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SOLUTION OF THE PROBLEM OF IDENTIFICATION OF AERODYNAMIC COEFFICIENTS OF AIRCRAFT ACCORDING TO THE DATA OF THEIR FULL-SCALE TESTS

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Abstract*—The methodology of the correct identification of the aerodynamic coefficients of the aircraft is considered, namely the determination of the partial derivatives of the aerodynamic forces and moments of the aircraft according to its state variables. The method of determining static (balancing) dependencies from short-term dynamic modes of a natural experiment is also presented. The effectiveness of the proposed approach is confirmed by the practice of determining the aerodynamic coefficients and aerodynamic characteristics of various aircraft.*

Index Terms—Identification; aerodynamic coefficients; aircraft; active experiment; non-linearity; non-stationarity; efficiency; correctness.

I. INTRODUCTION

In the process of creating new and improving existing aircraft, an important element is full-scale tests, especially the task of determining the stability and controllability of aircraft, i.e. aerodynamic coefficients (ADC) and aerodynamic characteristics (ADCh). There are many theoretical studies devoted to the problem of identification, that is, the construction of mathematical models (MM) of the studied dynamic object based on the data of an active experiment or passive observation of its behavior from the classics of the theory of identification [1], [2] to the works of modern researchers [3] – [7]. Thus, in [3] it is proposed (similar to the method of modeling functions) to move from linear differential equations MM to algebraic equations using the method of least squares (LSM). The paper [4] emphasizes the importance of goal orientation to the main task in the construction of the MM of the object under study. In [5], an exponentially weighted recurrence procedure of OLS for the identification of MM parameters is considered. The paper [6] emphasizes the importance of the broadband of the test signal for the correct identification of the missile ADC. In the paper [7], the method of maximum likelihood was used to identify aircraft's ADC. So, in general, we can conclude that the considered works have a theoretical rather than a practical result, consider linear or abstract (not related to the physics of processes) nonlinear MM. At the same time, the complexity of solving these problems is a consequence of the properties of real objects, which are characterized by:

- not autonomy (not isolation from an infinite number of external factors);
- the absence of absolutely constant parameters (matter and motion are inseparable);
- the absence of linear dependencies (law of general relationship);
- the impossibility of correct averaging of ADC and ADCh on the set of aircraft (due to their identity).

For the correct estimation of ADC in ADCh, it is necessary, taking into account these properties, to organize testing of aircraft in order to determine ADC and ADCh, if possible, invariant to the action of unaccounted for external factors. Thus, the spatial movement of the aircraft is divided into longitudinal (in the vertical plane) and lateral (in the horizontal plane). To reduce the impact of non-stationarity, the time interval of the experiment is limited as much as possible. To reduce the effect of nonlinearity, ADC and ADCh limit the range of deviations of state variables from some stationary flight mode.

Using the mathematical model of the aircraft as an undeformed body, the rate of dynamic modes is limited so that the aeroelasticity of the aircraft body does not affect the determination of ADC.

II. PROBLEM STATEMENT

According to specially planned full-scale tests of aircraft, which minimize the influence of many external factors not taken into account in the mathematical model (MM) of aircraft (as an absolutely rigid body), under conditions of temporal and spatial limitation and the presence of random errors in the measurement of variables of the state of aircraft MM, by modifying the existing methods of ADC estimation, it is necessary to keep objective (without taking into account possibly incorrect a priori values) unbiased and effective estimates of ADC and ADCh of different aircraft. To achieve this goal, it is necessary to move from the super-complex equation of the spatial motion of the aircraft, by planning an experiment, to a simplified longitudinal or lateral short-period motion with limited deviations of the variables from the basic regime. Therefore, the total MM of the arbitrary spatial motion of the aircraft [8] is

$$m\left\{[\omega V]+\frac{dV}{dt}\right\}=R,\quad \frac{dK}{dt}=M, \tag{1}$$

where ω is the angular velocity vector; V is the center of mass velocity vector; R is the vector of external forces; K is the kinematic moment of the system; M is the moment of external forces.

