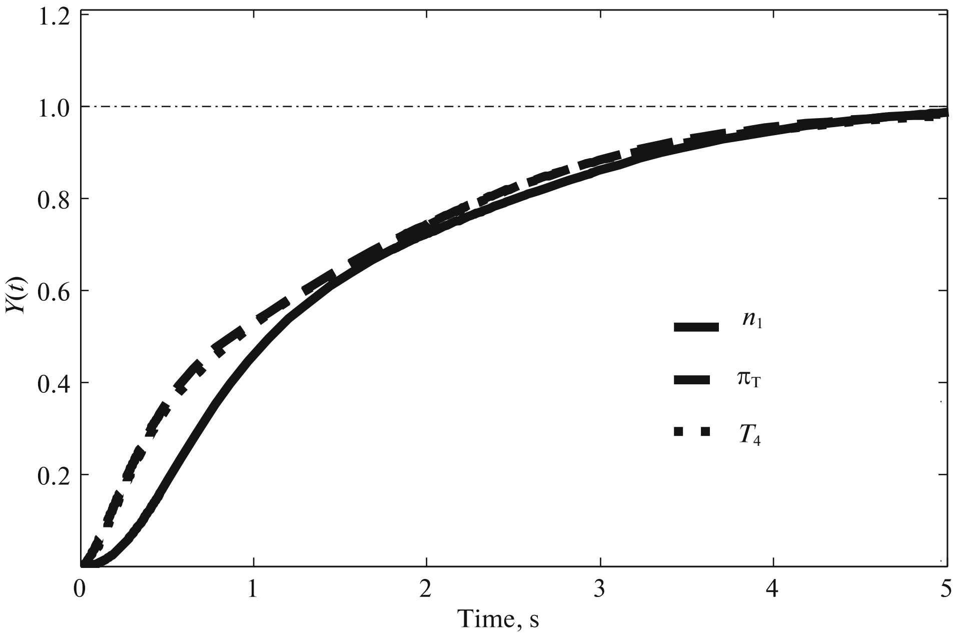

Fig. 9. Investigated logical-dynamical multiply connected automatic control system of two-shaft jet engine with augmentor: graph of transitional processes at calculated point.

