Information support of reconfigurable flight control system of the aircraft

V.M. Kazak, S.S. Drovnin

*Abstract***— The analysis of methods of recording the moment of time, place and the degree of damage of the aircraft exterior contour and the assessment of the impact of the quality of oil on the operation of the engine in conditions of aircraft's reconfiguration control with a damaged tail have been conducted. The expediency of heat transfer methods application for the recording for the purpose is shown, a theory of diagnosis the state of the exterior contour of aircraft based on its thermal fields and of the impact of oils quality used for lubrication of friction parts of aircraft engines is proposed. Simulation results of the influence of the exterior contour damage types on the flow pattern and temperature distribution are provided. The experimental research data from semi-natural tests in the wind tunnel of the National Aviation University has been obtained.**

*Index Terms***— reconfigurable system, exterior contour, aircraft damage, heat sensor, information system.**

I. Introduction

The increase of flights intensity of aircrafts, the density of their distribution over the echelons and stiffness requirements for compliance with flights schedule significantly affect on the safety level. There is a risk of aircraft's collision during flight with biological, mechanical and electrical units, which can lead to the destruction of the aircraft's structural elements or damage of its exterior contour, which can give rise to special situations in flight. Comparative analysis of the ICAO statistics showed that more than 35% of accidents caused by the aircraft's exterior contour damage and failure of flight modes and navigation complex and reduction of power characteristics of aircraft engines. According to the Federal Aviation Administration (FAA) in the civil aviation takes up to five high risk accidents annually, which account for a significant part of the aircraft's collision with biological, mechanical or electrical units and due to reduce quality of lubricants. We should also mention an extremely high rate of development of the situation in the air, which requires instant intervention in the situation to take the necessary control actions to prevent it from escalating into a catastrophic one, or at least stabilizing the speed of its development. This task can handle only high-speed reconfigurable control system, the information system of which is the basis that can instantly determine the moment of time, place and the degree of damage. as well as performance reduction of aircraft engine.

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We study the problem of monitoring the state of the aircraft in flight and its air propulsion and, in particular, its exterior contour to identify and transmit information about faults and failures in the automatic control system (ACS), which is used for reconfiguration: control actions (parametric reconfiguration), the structure of the control system (structural reconfiguration), aircraft configuration (reconfiguration of the aerodynamic configuration or shape of the aircraft), the reconfiguration of the targets of flight, ie the preservation of a safe flight regime. The urgency of this problem is obvious, as the number of aircraft collisions in the air with various kinds of units increases, the intensity of operations and the distribution density of the aircraft on the route (flight level) is also increasing, which significantly reduces air transportation safety and efficiency.

II. Analysis of published data and the formulation of the problem

A. An analysis of the literature on information support in special situations reconfigurable flight control system

Analysis of publications has shown that the science direction of diagnostics the state of the aircraft's exterior aerodynamic contour in order to prevent the development of special situations in flight is not well-developed. There is no complete agreement which of the suggested methods of recording the moment of time, place and the degree of damage of the aircraft's exterior contour in flight is the most effective to date. A group of researchers from the National Aviation University, Kyiv, Ukraine led by the supervisor of this science direction, is working in four areas of diagnosis of the aircraft exterior contour: electro-mechanic, thermodynamic, infra-red and marker-ion methods. In [1] the theoretical basics of diagnostics the state of the aircraft's exterior aerodynamic contour in flight is laid. In [2,3] all materials on the diagnosis of the aerodynamic contour, the new methods of diagnosis, the mathematical models of intact aircraft and damaged one and model the impact of injuries on the aerodynamic characteristics of the aircraft were systematized. The expediency and necessity the synthesis of control system adaptive to the aircraft's exterior contour damage and to the power plant is done. In [5] proposed a method for diagnostics the state of the aerodynamic contour of the aircraft based on the temperature field area of its airframe, and developed a system for implementing this method. Many articles [10, 11, 12] devoted to the fiber-optic diagnostics. In [6] proposed a method of diagnostics of aircraft's exterior contour in flight using film of capacitors.