It is necessary to reduce to simple linear stationary MMs of short-period motion in vertical

$$J_z\frac{d\omega_z}{dt}=M_z \tag{2}$$

or horizontal plane

$$\begin{cases} J_x\dfrac{d\omega_x}{dt}+\left(J_z-J_y\right)\omega_y\omega_z=M_x,\\ J_y\dfrac{d\omega_y}{dt}+\left(J_x-J_z\right)\omega_x\omega_z=M_y,\end{cases} \tag{3}$$

where J_x, J_y, J_z are moments of inertia of the aircraft with respect to the axes *x*, *y*, *z*; M_x, M_y, M_z are aerodynamic moments, the dependence of which on the variables of the aircraft state should be determined. Analogous dependencies are to be determined for aerodynamic forces F_x, F_y, F_z.

The equations of forces and moments will be considered for small deviations of the aircraft state variables from horizontal motion with constant speed *V*, configuration, engine operating mode and other factors not taken into account in MM (2) and (3).

To generalize from forces *F* and moments *M*, let's move on to their given values:

$$C_x=\frac{F_x}{qS},\ C_y=\frac{F_y}{qS},\ C_z=\frac{F_z}{qS},$$

$$m_x=\frac{M_x}{qSl},\ m_y=\frac{M_y}{qSl},\ m_z=\frac{M_z}{qSb_a},$$

where $q=\rho V^2/2$ is the velocity head; ρ is the air density; S, l, b_a is the geometrical parameters of the aircraft [8], [9].

Unknown linearized in the zone of the base mode dependencies of reduced forces and moments on deviations of state variables are subject to determination:

- in longitudinal motion from the corner of attack α, angular velocity ω_z, height control δ_h;
- in the side (for the flick of the attack angle α from the sliding angle β, angular velocities ω_x and ω_y and control bodies, such as rudder directional δ_d and ailerons δ_a.

Thus, the partial derivatives of the non-linear non-stationary dependences for a fixed instant t_0 of time t and (theoretically) infinitesimally small deviations of the state variables from the basic mode are to be determined. Narrowing the scope of the experiment reduces the methodological error from the linearization of the nonlinear dependence, but increases the random error in the ADCh estimates. It is necessary to find such an approach to the determination of ADC from real plagued data, so that the methodological and random errors in the determination of ADC are as small as possible.

III. Solution of the Problem of Longitudinal Short-periodic Movement of Aircraft

A. *Definition of ADC*

Most winged aircraft have a geometric non-identity of the shape of the upper and lower surfaces of the fuselage. Therefore, even with small deviations from horizontal movement, the cab $(d\alpha/dt>0)$ and dive $(d\alpha/dt<0)$ modes will have different ADCs. In the first approximation, this asymmetry can be taken into account (for small deviations from the basic horizontal movement) using a linear-quadratic dependence $\Delta m_{z1}(\alpha,\omega_z,\delta_h)$ in a semi-coupled coordinate system [10]:

$$\begin{aligned}\Delta m_{z1}(t)&=\left.\frac{\partial m_{z1}}{\partial\alpha}\right|_{t_0}\Delta\alpha(t)+\left.\frac{\partial m_{z1}}{\partial\omega_{z1}}\right|_{t_0}\Delta\bar{\omega}_{z1}(t)\\&+\left.\frac{\partial m_{z1}}{\partial\delta_h}\right|_{t_0}\Delta\delta_h(t)+\frac{1}{2}\cdot\left.\frac{\partial^2 m_{z1}}{\partial\bar{\omega}_{z1}^2}\right|_{t_0}\left(\Delta\bar{\omega}_{z1}(t)\right)^2\\&+\left.\frac{\partial^2 m_{z1}}{\partial\delta_h^2}\right|_{t_0}\left(\Delta\delta_h(t)\right)^2+\left.\frac{\partial^2 m_{z1}}{\partial\alpha\partial\omega_{z1}}\right|_{t_0}\Delta\alpha(t)\Delta\bar{\omega}_{z1}(t)\\&+\left.\frac{\partial^2 m_{z1}}{\partial\alpha\partial\delta_h}\right|_{t_0}\Delta\alpha(t)\Delta\delta_h(t)+\left.\frac{\partial^2 m_{z1}}{\partial\bar{\omega}_{z1}\partial\delta_h}\right|_{t_0}\Delta\bar{\omega}_{z1}(t)\Delta\delta_h(t).\end{aligned} \tag{4}$$