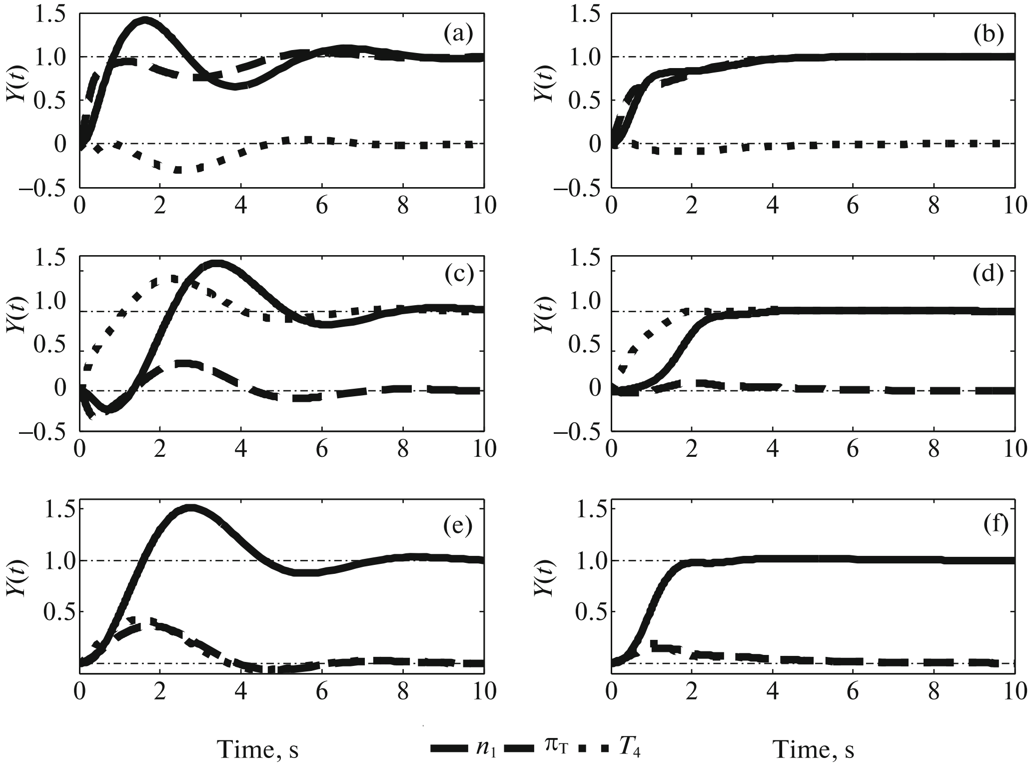

Fig. 10. Graphs **Y**(t) of transitional processes under given operating regimes of multiply connected automatic control system of jet engine with augmentor: (a, c, e) for case of linear controllers; (b, d, f) for case of logical-dynamical controllers.

augmentor under the workbench regime. The simulation results imply the following conclusion: both the logical-dynamical and linear controllers of the separate subsystems provide the required functioning quality for the investigated multiply connected automatic control system under the design regime.

Let us estimate the efficiency of the application of the two-channel logical-dynamical controller under off-design operating regimes of separate subsystems of a multiply connected automatic control system for a tandem jet engine with an augmentor.

The first operating regime of a multiply connected automatic control system is as follows: the separate subsystems controlling the rotation frequency n_1 of the low-pressure turbocompressor and the power $\pi_т$ of the pressure loss in the turbine operate in the control regime, while the separate subsystem controlling the gas temperature T_4 behind the turbine operates in the stabilization regime. From the simulation results (see Figs. 10a, 10b), we can conclude that the linear controller cannot preserve the required quality control under the given regime: substantial oscillations of the movement dynamics of the corresponding separate subsystems are observed in the transitional processes with respect to the controlled coordinates. Also, the linear controller admits a substantial deviation with respect to the stabilized coordinate (see Fig. 10a). The properties of the proposed logical-dynamical controller are such that the functioning quality of a multiply connected automatic control system for a tandem jet engine with an augmentor can be substantially improved under the given control program (see Fig. 10b).

The second operating regime of a multiply connected automatic control system is as follows: the separate subsystems controlling the rotation frequency n_1 of the low-pressure turbocompressor and the gas temperature T_4 behind the turbine operate in the control regime, while the separate subsystem controlling the power $\pi_т$ of the pressure loss in the turbine operates in the stabilization regime. From the simulation results (see Figs. 10c, 10d), we see damped oscillations in the transitional processes of the linear multiply connected automatic control system, but the functioning quality of the investigated system remains unsatisfactory (see Fig. 10c). Applying the proposed two-channel corrector in the control loop, we preserve the required control quality (see Fig. 10d).

The third operating regime of a multiply connected automatic control system is as follows: the separate subsystem controlling the rotation frequency n_1 of a low-pressure turbocompressor operates in the control regime, while the separate subsystems controlling the power π_{T} of the pressure loss in the turbine and the gas temperature T_4 behind the turbine work in the stabilization regime. From the simulation results (see Figs. 10e, 10f), we see that, by applying logical algorithms in a multiply connected automatic control system for a tandem jet engine with an augmentor (provided that the control program is given), we can prevent the oscillating movements of the coordinates with respect to the control (n_1) and with respect to the stabilization (π_{T} and T_4) compared with the linear algorithms.

The simulation modeling results confirm the promising prospects of applying the proposed logical-dynamical controller in multiply connected automatic control systems of complex technical objects because a double logical control signal is produced (due to the detailed analysis of the movement of multiply connected objects) for any separate subsystem.

CONCLUSIONS

We propose a design structure and conception for a logical-dynamical multiply connected automatic control system taking into account the structural, parametric, and functioning peculiarities of a multiply connected object, while a double logical control signal is formed for any separate subsystem. We propose a double logical control algorithm producing a control signal based on the analysis of the current state and the movement dynamics of the separate subsystem so that the influence of all the other separate subsystems is taken into account through the natural cross interfaces inside a multiply connected technical object.

The movement of the logical-dynamical multiply connected automatic control system is analyzed both for a one-shaft jet engine with augmentor, functioning in a broad range of flight heights and flight velocities for the aircraft and for a two-shaft jet engine with augmentor, operating under off-design operating regimes of separate subsystems. Results of our investigation confirm the efficiency of the proposed double logical control algorithm for multiply connected technical objects functioning under conditions of parametric and functional indefiniteness.

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