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COMBINED SYNTHESIS OF CONTROL LAWS OF THE AIRCRAFT BRAKING ON THE RUNWAY DURING LANDING

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Keywords: *aircraft, friction coefficient, synergetic synthesis, asymptotic observer.*

Abstract

There is automatic control laws developed enabling efficient deceleration of the aircrafts on the runway during landing as provided by stabilization of the landing gear wheels slippage on runway in irrespectively of the runway surface condition (change of friction coefficient).

1 Introduction

Airplane landing is one of the most critical and dangerous flight stages. According to results of statistical analysis, most of the air accidents and fatal accidents that take place during the landing occur when an aircraft overruns the runway or collides with ground objects.

Aviation security specialists and experts of air accidents give consideration to human factor that acts as the major part of experienced air accidents in increasing frequency. According to the analysis conducted by International Air Transport Association (IATA) and International Civil Aviation Organization (ICAO), human factor was the main reason of air accidents occurred during approach or landing in 80% of the air accidents occurred within the period under review. Reduction of minimal landing parameters while contemporary improving flight operating safety is only achieved by implementing automatic control processes of approach and landing. Need of automated approach and landing control processes on IFR meteorological conditions is attributed to the fact, that other capabilities increasing flight operation security and regularity are mainly exhausted at this time. Automation of control processes allows to destress the pilots' attention, as the amount of information in the time unit during approach is being increased, but human perceptual, learning and information processing abilities are limited; attention paid by the pilot and his reactions to aircraft deviations come close to his physiological threshold, which may result in an air accident if the threshold is exceeded.

To synthesize the operational algorithms for aircraft runway path control systems, in this work it is suggested to use combined synthesis method for control laws. Real-time control synthesis or "combined synthesis" is understood as optimization-based control laws or control algorithm synthesis which is performed nearly at the same time when the control actions are formed [1÷4].

The aircraft moving along the runway as a controlled object is a multi-level non-linear dynamic system including "aircraft-landing gear-runway" subsystems. Due to this, control law synthesis methods based on linear ideology of classic control theory which have been recently actively adapted and reliably approved themselves on a sufficiently wide range of controlled objects can not consider natural performances of dynamic object being under examination, interrelation and interdependence of subsystems included into this object.

In the result, a new synergic approach to control law synthesis shall be applied. Within the frames of synergic control theory, principally new methods of automatic regulator synthesis have been developed. These methods enable to obtain control algorithms for non-linear dynamic systems of different nature. One of the most advanced synergic synthesis methods is aggregated-regulators analytical design method (ADAR) which has been actively developed by professor A. Kolesnikov and academic school headed by him. The method proved its efficiency on a number of non-linear controlled objects of different nature [5].

As a result of unequal precipitation or dirt on the runway, tires friction coefficient is changed. Therefore, during the landing, in the runway path, the aircraft may be subject to considerable disturbances exposed by contact surface, which can not be measured.

To identify unobserved variables, it is suggested to use asymptotic observer synthesis technique. The asymptotic observer is meant to estimate the external non-measurable disturbance upon available prior information on the control object and by processing current information i.e. control object state vector. Variation of brake wheels friction coefficient is considered as the non-measurable disturbance.

2 Synergic synthesis of basic control laws

Synergic control concept is a new direction of general control theory based on principles of directional self-organization of non-linear dynamic systems developed in professor A. Kolesnikov's papers. Based on synergic control theory and aggregated-regulators analytical design method, synergic synthesis procedure of basic control law of aircraft motion path and braking at runway with desirable sliding values, has been developed [6].

Mathematical model of runway aircraft motion, supplemented by equations of movement and braking of main landing gear wheels, is a system of nonlinear differential equations by 8-th order (1).

State variables. V_x, V_z - linear velocity projection on OX and OZ axes of bound coordinate system; ω_y - yaw angular rate; x_g, z_g - aircraft center of gravity displacement along OX_g and OZ_g axes of normal earthbound coordinate system; ψ - yaw angle; ω_1, ω_2 - rotational speed of right and left landing gear brake wheels.