Equation (4) takes into account the asymmetry of the calibre and dive modes. However, the large number of its members, the mutual correlation, the limitation and proximity of measurements, the limitation of the time of one mode by the change of speed and altitude, make the task of estimating all ADCs impossible. To accurately estimate the ADC as a linear component of the model (4), we design the experiment in such a way that all the variables of equation (4) are more or less close in shape to a step or exponent. Then equation (4) can be approximated as follows:

$$\Delta m_{z1}(t) = a_2\Delta\alpha(t) + a_1\Delta\omega_{z1}(t) + b_1\Delta\delta_h(t), \qquad (5)$$

$$a_1 = m_{z_1}^{\bar{\omega}_z} + \Big[m_z^{\alpha^2}\Delta\alpha(\infty) + m_{z_1}^{\bar{\omega}_z^2}\Delta\bar{\omega}_{z_1}(\infty) + m_{z_1}^{\alpha\delta_h}\Delta\delta_h(\infty)\Big],$$

$$a_2 = m_z^{\alpha} + \Big[m_{z_1}^{\alpha\bar{\omega}_z}\Delta\alpha(\infty) + m_{z_1}^{\alpha\bar{\omega}_z}\Delta\bar{\omega}_{z_1}(\infty) + m_{z_1}^{\alpha\delta_h}\Delta\delta_h(\infty)\Big],$$

$$b_1 = m_z^{\delta_h} + \Big[m_z^{\delta_h\alpha}\Delta\alpha(\infty) + m_{z_1}^{\delta_h\bar{\omega}_z}\Delta\bar{\omega}_{z_1}(\infty) + m_z^{\delta_h^2}\Delta\delta_h(\infty)\Big].$$

The argument (∞) indicates the quasi-fixed values of the variables.

Thus, when the control influence $\Delta\delta_h(t)$ is applied in the form of a step, the state variables $\Delta\alpha(t)$ and $\Delta\omega_{z_1}(t)$, while maintaining linear independence, will be similar to aperiodic or oscillatory transition functions, the linear equation (5) is quite accurate, ADC a_2, a_1, b_1 estimates will have a shift $\Delta\alpha(t)$, $\Delta\omega_{z_1}(t)$, $\Delta\delta_h(t)$ proportional to the amplitude of the deviations $\alpha, \omega_z, \delta_h$. from the base value $\alpha, \omega_z, \delta_h$. To reduction of the spread of estimates due to the presence of random errors in the measurements of variables (taking into account the smoothness property of the exact values of variables) To filter the noise using the same linear low-pass filter for all variables. Different, albeit optimal, filters are not perfect, which will lead to a methodological error in the LSM estimation of ADC from the filtered data. Indeed, if in a linear equation for the exact values of the variables the left and right parts are applied with the same linear filter, then the equal sign is not violated. If there are different filters, then the equal sign will be for other ADC values.

