

Aircraft aerodynamic coefficients identification using flight tests data

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Abstract. This paper discusses the problems of aerodynamic coefficients identification from flight test data. The principal stages of identification procedure are considered, the more sophisticated stages such as data compatibility check and parameter estimation from flight data are discussed in details. The paper also presents the examples of flight test data processing, which confirm the opportunities for on-board measurement systematic error detection and wind tunnel aerodynamic parameter values correction.

1. Introduction

The system identification methods form an important part of flight test data analysis. Through these methods aircraft parameter estimates may be obtained [1-4], which is important for numerous applications, such as simulators and flight control systems design, aircraft modernization etc. Examples for some applications may be found in [5-7].

Technology of aircraft's mathematical model parameter identification is presented in [1-4]. It includes the following basic steps[1-4]:

- collecting a priory data of the aircraft, aerodynamic parameters, engine, control system from aircraft developer company;
- formulating the requirements for the on-board registration system, above all the list of registered parameters, the acceptable levels of measurements errors and registration frequency;
- analysis of a priory data and flight experiment design;
- running the flight test in order to gather experimental data for identification;
- checking the compatibility of aircraft's parameters recorded by on-board equipment;
- processing of the flight tests results using the identification methods and algorithms;
- comparing the identification estimates with a priory aerodynamic data.

2. Data compatibility check

Checking the recorded flight data compatibility and identification of lateral and longitudinal aerodynamic coefficients are the most complicated stages. So let us discuss them in details. Checking the compatibility is achieved by comparing the signals recorded during the flight with the results



obtained by numerical solution of the aircraft dynamic differential equations [1, 4]. Let us examine the examples of processing the flight test data.

Figures 1 and 2 show the results of the data compatibility check. Figure 1 represents the fitting of pitch and roll signals in case of normal functioning of the on-board measuring system. The figure shows that when measurements are correct the plots of measured and simulated pitches and rolls are visually indistinguishable.

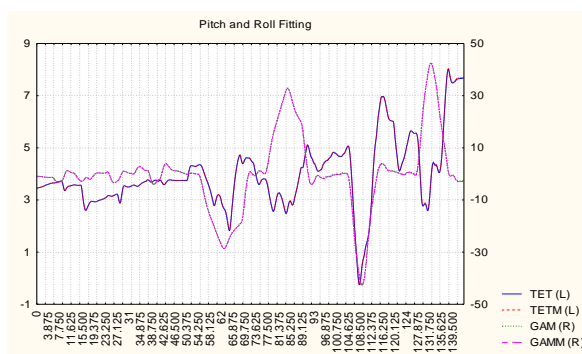


Figure 1. The pitch (plotted against left ordinate axis, degrees) and roll signals (plotted against right ordinate axis, degrees) fitting simulated (TETM(L) and GAMM(R)) and measured in flight (TET(L) and GAM(R)) at normal work of measuring and recording system.

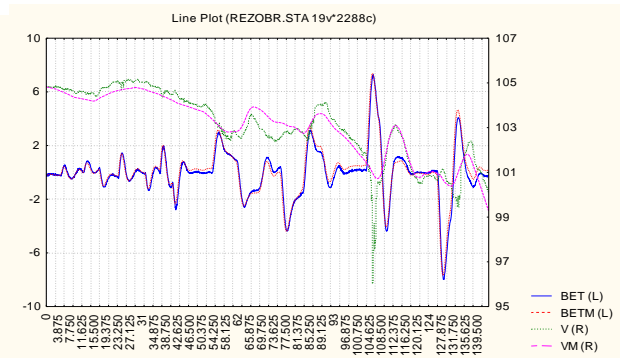


Figure 2. The error of barometric measurement of airspeed (measured airspeed $V(R)$ deviates abruptly from simulated airspeed $VM(R)$, plotted against the right ordinate axis, m/s), caused by sharp change of sideslip angle (measured sideslip $BET(L)$ and simulated sideslip $BETM(L)$ plotted against the left ordinate axis, degrees, coincide with high accuracy).