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Also the marker-ion method of diagnostics the state of the aircraft's exterior contour has been developed.

B. Setting objectives for research

Given above techniques for monitoring the external contour of the aircraft in flight have a number of drawbacks. In particular, the method of diagnosis based on the change of aerodynamic forces and moments, the essence of which is that the damage to the outer contours causes a change in the total resultant forces and moments, which can be determined through appropriate linear and angular acceleration:

$$Z_0 = [n_x, n_y, n_z, n_{x0}, n_{y0}, n_{z0}, \omega_x, \omega_y, \omega_z, \dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z]^T, \quad (1)$$

where n_i, n_{ia} - accelerations measured by the respective sensors arranged in a matrix of the wing and in the center of mass of the aircraft, respectively; $\omega_j, \dot{\omega}_j$ – angular velocity and acceleration disposed in the cells of the same matrix. If necessary, reducing the number of sensors n_i or $\dot{\omega}_j$ we can use the following system of equations:

$$\frac{g}{2J_z}(n_{x1} l_{yn} - n_{x2} l_{y2}) = \dot{\omega}_z;$$
$$\frac{g}{2J_x}(n_{y1} l_{zn} - n_{y2} l_{z2}) = \dot{\omega}_x; \quad (2)$$
$$\frac{g}{2J_y}(n_{z1} l_{xn} - n_{z2} l_{x2}) = \dot{\omega}_y,$$

Where J_i - moments of inertia about the associated axes; l_{in}, l_{i2} - distancing from the center of mass of the aircraft right and left, respectively. To implement the system (2) must be placed in accelerometers aircraft associated axes or parallel thereto. The advantage of this method of monitoring is: a small number of sensors; not disturbed flow over the surface of the air flow; the ability to service them. Drawbacks: difficulties in getting accurate fault location; require periodic calibration of the monitoring system by the individual characteristics of the aircraft.

Opto-electronic method of diagnosis, the essence of which is based on the integration of ultra-thin fiber-optic sensors into the overall structure of composite materials. The fiber Bragg grating sensor allows to register the time, location and depth of damage in real time.

The principle of operation of the sensor [11] is based on the fact that the luminous flux passing through the fiber with different refractive indices, can both reflect and refract at the border. The Bragg lattice measured quantity is the shift of the Bragg wave length $\Delta\lambda_B$. The relative shift of the Bragg wave length $\Delta\lambda_B/\lambda_B$, expressed by $\mathcal{E}$ and the temperature change ΔT, can be determined the approximate dependence [12]:

$$\frac{\Delta\lambda_B}{\lambda_B} \approx (1 - p_{\mathcal{E}})\mathcal{E} + (\alpha_\Delta + \alpha_n)\Delta T, \quad (3)$$

Where $p_{\mathcal{E}}$ – optical deformation coefficient; α_Δ - coefficient of thermal expansion; α_n - thermo-optic coefficient. Advantages of the method: the ability to diagnose the condition of the outer contour of aircraft on the ground and flight conditions; It is not disturbed during the air flow along the outer contours. Disadvantages: the impossibility of maintenance and replacement of sensors; such sensors may be embedded only in the structure of composite materials.

The capacitive method of diagnosing the state of the external contours of the aircraft. The essence of this method is to record changes in the charge of capacitors when a flight deformation and damage due to collision of aircraft with biological, mechanical and electrical units appear.

To implement the method of diagnosing the state of capacitive external contour of aircraft is pasted over the surface of the capacitor film, which is an array of capacitive sensors multilayer capacitors. In case of damage to the outer contours of aircraft, a charge the capacitor in place of damage varies, which allows to determine the time, place and degree of damage. For each individual such capacitor can be written as [6]:

$$C = \frac{\mathcal{E}_r \mathcal{E}_0 S_0}{d}, \quad (4)$$

where S_0 - the initial surface area; $\mathcal{E}_r$ - the relative permittivity; d - the distance between the layers. To determine the corresponding change in capacitor charge after the injury, on condition that the changed area smaller than the initial area, we use equation:

$$\Delta U = \frac{i_c d \Delta t}{\mathcal{E}_r \mathcal{E}_0}\left(\frac{1}{S_0 - S_n}\right), \quad (5)$$

where i_c - the charge current of the capacitor, ΔU- voltage change; Δt- time interval.