Real example. Let's consider the effectiveness of this approach. We have seven modes (Fig. 1) of different amplitudes of changes in rudder height δ_h, angle of attack $\alpha(t)$ and angular speed $\omega_{z_1}(t)$ of a passenger aircraft. For each of the regimes, the estimates $\hat{a}_j, j = 1,2,3$ of the coefficients of the model (5) shifted as a result of the approximation of the linear model were determined. They were used to calculate the margin $\hat{\sigma}_n$ of aperiodic stability

$$\hat{\sigma}_n = \frac{J_{z_1}}{qSb_a}\left(a_2 + \frac{g}{V}a_1\right),$$

where J_{z_1}, g, V, q, S, b_a are known aircraft parameters.

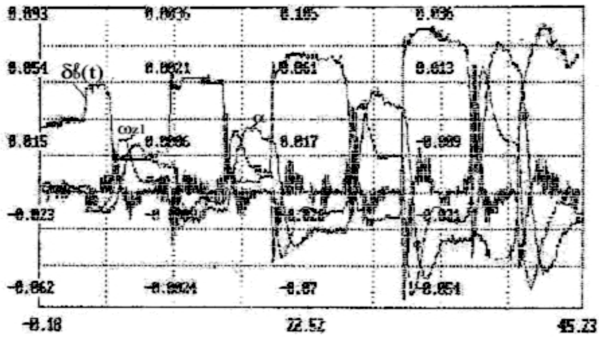


Fig. 1. Modes for changing rudder height, angle of attack and angular speed

The margin of stability $\hat{\sigma}$ was approximated linear dependence (6) by the LSM as a function of the norm of deviations $\|\alpha\|$ (Fig. 2)

$$\hat{\sigma}(\|\alpha\|) = 0.22 - 0.075\|\alpha\|, \qquad (6)$$

where 0.22 is the sought unbiased estimate under conditions of infinitesimally small deviations $\Delta\alpha(t)$, $\Delta\omega_{z_1}(t)$, $\Delta\delta_h(t)$ from the basic mode.

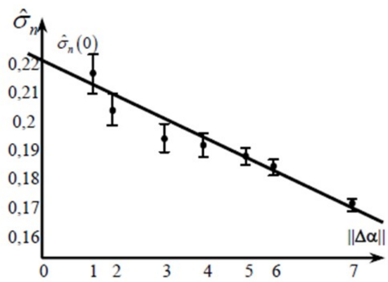


Fig. 2. Dependence of the biased estimate $\hat{\sigma}_n$ and its linear approximation (6) on the amplitude of deviations of the angle of attack α

If we determine the coefficients $\hat{a}_j, j = 1,2,3$ of the linear model (5) for the entire data sample of the seven regimes by LSM we will get the estimate. If, on the other hand, the nonlinear model (4) is used for the entire sample and all nine ADCs are determined according to the LSM, then the incoherence ε between the left and right parts of the model (4) will approach the noise component in $\Delta\omega_{z_1}(t)$, but the ADCs (due to the innateness of the information matrix of the LSM) will have any, but far from valid values.

Test. The nonlinear model

$$y(k)=\sum_{j=1}^{3}x_j(k)+\sum_{j,q=1,j\geq q}^{3}x_j(k)x_q(k)$$

with single coefficients a_i for four samples of different amplitudes $X_{\max}$ of sinusoidal linearly independent variables was approximated by its linear part. The estimates $\hat{a}_j, j=1,2,3$ were calculated according to LSM. The approximation problem is solved quite qualitatively. But the coefficients a_i were significantly shifted and the linear dependences of the shifts Δa_j, $j=1,2,3$ from $X_{\max}(l)$, $l=1,2,3,4$ converge to zero (Fig. 3), according the estimates $\hat{a}_j$ coincide to the valid ones $a_j=1$.

Taking into account the fundamental property of real processes – their smoothness allows further refinement of ADC estimates by constructing their regression dependences on the initial values of the angle of attack α and its derivative α' (the latter determines the mode of cabring or diving).The linear regression dependences of the ADC on the initial value of the angle α (coefficient a1) and its derivative (coefficient a2) of the Jet Transport Aircraft are shown in the Table I. Taking into account only α and α' made it possible to double the accuracy of ADC estimates. The data that confirm the effectiveness of specifying the margin of stability σ_n by regression dependence on various flight parameters ΔX are given in the Table II.