Control actions. Let us review synthesis procedure by the example of Be-200ES-E amphibian developed by Beriev Aircraft Company. Structurally, landing gears are tricycle landing gears with front (nose) strut [7]. Aircraft runway motion path is controlled by operated steering wheels of nose landing gear. Braking process is controlled by main landing gear brake wheels. Thus, control actions are: δ_n - nose wheel steering angle; M_{T1}, M_{T2} – braking moments applied to main landing gear wheels. Nose wheel steering angle control δ_n is included as non-linear into the first three system equations (1). Braking moments M_{T1}, M_{T2} is included as linear in the 7-thand 8-th equation.

$$\begin{aligned}
&\dot{V}_x = -V_z\omega_y + (-c_x qS + 2P\cos\varphi_P - T_y(k_{f1}\mu_1 - \\
&-k_{f2}\mu_2 - k_{fn}(\mu_n \cos\delta_n - c_{zk}^{\beta}(\beta-\delta_n)\sin\delta_n)))/m; \\
&\dot{V}_z = V_x\omega_y + ((c_z^{\beta}\beta + c_z^{\delta_{pn}}k_n\delta_n)qS - T_y c_{zk}^{\beta}\beta(k_{f1} - \\
&-k_{f2}) - k_{fn}T_y(\mu_n \sin\delta_n + c_{zk}^{\beta}(\beta-\delta_n)\cos\delta_n))/m; \\
&\dot{\omega}_y = ((m_y^{\beta}\beta + m_y^{\delta_{pn}}k_n\delta_n)qSl\cos\alpha_0 - \\
&-T_y[k_{f1}\mu_1 r_{z1} + k_{f2}\mu_2 r_{z2} + c_{zk}^{\beta}\beta(k_{f1}r_{x1} + k_{f2}r_{x2}) + \qquad (1) \\
&+k_{fn}r_{xn}(\mu_n \sin\delta_n + c_{zk}^{\beta}(\beta-\delta_n)\cos\delta_n)])/I_y; \\
&\dot{x}_g = V_x\cos\psi + V_z\sin\psi; \\
&\dot{z}_g = -V_x\sin\psi + V_z\cos\psi; \\
&\dot{\psi} = \omega_y; \\
&\dot{\omega}_1 = k_{f1}T_y\mu_1 R/J - M_{T1}/J; \\
&\dot{\omega}_2 = k_{f2}T_y\mu_2 R/J - M_{T2}/J
\end{aligned}$$

Control target. In this problem, control targets are as follows:

1) aircraft motion along desired path, to be exact, selection of such aircraft path that would enable performance of desirable technological system invariant – nullification of lateral aircraft displacement from runaway axis $z_g = z_g^* = 0$;

2) main landing gear braking with desirable sliding values $s_1 = s_1^*$, $s_2 = s_2^*$.

Setting up a problem. It is required to find a control vector in analytical form

$$u = [M_{T1}(x), M_{T2}(x), \delta_n(x)],$$

As coordinate function of x state system (1), enabling performance of specified technological invariants:

$$z_g = z_g^* = 0\,,\; s_1 = s_1^*\,,\; s_2 = s_2^* \qquad (2)$$

Controlling strategy procedure for control autopilot of runway aircraft motion in braking mode is performed by setting of parallel collection of invariant manifolds based on control channel numbers:

$$\begin{aligned} &\psi_1 = (1 - s_1^*)V_X - R\omega_1 = 0; \\ &\psi_2 = (1 - s_2^*)V_X - R\omega_2 = 0; \qquad (3) \\ &\psi_3 = -V_x \sin\psi + V_z(\mathrm{t})\cos\psi + \alpha_3(z_g - z_g^*) = 0 \end{aligned}$$