Figure 2 shows the opportunities for error detection. It shows that measured and simulated signals of sideslip angle and airspeed normally coincide with high accuracy, whereas at a sharp change of sideslip angle by about 9 degrees the measured airspeed deviates by 5 m/s from the simulated value. It is evident that in case of airspeed barometric sensor, positioned on the fuselage surface, error increases with the growth of sideslip angle. This error is clearly systematic and is to be corrected.

The experience shows that the data compatibility check is capable of detecting systematic measurement errors for such major flight parameters as angles of attack and sideslip, overloads, altitude and airspeed, etc. This approach may also detect the effect of the coordinates of the sensor position, and time shifts caused by insufficient synchronization of heterogeneous data flows registered on-board. Identification of the measurement errors caused by the wind is discussed in [8].

3. Aircraft aerodynamic coefficients identification

It is reasonable to carry out identification separately for longitudinal and lateral movement. The corresponding equations are selected from the general nonlinear dynamic model of the aircraft spatial movement [9]. The object model takes the form:

longitudinal channel

$$\begin{aligned} \frac{d\alpha}{dt} &= \omega_z - \frac{1}{\cos\beta} \left[\left(\frac{a_x}{V} - \omega_y \sin\beta \right) \sin\alpha + \left(\frac{a_y}{V} + \omega_x \sin\beta \right) \cos\alpha \right], \\ \frac{d\omega_z}{dt} &= \frac{I_x - I_y}{I_z} \omega_x \omega_y + q \frac{S b_A}{I_z} m_z - \frac{k \omega_y}{I_z} - \frac{(P_{right} + P_{left}) y}{I_z}; \end{aligned} \quad (1)$$

lateral channel

$$\begin{aligned}\frac{d\beta}{dt} &= \frac{a_z}{V} \cos \beta - \left(\frac{a_x}{V} \sin \beta - \omega_y \right) \cos \alpha + \left(\frac{a_y}{V} \sin \beta + \omega_x \right) \sin \alpha, \\ \frac{d\omega_x}{dt} &= \frac{I_y - I_z}{I_x} \omega_y \omega_z + q \frac{S l}{I_x} m_x \\ \frac{d\omega_y}{dt} &= \frac{I_z - I_x}{I_y} \omega_x \omega_z + q \frac{S l}{I_y} m_y + \frac{k\omega_z}{I_y} + \frac{(P_{right} - P_{left})z}{I_y};\end{aligned}\quad (2)$$

accelerations along axes of body-fixed coordinate system

$$\begin{aligned}a_x &= \frac{qS(-c_x + c_p)}{m} - g \sin \nu, \\ a_y &= \frac{qSc_y}{m} + g \cos \nu \sin \gamma, \\ a_z &= \frac{qSc_z}{m} + g \cos \nu \sin \gamma;\end{aligned}\quad (3)$$

overloads along axes of body-fixed coordinate system:

$$n_x = \frac{qS(-c_x + c_p)}{mg}, n_y = \frac{qSc_y}{mg}, n_z = \frac{qSc_z}{mg}, \quad (4)$$

where α, β – angles of attack and sideslip, rad; $\omega_x, \omega_y, \omega_z$ – angular velocities related to body-fixed coordinate system, rad/s; ν, γ, ψ – angles of pitch, roll, yaw, rad; V – airspeed, m/s; H – flight altitude, m; m_x, m_y, m_z – coefficients of aerodynamic torques; c_x, c_y, c_z – coefficients of aerodynamic force in body-fixed coordinate system; I_x, I_y, I_z, I_{xy} – moments of inertia related to axes of body-fixed coordinate system, kg m²; m – aircraft weight, kg; l, b_A – wing span and length of mean aerodynamic chord, m; S – wing surface area, m²; $q = \rho_H V^2 / 2$ – dynamic air pressure, Pa; ρ_H – air density at the altitude of flight, kg/m³; $c_p = P/qS$ – thrust coefficient; P_{right}, P_{left} – thrust of right and left engine, N; k – kinematic momentum of engine rotors, kg m²/s; y, z – engine coordinates in body-fixed coordinate system, m.

For coefficients of aerodynamic torques m_x, m_y, m_z and forces c_x, c_y, c_z linearized and nonlinear decomposition are used.

