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SYNTHESIS OF AIRCRAFT MOTION CONTROL LAWS USING AGGREGATIVE CONTROLLER ANALYTICAL DESIGN PROCEDURE DURING AUTOMATIC IN-FLIGHT REFUELING

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Abstract

The report is aimed to solve the problem of automatization of in-flight aircraft refueling. The stated above process is quite complicated and requires extremely precise flying skills from the pilot. As for the motion control system, it shall be very accurate and flexible. The report contains the solution to the tasks of autopilot synergic synthesis to enable control of motion of the aircraft being refueled at the stage of final approach and fuel-feed line drogue capture. The synthesized adaptive controllers ensure high positioning accuracy including compensation of force and wind disturbances taking into consideration aircraft mass variation during fuel servicing.

In-flight refueling extends aircraft functional capabilities significantly. Therefore, currently, the interest to the in-flight refueling has considerably increased, in particular, as demands related to operation of unmanned vehicle grow up. Unfortunately, the refueling procedure is very difficult and hazardous to be implemented therefore, currently it is used only for military aircraft. To carry out automatic in-flight refueling, it is required to use the system able to carry out automatic approach to the tanker aircraft within the selected range of design parameters as well as stabilization of motion during fuel transfer process. In this regard, the system shall be stable to environmental disturbances, such as: wind gusts, aircraft force impact as well as aircraft weight variation associated with refueling process.

In the present document the task of synthesis of adaptive autopilots ensuring safe functioning at various environmental disturbances for motion control at the stage of approaching the tanker is being reviewed. The results of computer simulation demonstrate operability of in-flight aircraft automatic refueling system.

1. Control object mathematical model

The dynamics of aircraft approach to the refueling point when in-flight may be described using differential equation system [1]:

$$\begin{aligned}
&\dot{X}(t) = V_x, \\
&\dot{H}(t) = V_y, \\
&\dot{Z}(t) = V_z, \\
&\dot{V}_x(t) = \frac{P - \frac{1}{2}(C_{x0} + (C_y^{\alpha}\alpha)^2)((V_{ZPR} + V_x(t))^2 + V_y^2(t) + V_z^2(t))\rho S}{m} + a_x, \\
&\dot{V}_y(t) = \frac{\frac{1}{2} C_y^{\alpha}\alpha((V_{ZPR} + V_x(t))^2 + V_y^2(t) + V_z^2(t))\rho S \cos(\gamma)}{m} - g + a_y, \qquad (1.1) \\
&\dot{V}_z(t) = \frac{C_y^{\alpha}\alpha((V_{ZPR} + V_x(t))^2 + V_y^2(t) + V_z^2(t))\rho S \sin(\gamma)}{2m} + a_z.
\end{aligned}$$

A standard system of coordinates is used. The refueling point (current position of feed pipe drogue) is a datum point, X is in-between distance to the refueling point in horizontal plane; Y is the distance to the refueling point in vertical plane; Z is the cross-track deviation from the refueling point; γ is the bank angle; V_{ZPR} is horizontal speed of tanker travel; V_x is horizontal speed of aircraft travel related to the tanker; V_y is the projection of speed of aircraft travel to the vertical axis; V_z is the projection of speed of aircraft travel to the lateral axis; m is aircraft mass; $G = mg$ is aircraft weight; P is engine thrust; $Y = c_y \frac{\rho V^2}{2} S$ is lifting force, $c_y = c_y^\alpha \alpha$ is lifting force coefficient; ρ is air density, S is wing area, $V = \sqrt{(V_{ZPR} + V_x)^2 + V_y^2 + V_z^2}$ is aircraft speed relative to air masses, $Q = c_x \rho \frac{V^2}{2} S$ is drag force, $c_x = c_{x0} + c_y^2$ is drag force coefficient, $\mathbf{a} = [a_x\ a_y\ a_z]^T$ is acceleration vector resulted from external disturbance.

2. Autopilot synthesis procedure

Let's assume the autopilot synthesis task as the task of determination of thrust variation laws, angle of attack and bank angles using model status variable functions (1.1) ensuring aircraft asymptotical approach to the refueling point. In this case the terminal distance between the aircraft and refueling point as well as target speed of relative travel in the point of contact shall be equal to zero. Whereas compensation of environmental disturbance, for instance, wind disturbance, shall be ensured.