Advantages of the method: the possibility of diagnostics the state of the aircraft's exterior contour during flight and on the ground. Disadvantages: The air flow along the exterior contour can be disrupted; inability to service the sensor system; replacement sensors can be the groups only; short circuits with sparks increase the risk of fire.

Marker-ion method of diagnosis is a promising method for diagnostics the aircraft's exterior contour. The method grounded on placing the chargers which charging the ions of air flow in the front edge of the wing or tail in a certain order. The receivers of charged ions set on the trailing edge, in the same order. Sensors are use kinematic method - the mark with ion pronounced electrostatic charge is formed in air flow and then moving together with a controlled airflow and has its parameters of motion speed and direction. There will not signal in the receivers in the case of damage types like gaps or holes in addition to those changes because the corresponding ion generators will be destroyed. The amplitude of the output signal of the preamplifier ion mark sensor is proportional to the current induced by mark on the electrode:

$$U_a = q_m(t) V k_{ny} S F(\alpha, \beta) n(\alpha, \beta), \quad (6)$$

Where $q_m(t)$ - the magnitude of the charge of ion marks at the registration time; V - velocity of mark's moving; k_{ny}- The pre-amplifier conversion coefficient of "current-voltage" parameters; S - area of the receiving electrode; $F(\alpha, \beta)$ - receiving electrode angular characteristic which characterize the amplitude of the current induced by deflection angles mark trajectory relative to the center electrode; $n(\alpha, \beta)$- number of marks received based on the curvature of their trajectory due to exterior contour's sudden damage.

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A more detailed study of the proposed diagnosis method is conducting by the research group in National Aviation University, Kyiv, Ukraine under the supervision of Professor Kazak V.N.

Drawbacks: the generation of the ion as a discharge mark requires high electrical power; this method causes with some difficulties at current level of development of science and technology.

The method of diagnostics the aircraft's exterior contour based on its thermal fields. The method is based on the exterior contour heating physical phenomena as a result of interaction airflow with the aircraft in flight. The heating process of the aircraft's exterior contour is as follows. The gas particles adjacent by the aircraft's exterior contour during moving the aircraft in the atmosphere are captured by a wall, and it is the same, they slowed by friction at the wall. There is the process of air particles sticking to the aircraft's exterior contour surface in the direction of oncoming flow occurs, and the boundary layer in which the velocity varies from zero at the outer surface contours to its full speed of the overall flow has formed. If the airspeed is high enough, a layer of air with a temperature differing from the outer flow surface temperature is formed close to the exterior contour, i.e. a process of heating the outer contours is occurring. The temperature distribution in the boundary layer close to the contour is uneven. The highest temperature is on the leading edges of the exterior contour, where the incoming air stream is undergo to maximum compression.

Using Fourier equation, we can rewrite it in partial derivatives with respect to the exterior contour of the aircraft:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right), \qquad (7)$$

where α - the coefficient of heat transfer from the environment to the skin, which can be calculated using the gas parameters depending on the Mach number, the altitude and the distance from the tip of the profile up to the calculated point; T - the temperature of the surface of the aircraft's exterior contour.

Taking into account the dependence (7) the heat balance equation of unsteady heat transfer mode is:

$$\alpha(T_r - T_{dem}) - \varepsilon\tau T_{dem}^4 + \beta_c G_c \cos\Psi = \lambda'\left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z}\right)_{dem}, \qquad (8)$$

where ε – emissivity coefficient; τ - blackbody radiation constant; β_c - absorption coefficient of the material of the aircraft's exterior contour; G_c - the heat flow from solar radiation which is perpendicular to the surface of exterior contour; λ' - thermal conductivity of the aircraft's exterior contour material; Ψ - the angle between the sun and the normal to the surface.