With this, parallel manifold collection (3) must satisfy solution of functional equation system

$$\begin{aligned} &\dot{\psi}_1 + \alpha_1\psi_1 = 0; \\ &\dot{\psi}_2 + \alpha_2\psi_2 = 0; \qquad (4) \\ &\dot{\psi}_3 + \alpha_4\psi_3 = 0 \end{aligned}$$

where: $\alpha_1 - \alpha_4$ – coefficients which influence on process dynamics quality in closed system. According to aggregated-regulators analytical design method procedure, we can obtain expression for controlling action δ_n from joint solution (3), functional equations (4) and model equation (1)

$$\begin{aligned} \delta_n = {} & ([T_y(k_{fn}\mu_n + k_{f1}\mu_1 + k_{f2}\mu_2) - R_x]\sin\psi + \\ & + [qSc_z^\beta\beta - T_y c_{zk}^\beta \beta(k_{fn} + k_{f1} + k_{f2})]\cos\psi + m(\alpha_3 + \\ & + \alpha_4)(V_z\cos\psi - V_x\sin\psi) + \alpha_3\alpha_4 m z_g)/(k_{fn}T_y c_{zk}^\beta \beta\,\cdot \qquad (5) \\ & \cdot\sin\psi - qSc_z^{\delta_{pn}} k_n\cos\psi + T_y(k_{fn}\mu_n + k_{fn}c_{zk}^\beta)\cos\psi) \end{aligned}$$

where

$$R_x = (c_y\sin\alpha_0 - c_x\cos\alpha_0)qS + 2P\cos\varphi_P\,; \qquad (6)$$

and expressions for braking moments M_{T1}, M_{T2}, applied to main landing gear wheels:

$$\begin{aligned} & M_{T1} = Rk_{f1}T_y\mu_1 - \frac{J}{R}((1 - s_1^*)\cdot \\ & \cdot(\frac{X}{m} - V_Z\omega_y + \alpha_1 V_X) - \alpha_1 R\omega_1); \\ & M_{T2} = Rk_{f2}T_y\mu_2 - \frac{J}{R}((1 - s_2^*)\cdot \qquad (7) \\ & \cdot(\frac{X}{m} - V_Z\omega_y + \alpha_2 V_X) - \alpha_2 R\omega_2), \end{aligned}$$

where X – projection of total forces, applying on aircraft, OX axis of coordinate bound system

$$\begin{aligned} & X = -c_x qS + 2P\cos\varphi_P - T_y(k_{f1}\mu_1 - k_{f2}\mu_2) - \\ & -k_{fn}T_y(\mu_n\cos\delta_n - c_{zk}^\beta(\beta - \delta_n)\sin\delta_n) \end{aligned} \qquad (8)$$

Nose wheel deviation angle limitations are -8° ≤ δ_n ≤ 8° and are introduced by piecewise continuous function:

$$\delta_n = \begin{cases} u_{\min} & if \;\; u < u_{\min} \\ u & if \;\; u_{\min} \le u \le u_{\max} \\ u_{\max} & if \;\; u > u_{\max} \end{cases} \qquad (9)$$

Modeling results at different initial aircraft deviation from axis runway line (5m – black, 15m – blue, 25m – red color), given in fig. 1-10, show synthesized system operability.