To resolve the specified above task, the philosophy of synergic control concept and the procedure of aggregative controller analytical design [2] based on the theory of implementation of attracting invariant variety within the controllable system state space, are used.

For environmental disturbance counteraction, such as gusts, force impact or weight variation, resulted from fuel transfer, a technique of variable status space extension is applied by means of introduction of additional differential equations.

As for the case currently reviewed, model (1.1) shall be completed with two differential equations as stated below:

$$\begin{aligned} \dot{z}_1(t) &= k_1 X, \\ \dot{z}_2(t) &= k_2 Y, \qquad (1.2) \\ \dot{z}_3(t) &= k_3 Z. \end{aligned}$$

Within the first synthesis stage, the stated below combination of invariant varieties is introduced as:

$$\begin{aligned} \psi_1 &= V_x - k_4 X - k_7 z_1 = 0, \\ \psi_2 &= V_y - k_5 Y - k_8 z_2 = 0, \qquad (1.3) \\ \psi_3 &= V_z - k_6 Z - k_9 z_3 = 0. \end{aligned}$$

The target formula for P, α and γ shall be determined by solving the set of the stated below functional equations:

$$\begin{aligned} T_1 \dot{\psi}_1(t) + \psi_1 &= 0, \\ T_2 \dot{\psi}_2(t) + \psi_2 &= 0, \\ T_3 \dot{\psi}_3(t) + \psi_3 &= 0 \end{aligned}$$

in view of extended system model (1.1), (1.2).

Coefficients $k_i,\ i = 1, \dots 9$ are chosen based on the conditions of stability of decomposed system describing the invariant variety intersection dynamics (1.3):

$$\begin{aligned} \dot{X}(t) &= k_4 X + k_7 z_1, \\ \dot{H}(t) &= k_5 Y + k_8 z_2, \\ \dot{Z}(t) &= k_6 Z + k_9 z_3 \\ \dot{z}_1(t) &= k_1 X, \\ \dot{z}_2(t) &= k_2 Y, \\ \dot{z}_3(t) &= k_3 Z. \end{aligned}$$

3. Computer simulation results

Closed-loop system computer simulation was carried out using parameters of model (1.1) under the stated below initial conditions:

$$m = 2200\ kg, \quad S = 25\ m^2, \quad V_{zpr} = 111 \frac{m}{\sec},$$

$$c_y^\alpha = 4.5, \quad c_x = 0.03,$$

$$a_x = -0.2 \frac{m}{\sec^2}, a_y = -0{,}1 \frac{m}{\sec^2}, a_z = 0{,}1 \frac{m}{\sec^2}$$

The results of computer simulation for closed-loop system for refueling aircraft approach are given in Fig. 1–5.

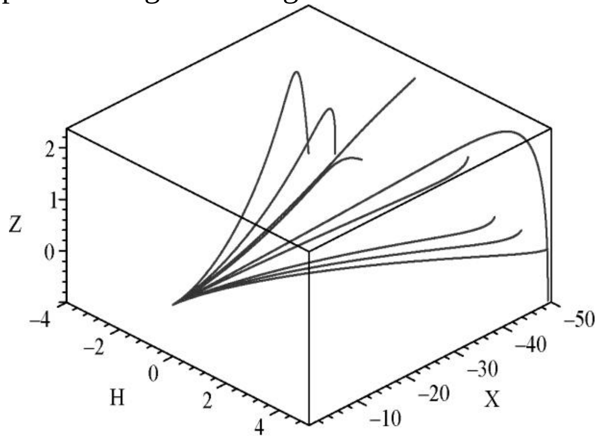

Fig.1. Aircraft flight path during approach to the refueling point when started from various initial conditions

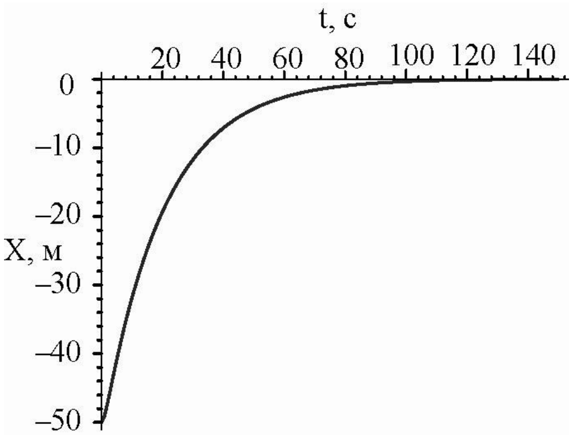

Fig.2. Transient process along X-coordinate axis.