The coefficient α is a parameter for laminar and turbulent flows. For the ogive shape of surfaces, for example, the nose of the fuselage, the leading edge of the wing and tail, this ratio is calculated:

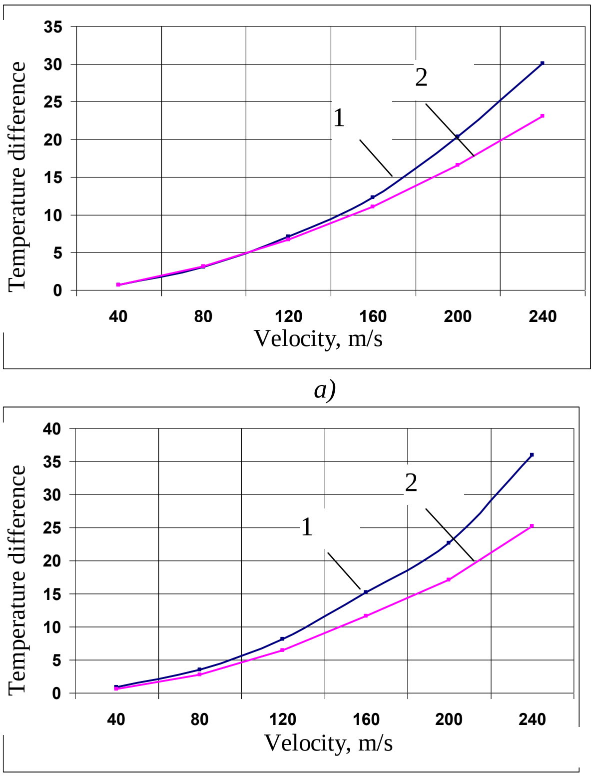
$$\alpha \approx 14kT_n^{0,75}T_{dem}^{0,25}M^{-0,116}\sqrt{\frac{\rho M}{R(120+T_{dem})}}, \qquad (9)$$

where R - radius of the surface; k - coefficient of proportionality, which take into account the sweep of the wing (stabilizer). From analysis of the above relations (7, 8, 9) follows that the measurement of temperature change of damaged surface can determine the moment of time, place and the degree of damage, and in accordance with this take action for aircraft control reconfiguration, i.e. redistribute control action of established controls; change the structural control loop by adding the deviation of the moving aircraft's controls with not peculiar control functions (chassis, brake pads, flaps, etc.); change the configuration of the aircraft; change the purpose of the flight.

The statistical analysis of ICAO data shows that the most of aircrafts collisions with biological, mechanical and electrical units occurs during takeoff and landing. According to this, it is advisable to study the transition regime of heat transfer between the boundary layer and the aircraft's exterior contour. The total amount of heat dQ_Σ which goes to the heating of the aircraft's exterior contour in flight is the sum of amount of boundary layer heat dQ_T as a result of flow turbulence and the heat quantity of the heating by direct collision.

$$dQ_\Sigma = dQ_t + dQ_{gh} \mid t' \to 0. \qquad (11)$$

Sudden damage of the aircraft's exterior contour as a result of collision with different kinds of units in the air followed by the transformation of a certain part of the kinetic energy of motion into heat, ie, a one-time heat evolution as result of the collision. Some of the heat evolution dissipates and promotes to increase the temperature of the boundary layer; the other is to increase the temperature of the exterior contour (Figures 1-4).



a)

b)

Fig. 1 Dependence of the local temperature difference between damaged and undamaged sections of the wing