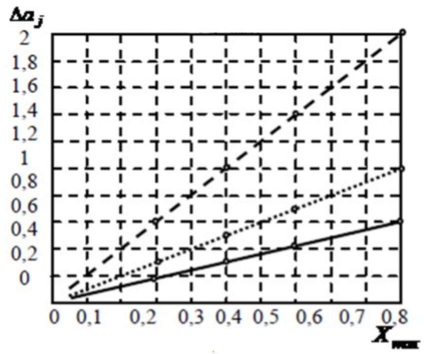


Fig. 3. Variance dependencies Δa_j from $X_{\max}$

TABLE I. DEPENDENCE OF ADC ESTIMATES ON α AND α'

ADC	a_0	a_1	a_2	**Mean square error of approximation**	**Average**	**Root mean squared error of the average**
$m_z^{\bar{\omega}_z}$	-8.54	-0.2289	-0.0112	0.01	-10.61	0.02
m_z^{α}	-0.0092	0	0	0.0007	-0.0091	0.007
$m_z^{\delta_e}$	-0.0161	-0.0012	0	0.003	-0.02	0.009
$m_z^{C_y}$	-0.0873	-0.0029	0	0.004	-0.0928	0.006
σ_n	-0.2301	0.0071	0.0001	0.001	-0.2119	0.002

TABLE II. DEPENDENCE OF ADC ESTIMATES ON VARIOUS PARAMETERS ΔX OF FLIGHT

Aircraft Type	**Mean square error, %**		**Dimension**	**Number of modes**
	Model	***Average***		
Jet Transport Aircraft	5	102	6	190
Passenger Aircraft 1	7	31	2	25
Passenger Aircraft 2	4	13	4	70
Jet Fighter	7	50	4	50
Subsonic Jet	0.5	1.5	2	15

B. Determination of Nonlinear Static (Balancing) Dependencies from Dynamic Modes of aircraft

The traditional approach to the determination of static (balancing) dependencies between aircraft state variables (angle of attack α, overload n_y, etc.) consists in performing quasi-static modes of smooth change of the state variable, as a reaction to a slow change of the aircraft control body, for example, the static dependence between the height control δ_h and overload n_y. This requires a significant investment of time, and for unstable aircraft (Subsonic Jet) it is not possible at all.

This dependency can be obtained from dynamic modes (Fig. 1) if you do the following:

1) Submit the link $\delta_h(t)$ and $n_y(t)$ by Hamerstein's model [11, 12]

$$a_2 \frac{d^2 n_y(t)}{dt^2} + a_1 \frac{dn_y(t)}{dt} + n_y(t) = f(\delta_h(t)),$$

where $f(\delta_h(t))$. The sought-after smooth balancing relationship between δ_h and n_y.

2) Given the smoothness of the dependence $n_y(\delta_h)$, we will determine the coefficients a_1 and a_2 (if unknown $f(\delta_h(t))$) provided that the second derivative of the corrected overload $n_{ycor}(t_k)$ on $\delta_h(t_k)$ is at least.

$$(a_1, a_2) = \arg\min \sum_{k=1}^{N} \left(\frac{d^2 n_{ycor}(t_k)}{d\delta_h^2} \right)^2, \quad (8)$$

where

$$n_{ycor}(t) = n_y(t_k) - a_1 \frac{dn_y(t_k)}{dt} - a_2 \frac{d^2 n_y(t_k)}{dt^2}. \quad (9)$$

To calculate the second derivative $n_{ycor}(t_k)$ of by $\delta_h(t_k)$, to first it is necessary smooth the arrays of these data and arrange them in ascending order $\delta_h(t_k)$, to move from the derivative to the difference of the second order.