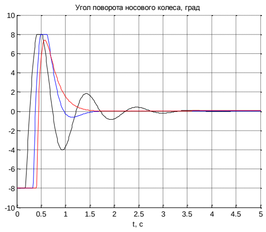

Fig. 1. Nose Wheel Steering Angle, grade

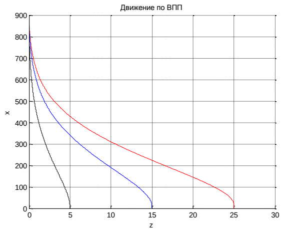

Fig. 2. Lateral Aircraft Drift z_g in Coordinate Function x_g, m

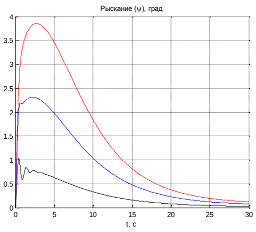

Fig.3.Yaw Angle, grade

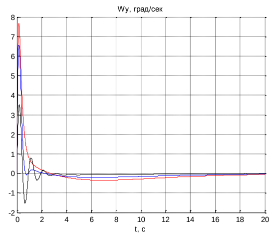

Fig. 4. Yaw Angular Speed, grade/sec

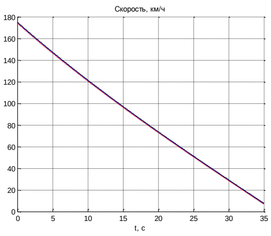

Fig.5. Aircraft Speed, km/h

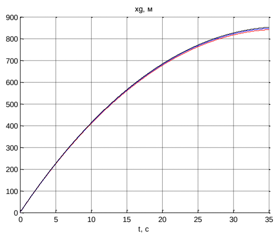

Fig.6. Coordinate x_g, m

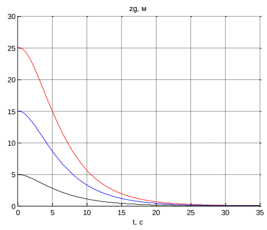

Fig.7. Lateral Aircraft Time Drift, m

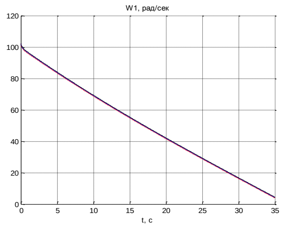

Fig.8. Angular Wheel Rotational Speed, rad/sec

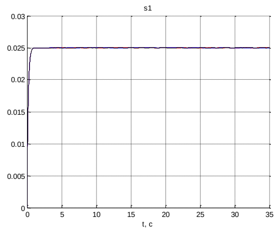

Fig. 9. Wheel Sliding

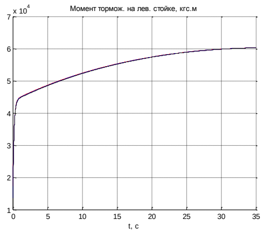

Fig. 10. Wheel Brake Moments, kgf.m

The regulator obtained enables to enhance strategy of aircraft behavior at runway and solve problem complexly avoiding lateral aircraft drift and enabling aircraft braking with sliding to be regulated in predetermined value.

3 Synergetic synthesis of adaptive regulators

Adaptive regulators synergetic synthesis technique was developed on the basis of Synergetic Control Theory and ADAR method. For the aircraft, control laws' synthesis is realized under exposure of external non-measurable disturbances, i.e. under change of brake wheels friction coefficient, and on the basis of approach developed in the previous section. First, disturbances' non-measurable variables are entered, and then asymptotic observer is constructed to estimate the variables variation.

Synthesis of dynamic regulator with friction *coefficient observer*. To synthesize the regulator, the model of controlled object and the one for disturbances acting on the object are used in the following form:

$$\dot{x} = g_0(x,u) + G_1(x)z; \quad \dot{z} = h_0(x,u) + H_1(x)z, \tag{10}$$

where: x is observable variables' vector, z – non-observable variables' vector, u – control vector; g_0 & h_0 – continuous non-linear function, G_1 & H_1 – functional matrices.

Task specification: it is required to synthesize the external non-measurable disturbances' observer, providing the asymptotic stability of closed-loop system, completion of prescribed technological invariants (2), and estimation of non-observable external effects at current values of observable state coordinates.

First Stage – search of control vector $u(x)$ as a function of extended model state coordinates. The vector has to implement the synthesis of technological invariants determined by formulas (2). It is assumed that all the system state coordinates are observable, including runway surface condition (friction coefficient).

Second Stage – asymptotic observer synthesis in the following form:

$$\dot{y}(t) = R(x,\ y), \quad \hat{z}(t) = K(x,\ y),$$

where: y –is observer state vector, $\hat{z}$ – non-measurable external disturbance estimation vector.