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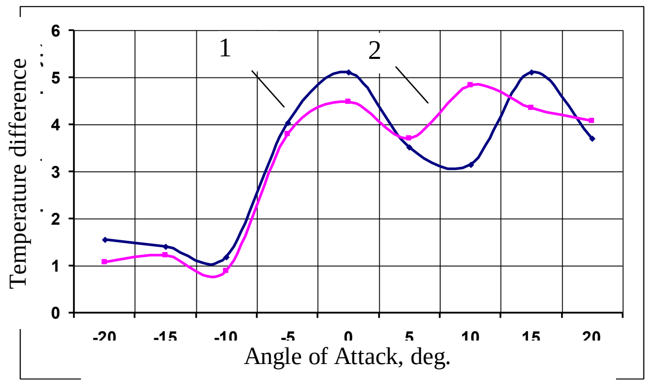
model profile of the speed of the oncoming flow over the top plane of profile (a) and the lower (b) plane of profile on the distance 1/3 chord (1) and 2/3 chord from the leading edge (2)



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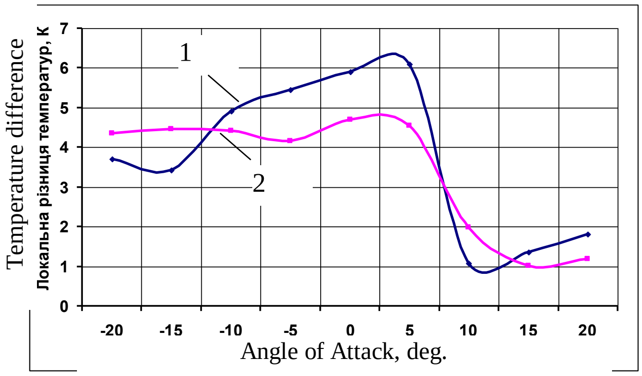

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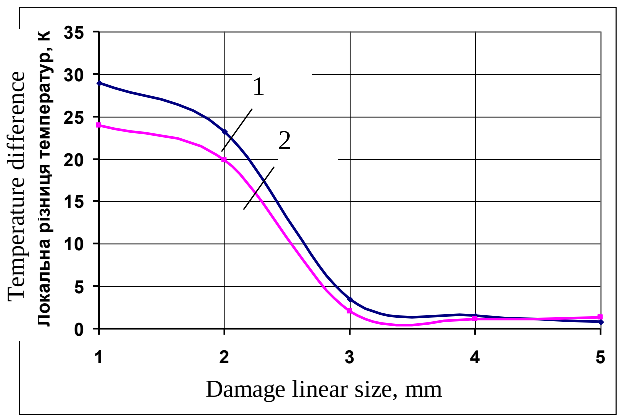
Fig. 2 Dependence of the local temperature difference between damaged and undamaged sections of the wing model profile from the angle of attack over the top plane of profile (a) and the lower (b) plane of profile on the distance 1/3 chord (1) and 2/3 chord from the leading edge (2)



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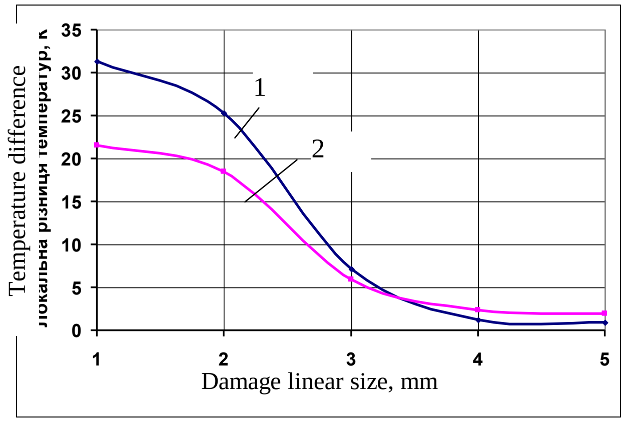
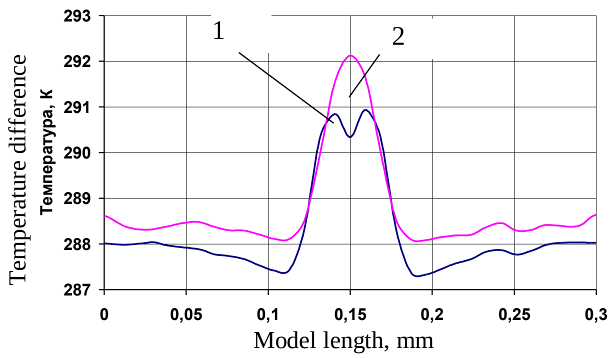


b)