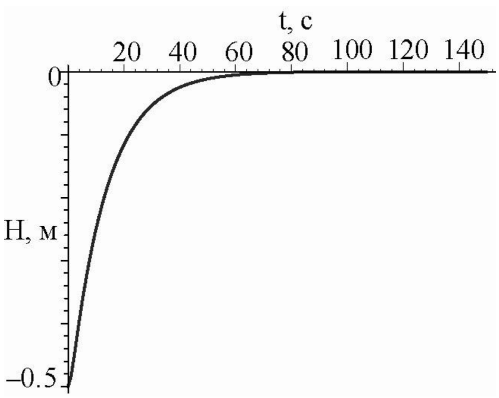

Fig.3. Transient process along H-coordinate axis.

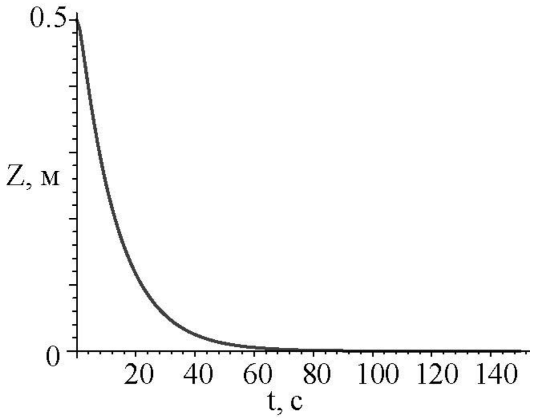

Fig.4. Transient process along Z-coordinate axis.

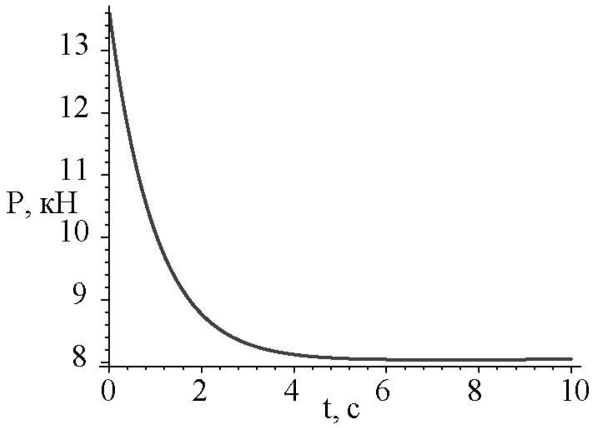

Fig. 5. Thrust versus time variation.

The results of simulation for closed-loop system during refueling at piecewise-constant disturbance at external force of Wy=1m/sec (vertical gust velocity), Fp=500kgf (uncoupling force) are given in Fig. 6–8.

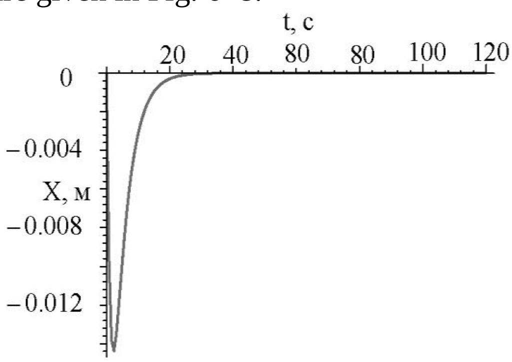

Fig.6. Transient process along X coordinate axis

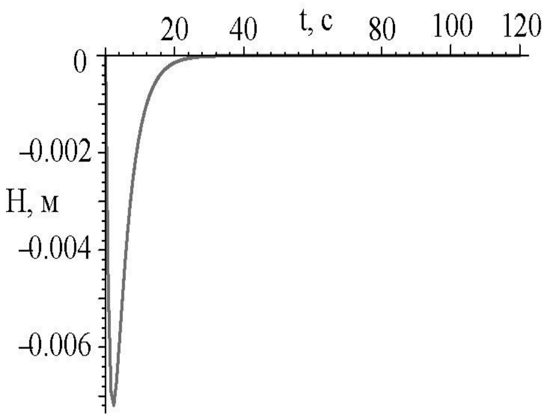

Fig.7. Transient process along H coordinate axis.