Third stage: The extended model is completed with y observer equations, and non-observable variables are replaced in the control laws with $\hat{z}$ asymptotic estimations.

It is required to synthesize the dynamic regulator with asymptotic observers for mathematical model (1). New non-observable variables z_1 & z_2 replace respective friction coefficients μ_1 & μ_2 in the right part of the equations. Initial model (1) is completed with the equations built for $\dot{z}_1$ & $\dot{z}_2$. Mathematical model of extended system takes following form (11):

$$\begin{aligned}
&\dot{V}_x = -V_z\omega_y + (-c_x qS + 2P\cos\varphi_P - T_y(k_{f1}z_1 - \\
&-k_{f2}z_2 - k_{fn}(\mu_n\cos\delta_n - c_{zk}^{\beta}(\beta-\delta_n)\sin\delta_n)))/m; \\
&\dot{V}_z = V_x\omega_y + ((c_z^{\beta}\beta + c_z^{\delta_{pn}}k_n\delta_n)qS - T_y c_{zk}^{\beta}\beta(k_{f1} - \\
&-k_{f2}) - k_{fn}T_y(\mu_n\sin\delta_n + c_{zk}^{\beta}(\beta-\delta_n)\cos\delta_n))/m; \\
&\dot{\omega}_y = ((m_y^{\beta}\beta + m_y^{\delta_{pn}}k_n\delta_n)qSl\cos\alpha_0 - \\
&-T_y[k_{f1}z_1r_{z1} + k_{f2}z_2r_{z2} + c_{zk}^{\beta}\beta(k_{f1}r_{x1} + k_{f2}r_{x2}) + \\
&+k_{fn}r_{xn}(\mu_n\sin\delta_n + c_{zk}^{\beta}(\beta-\delta_n)\cos\delta_n)])/I_y; \\
&\dot{x}_g = V_x\cos\psi + V_z\sin\psi; \\
&\dot{z}_g = -V_x\sin\psi + V_z\cos\psi; \\
&\dot{\psi} = \omega_y; \\
&\dot{\omega}_1 = k_{f1}T_y z_1 R/J - M_{T1}/J; \\
&\dot{\omega}_2 = k_{f2}T_y z_2 R/J - M_{T2}/J; \\
&\dot{z}_1 = 0; \\
&\dot{z}_2 = 0.
\end{aligned} \tag{11}$$

Path control regulator and wheel skidding regulator is created in similar way, as the aforesaid regulators, on the base of the model (11), assuming that all the model variables are observable. Then external effects observer - changing of runway surface condition is synthesized.

Observer equations take the final form given below:

$$\dot{y} = Ly - L\int_0^x \Gamma(x)\,dx - h_0(x) + \Gamma(x)\,g_0(x,u) \qquad (12)$$

Estimations of non-observable external exposures:

$$\hat{z}_1(t) = -\frac{\lambda_1 r_{z2} m}{k_f(r_{z2}-r_{z1})}V_x + \frac{\lambda_1 I_y}{k_f(r_{z2}-r_{z1})}\omega_y - z_1(t);$$
$$\hat{z}_2(t) = \frac{\lambda_2 r_{z1} m}{k_f(r_{z2}-r_{z1})}V_x - \frac{\lambda_2 I_y}{k_f(r_{z2}-r_{z1})}\omega_y - z_2(t). \qquad (13)$$

It has been demonstrated during computer simulation performed for the Be-200 airplane that synthesized control laws provide asymptotic stability of close-looped system, implement the prescribed technological invariants, and estimate non-observable external disturbances. Therefore, brand-new control system was synthesized. This system allows accomplishing multiple tasks as an integral unit: stabilizes the value specified for wheel skidding, adjusts the aircraft runway path, and traces the change of runway surface characteristics in real time (fig. 11-20).