Fig. 3 Dependence of the local temperature difference between damaged and undamaged sections of the wing model profile of the damage size over the top plane of profile (a) and the lower (b) plane of profile on the distance 1/3 chord (1) and 2/3 chord from the leading edge (2)



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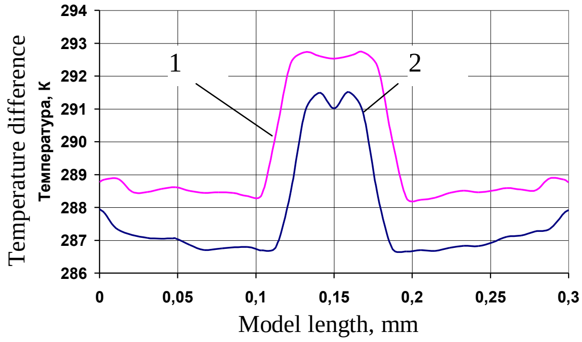

b)

Fig. 4. Temperature distribution in boundary layer along the upper (a) and bottom (b) planes of external contour of the wing model with damage like a semicircle radius 50 mm on distance from the leading edge to 1/3 of the chord (1) and 2/3 chord (2)

Given that the mass m_n of foreign object is much less compare to aircraft's mass, almost all of the foreign object kinetic energy at time t' expended on the deformation of the object and the exterior contour at the location of damage, as well as exterior contour heating:

$$E_{air} + E_n = E_\Sigma + Q_{gh};$$

$$E_{ЛА} = \frac{m_{air} V_{air}^2}{2}; \quad (11)$$

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$$E_n = \frac{m_n \bar{V}_n^2}{2},$$

Where E_{air}, E_n, E_Σ - the kinetic energy of the aircraft, the kinetic energy of foreign object and the total energy, respectively; Q - quantity of heat, which is converted into the kinetic energy as result of the impact. It can be defined as follows [2,4,9]:

$$Q_{gh} = \frac{m_{air} m_n}{2(m_{air} + m_n)} (\bar{V}_{air} - \bar{V}_n)^2, \qquad (12)$$

and its change:

$$\frac{dT_{gh}}{dt} = \frac{m_{air}}{2C_c(m_{air} + m_n)} * \frac{[(\bar{V}_{air} - \bar{V}_n)^2]}{dt_{gh}}, \qquad (13)$$

where C_c - the heat capacity of a foreign object.

The emergence of sudden damage in the wing leading edge causes a change in the geometric characteristics of the wing profile, in particular the linear dimensions of the wing chord pattern, which can be calculated by determining the projection of the segment minimum and maximum curve damage (Fig. 3) on axis x b'_d,. In this case, local thermal Reynolds number can be calculated as [8]:

$$Re_{Te} = \rho(b - b'_d)\left(\sqrt{\frac{(T_d^* - T) * 2Cp}{r}} * \left(2{,}34 * 10^3 gh \frac{T+120}{T^{2,5}}\right)\right), \qquad (14)$$

where T_d^* - the flow temperature of the outer walls of aircraft's exterior contour; $r = pr^n$ - the coefficient of restitution; $n = 1/2$ for laminar flow $n = 1/3$ - for turbulent one; *h* - height of the flight.