3) Having determined the coefficients a_1 and a_2, according to the LSM under condition (8), substitute them in equation (9) and construct a non-parametric dependence $n_{ycor}(\delta_h)$.

As an example, in Fig. 4 shows the balancing dependence $\delta_h(n_y)$,constructed from the dynamic modes (see Fig. 1) of a jet subsonic aircraft (Table II) without dynamics compensation (line 3), with compensation without smoothing (line 2) and with smoothing (line 3).

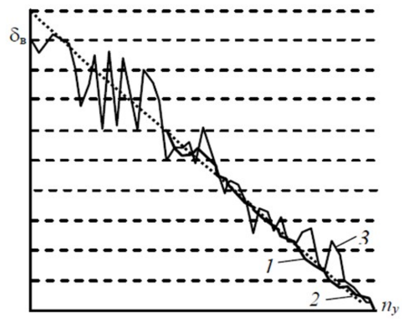


Fig. 4. Balancing dependency $\delta_h(n_y)$

C. Solving the Problem for Lateral Short-Period Movement of aircraft

In lateral movement (3) of aircraft ADC is subject to identification, i.e. partial derivatives of reduced forces F_z and moments m_x, m_y on state variables:

$$\Delta C_z = C_z^{\beta} \Delta\beta + C_z^{\delta_e} \Delta\delta_d + C_z^{\delta_e} \Delta\delta_a, \quad (10)$$

$$\Delta m_x = m_x^{\bar{\omega}_x} \Delta\bar{\omega}_x + m_y^{\bar{\omega}_y} \Delta\bar{\omega}_y + m_x^{\beta} \Delta\beta + m_x^{\delta_d} \Delta\delta_d + m_x^{\delta_a} \Delta\delta_a, \quad (11)$$

$$\Delta m_y = m_y^{\bar{\omega}_x} \Delta\bar{\omega}_x + m_y^{\bar{\omega}_y} \Delta\bar{\omega}_y + m_y^{\beta} \Delta\beta + m_y^{\delta_d} \Delta\delta_d + m_y^{\delta_a} \Delta\delta_a, \quad (12)$$

where the deviation of the respective controlling unit $\Delta\delta_d$ and $\Delta\delta_a$, angular velocities $\Delta\omega_x$ and $\Delta\omega_y$, sliding angle $\Delta\beta$.

Due to the symmetry of the aircraft with respect to the vertical plane, the quadratic terms are absent in the decomposition into a series of nonlinear dependencies of forces and moments, and the cubic terms (with small deviations from the basic regime) are insignificant. The optimal planning of the experiment consists in choosing such a sequence of four pulses $\Delta\delta_d(t)$ and $\Delta\delta_a(t)$, which achieves the best indicator of the information matrix of the LSM. Inaccuracy or absence of a priori information about the ADC of lateral movement leads to the need to implement a relaxation process:

1) Delivery of arbitrarily arranged four pulses $\Delta\delta_d(t)$ and $\Delta\delta_a(t)$.

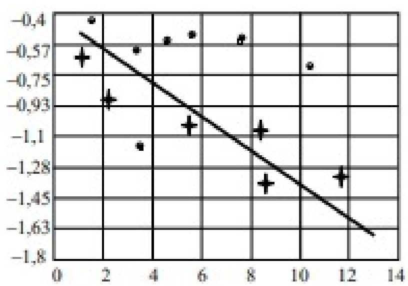
2) Estimation according to LSM ADC and clarification of the location of pulses according to the information criterion.

3) Repetition of steps 1, 2 until the desired accuracy of ADC estimates is achieved.