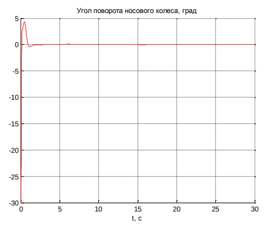

Fig. 11. Nose Wheel Steering Angle, deg

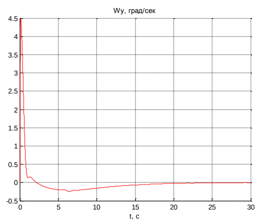

Fig. 12. Yaw Rate, deg/s

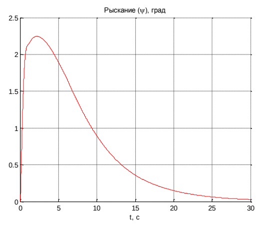

Fig. 13. Angle of Yaw, deg

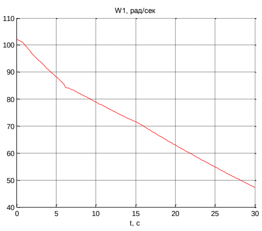

Fig. 14. Tire Angular Speed, rad/s

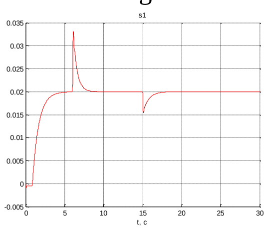

Fig. 15. Left Wheel Skidding

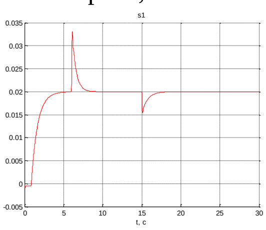

Fig. 16. Right Wheel Skidding

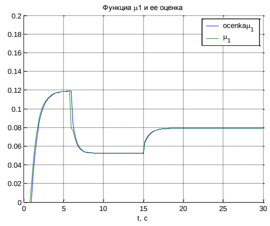

Fig. 17. Friction Coefficient μ_1 and its Estimation

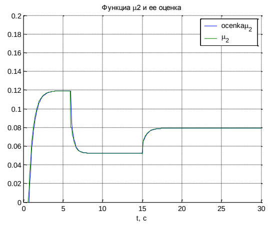

Fig. 18. Friction Coefficient μ_2 and its Estimation

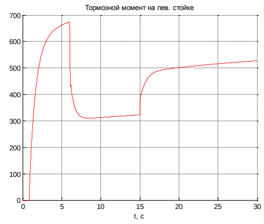

Fig. 19. Left Wheels Brake Torque, kgf.m

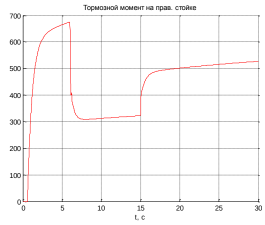

Fig. 20.Right Wheels Brake Torque, kgf.m

4 Conclusion

Synergetic approach to combined synthesis of aircraft runway path control laws applicable during braking with current identification of its parameters is reviewed in the work. Following basic results were obtained in the course of the work:

1. Synergetic synthesis was developed for basic vector control laws applicable for model of the aircraft running along the runway: brake (skidding) regulators for the brake wheels, and aircraft runway path control law which allow enhancing the aircraft behavior on the runway and finding the complex solution for control problem.
2. Synergetic synthesis was developed for aircraft runway path control law applicable while braking. The law considers contact surface condition (friction coefficient) asymptotic observers, therefore the procedure allows: to stabilize the skidding value regardless of runway condition; implement smooth control modes and reduce the wear of brake system actuators, in contrast to existing anti-skid cycling servo system (impulse, quasi-modulating and fully modulating systems).

Obtained results formed theoretical and methodological base for brand-new aircraft runway path control systems applicable during the landing and braking; which provide effective aircraft braking dynamics depending on specified skidding mode and external conditions.

Thus the procedure of combined synthesis of control laws under review enables not only to improve the aircraft behavior on the runway and to solve wholistically the control task, but also to decrease the pilot's load that increase the flight safety in all.

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