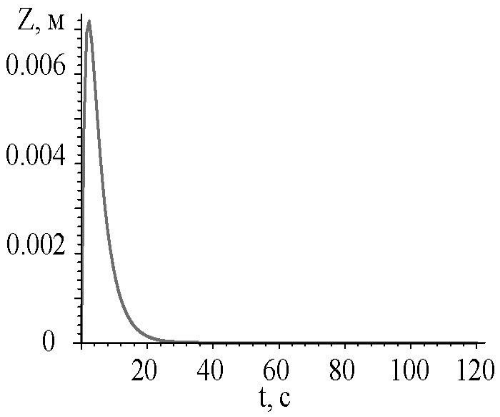

Fig.8. Transient process along Z coordinate axis.

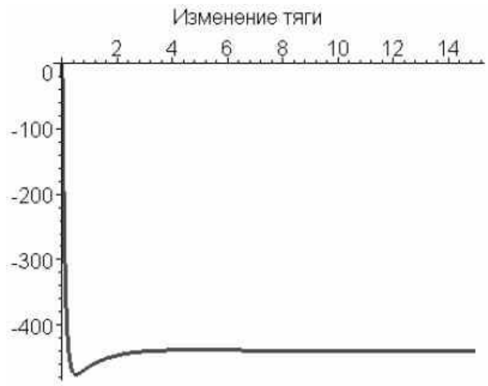

Fig. 9. Thrust versus time variation.

The results of simulation for closed-loop system at weight variation caused by fuel transfer are given in Fig. 10–12;

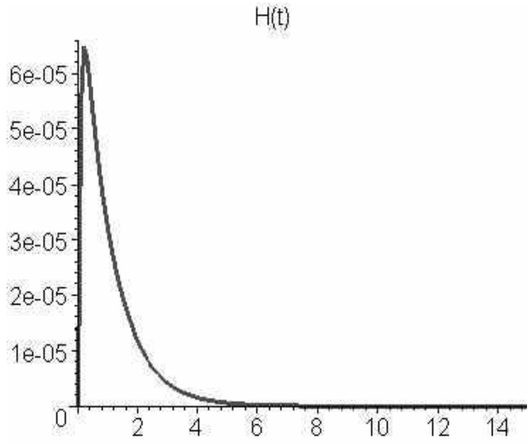

Fig.10 Aircraft altitude hold during fuel servicing

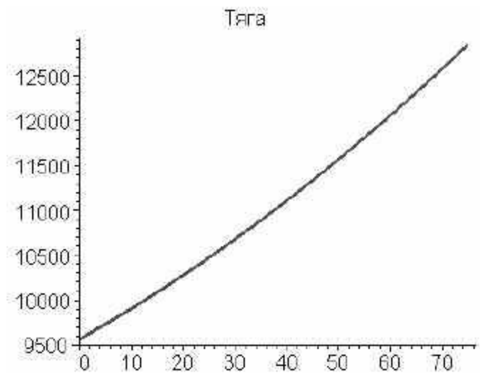

Fig.11 Thrust variation during fuel servicing

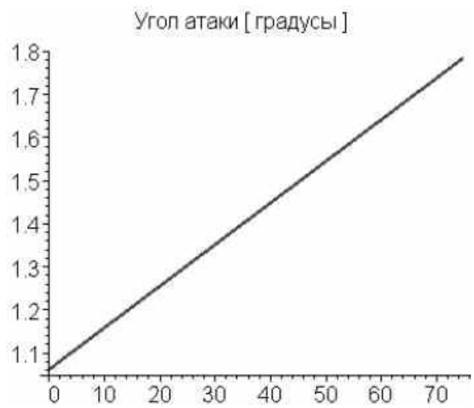

Fig.12 Law of angle of attack variation during fuel servicing

Based on the diagrams, it is clear that autopilot ensures counteraction of environmental disturbance and holds aircraft position at a refueling point thus, preventing from fuel transfer discontinuity.

The results of simulation of closed-loop system demonstrate the completion of the target control tasks during approach to the refueling point as well as during fuel transfer under conditions of environmental disturbance. Consequently, application of procedures of synergic control theory enables improvement of in-flight automatic refueling control system.

References

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[2] A. A. Kolesnikov *Applied synergetics: System synthesis principles* **-** Taganrog: TTI YFU, 2007.

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