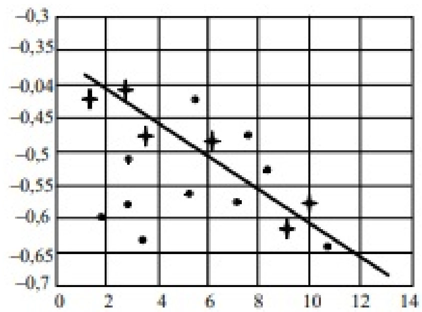
In addition to dimensionality (5 variables), the problem of obtaining ADC in lateral movement is their dependence on the angle of attack α. Therefore, it is desirable to keep it unchanged, and then to approximate the obtained ADCs by regression dependence on. Thus, based on the results of 50 modes of the jet fighter, equations (10), (11), (12) were obtained and approximated by a linear dependence ADC on the α:

$$m_x^{\bar{\omega}_x}(\alpha) = -0.64 + 0.024\alpha,\; m_y^{\bar{\omega}_y}(\alpha) = -0.66,$$
$$m_x^{\beta}(\alpha) = -0.143 + 0.0095\alpha,$$
$$m_x^{\delta_d}(\alpha) = -0.068 + 0.0047\alpha,$$
$$m_x^{\delta_a}(\alpha) = -0.068 + 0.0027\alpha,\; m_y^{\bar{\omega}_x}(\alpha) = -0.21,$$
$$m_y^{\bar{\omega}_y}(\alpha) = -0.565 + 0.064\alpha,\; m_y^{\beta}(\alpha) = -0.124 + 0.01\alpha,$$
$$m_y^{\delta_d}(\alpha) = -0.14 + 0.01\alpha,\; m_y^{\delta_a}(\alpha) = -0.018,$$
$$c_z^{\beta}(\alpha) = -1.41 + 0.097\alpha,\; c_z^{\delta_d}(\alpha) = -0.36 + 0.025\alpha,$$
$$c_z^{\delta_h}(\alpha) = -0.045 + 0.0032\alpha. \tag{13}$$

Estimates of some ADC before the optimization of the LSM information matrix (dots in Fig. 5) and after one or two steps of the relaxation process of clarification of the location of the control impulses (crosses) are shown in Fig. 5.



a)



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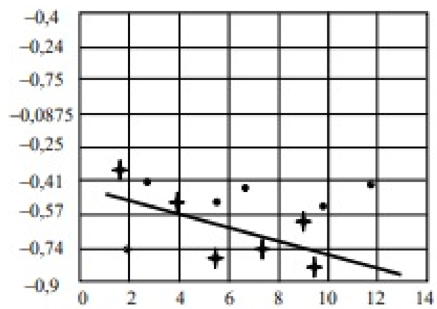
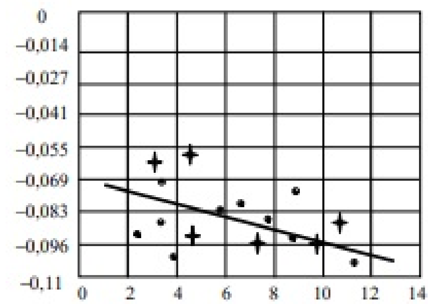


c)



d)

Fig. 5. Initial (points) and refined (crosses) values of some ADC and their linear approximation from the angle α: (a) is the $c_z^{\beta}(\alpha) = -1.41 + 0.097\alpha$; (b) is the $c_z^{\delta_d}(\alpha) = -0.36 + 0.025\alpha$; (c) is the $c_z^{\delta_h}(\alpha) = -0.045 + 0.0032\alpha$; (d) is the $m_x^{\delta_a}(\alpha) = -0.068 + 0.0027\alpha$

In contrast to the identification of longitudinal traffic ADC, where both "on-line" and "off-line" modes are possible, the identification of lateral traffic ADC must take place in "on-line" mode.

III. Conclusion

The methodology and methods of active identification proposed in the article made it possible to solve the traditional problem of identification of ADC and characteristics of aircraft.

References

[1] P. Eykhoff, *System identification: Parameter and State Estimation*, London: John Wiley & Sons, 1974, 600 p.