The dependence which links the lift changing of the damaged and undamaged contour (Fig. 4) with a temperature difference of these regions is established during the research [8]:

$$\alpha = \frac{90Y * r}{\pi^2 * \rho Cp(T_d^* - T)(S - \sum_{i=1}^{n} \iint f(x,z) d S_{di})}, \qquad (15)$$

where *Y* - the total lifting force; *S* - total area of aircraft's exterior contour.

It is known that internal processes at aircraft in actual operating condition except the influence above possible external effects of random factors can lead to deteriorating results. It is most evident that the change of the quality of working materials due to sudden changes in temperature, the appearance of water-containing compounds, gases and products of engine's rubbing parts wear with regard to aircraft engine, which in turn, can influence the change of the aircraft propulsion system total thrust vector. Tractive force of symmetric-planar twin-engine aircraft acts in the plane of symmetry, which can be presented in the Cartesian coordinate system by the following components:

$$P_{SV} = P(\delta_R, V, H)[\cos\varphi \;\; \sin\varphi \;\; 0]^T, \qquad (16)$$

where φ – the angle between the *x*-axis of the associated coordinate system and a thrust vector which can be constant in normal flight conditions and high quality of the aircraft oil, and can be variable over a certain range in cases of the implementation of the thrust vector control or its asymmetry in the case of poor lubrication of engine's rubbing parts (bearing supports and drive units, gears and gear drives, etc.). Thus, the magnitude of thrust of each engine $P_{SV} = P(\delta_R, V, H, \Lambda(t))$ depends on the position of the thrust lever, aircraft's speed and altitude, as well as the state of working oil $\Lambda(t)$ at the moment [2]. Consequently, the differential equation which describes the nonlinear dynamics and, generally, the non-stationary control system by varying the parameters of the engine due to reducing the quality of oils can be represented as follows:

$$\dot{x}(t) = f\left[X(t), \delta_R(t), V(t), H(\varphi), \Lambda(t), t\right] \qquad (17)$$

where *x* (*t*) – n-dimensional state vector of the system, $\delta_R(t)$ – the angle defining the position of the thrust lever, $\Lambda(t)$ – diagonal matrix with $s \times s$ dimension of parameter variations of the working oil.

To assess the quality of lubrication system working oil of the engine, we assume that there are no external disturbances, the initial conditions are $x_0(t_0)$. Then the model (17) can be presented in the form of explicit dependencies of state variables on the parameters and their variations:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B\delta_R(t) + G\Lambda(t) \\ y(t) &= Cx(t) + B_i\delta_R(t) + G_i\Lambda(t) \end{aligned}, \qquad (18)$$

where *A*, *B*, B_i, *G*, G_i – matrices of constant coefficients, the dimension is determined by the dimension of the system (18). For linear (linearized) system the equations (18) can be presented as:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B\delta_R(t) + G\Lambda(t) \\ y(t) &= Cx(t) \end{aligned}. \qquad (19)$$

From the analysis of the dependencies (16-19), we can conclude that the control of yaw of aircraft in case of damage to its tail can be possible using thrust vectoring, which is achieved in particular by the presence of high-quality lubricants and breathing of the aircraft engines.

This reconfiguration control of an airplane is advisable to transfer to ACS which has the reaction time is much higher compare to pilots', moreover, eliminates the human factor.

III. Conclusions

The timely intervention in the aircraft's control, in case of sudden damage, is only possible provide the timely detection of the moment of time, place and the degree of damage of the aircraft exterior contour and the transfer this information to reconfigurable control system. According to the results of the comparative analysis concluded that one of the promising methods of information support reconfigurable ACS

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monitoring system can be built based on real-time measurement of temperature fields of the aircraft's exterior contour. The models of dependences of temperature versus location and extent of damage were formalized. The results of research of wing model of aircraft AN-148 in the wind tunnel of NAU, subject to the types of damage, are shown in graphs (Fig. 1 - Fig. 4).

It is concluded that the control of yaw of aircraft in case of damage to its tail can be possible using thrust vectoring, which is achieved in particular by the presence of high-quality lubricants and breathing of the aircraft engines.

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