[2] Lennart Ljung, *System Identification: Theory for the User,* Prentice Hall PTR, 1999, 609 p. ISSN 0891-4559

[3] A. A. Mizyukanova, G. P. Chikildin and I. I. Karasenko, "On Linear Algebraic System Forming in Parametric Identification Problems," *2023 IEEE XVI*

International Scientific and Technical Conference Actual Problems of Electronic Instrument Engineering (APEIE), Novosibirsk, Russian Federation, 2023, pp. 940–943, [in Russian]. https://doi.org/10.1109/APEIE59731.2023.10347633.

[4] M. Ostroverkhov, S. Anton and G. Kryvoboka, "The problem of identification in the theory of identification," *2021 IEEE 2nd KhPI Week on Advanced Technology (KhPIWeek)*, Kharkiv, Ukraine, 2021, pp. 181–184, [in Ukrainian] https://doi.org/10.1109/KhPIWeek53812.2021.9569971

[5] J. Shao, X. Jie, Z. Zhai and M. Wu, "Parameter Identification of MIMO Objects Based on Attenuation Factor Recursive Least Squares," *2022 2nd International Conference on Electrical Engineering and Control Science (IC2ECS)*, Nanjing, China, 2022, pp. 432–436, https://doi.org/10.1109/IC2ECS57645.2022.10087912.

[6] D. Miedziński, K. Kaczmarek, P. Rodo, N. Sahbon, M. Sochacki and M. Łukasiewicz, "Missile Aerodynamics Model Identification Using Flight Data," *2023 IEEE Aerospace Conference*, Big Sky, MT, USA, 2023, pp. 1–12, https://doi.org/10.1109/AERO55745.2023.10115928.

[7] G. Dai, L. Cheng, D. Li, H. Ma and L. Zhang, "Identification of Aerodynamic Parameters Based on Maximum Likelihood Estimation," *2022 8th Annual International Conference on Network and Information Systems for Computers (ICNISC)*, Hangzhou, China, 2022, pp. 923–929, https://doi.org/10.1109/ICNISC57059.2022.00186.

[8] V. M. Sineglazov and M. K. Filiashkin, *Automated aircraft control systems: textbook*, Kyiv: NAU, 2003, 502 p. [in Ukrainian]

[9] V. P. Babak, V. P. Kharchenko, V. O. Maksymov, and others, *Aviation safety*, Kyiv: Tekhnika Publ., 2004, 584 p. [in Ukrainian]

[10] V. V. Samsonov, A. M. Silvestrov, and L. Yu. Spinul, *Multyple adaptive system of identification*, Kyiv: NUFT, 2018, 228 p.

[11] V. M. Sineglazov and A. M. Silvestrov, *Theory of identification: textbook*. Kyiv: NAU, 2015, 452 p. [in Ukrainian]

[12] A. Silvestrov, M. Ostroverkhov, L. Spinul, A. Serdyuk and M. Falchenko, "Structural and Parametric Identification of Mathematical Models of Control Objects Based on the Principle of Rational Complication," *2022 IEEE 3rd KhPI Week on Advanced Technology (KhPIWeek)*, 2022, https://doi.org/10.1109/KhPIWeek57572.2022.9916340

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А. М. Сільвестров, М. Я. Островерхов, Л. Ю. Спінул. Вирішення проблеми ідентифікації аеродинамічних коефіцієнтів літальних апаратів за даними їх натурних випробувань

Розглянуто методологію коректної ідентифікації аеродинамічних коефіцієнтів літальних апараті, а саме визначення частинних похідних від аеродинамічних сил і моментів літального апарату за змінними його стану. Також подано метод визначення статичних (балансировочних) залежностей з коротко-часових динамічних режимів натурного експерименту. Ефективність запропонованого підходу підтверджено практикою визначення аеродинамічних коефіцієнтів і аеродинамічних характеристик різних літальних апаратів.

Ключові слова: ідентифікація; аеродинамічні коефіцієнти; літальні апарати; активний експеримент; нелінійність; нестаціонарність; ефективність; коректність.

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