In case of the identification in the longitudinal channel state or output vector is $\mathbf{y}^T(t) = [\alpha(t) \omega_z(t)]$, and scalar input signal is $u(t) = [\phi_B(t)]$ or $u(t) = [\delta_B(t)]$, where $\phi_B(t)$ – angle of symmetric stabilizer deflection, $\delta_B(t)$ – angle of elevator deflection.

When identifying the lateral channel the state vector is $\mathbf{y}^T(t) = [\beta(t) \omega_x(t) \omega_y(t)]$, and input vector $\mathbf{u}^T(t) = [\delta_A(t) \delta_R(t) \Delta\phi_{st}(t)]$, where $\Delta\phi_{st}(t)$ – angle of differential stabilizer deflection, $\delta_A(t), \delta_R(t)$ – angles of aileron and rudder deflection.

In numerical integration of the aircraft dynamics equations we substitute to the right part of equations the measured values of signals which are not included in the state vector. For example, for longitudinal movement these are the signals $\beta(t), \omega_x(t), \omega_y(t), H(t), V(t)$. Values of engine thrust are substituted based on the available engine thrust model. While defining the problem of identification it is necessary to keep in mind that separate identification of the forces of air drag and engine thrust is normally impossible. The traditional solution is to estimate engine thrust, for example, from the available engine model and carry out identification of air drag force, or vice versa [1-4].

Observation models for the identification of the longitudinal and lateral channel coefficients are given by, respectively

$$\mathbf{z}(t_i) = \begin{bmatrix} \alpha(t_i) \\ \omega_z(t_i) \\ n_y(t_i) \end{bmatrix} + \boldsymbol{\eta}_B(t_i), \quad (5)$$

$$\mathbf{z}(t_i) = \begin{bmatrix} \beta(t_i) \\ \omega_x(t_i) \\ \omega_y(t_i) \\ n_z(t_i) \end{bmatrix} + \boldsymbol{\eta}_b(t_i),$$

where $\boldsymbol{\eta}_B(t_i)$, $\boldsymbol{\eta}_b(t_i)$ - vector measurement noise in longitudinal and lateral channels.

4. Examples

Examples of parameter identification for various aircraft from flight tests data appear below. So, figures 3-4 show roll and yaw angular rates for the a priori model, indicating remarkable error between model and measurements. After identification (interceptors' efficiency proved to be 10% of the a priori value) the error reduces considerably (figures 5-6).

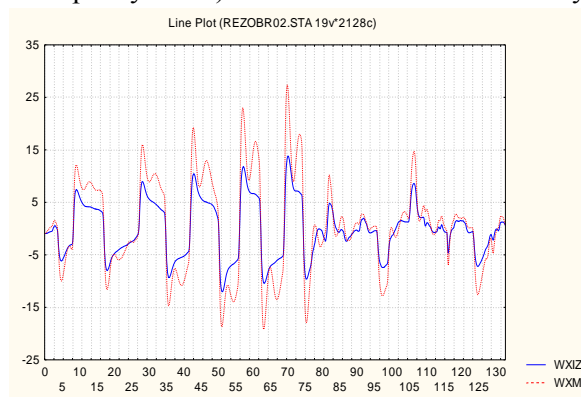


Figure 3. Measured and simulated roll rate.

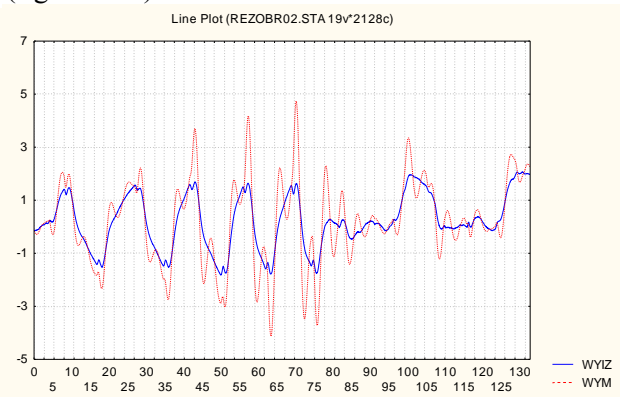


Figure 4. Measured and simulated yaw rate.

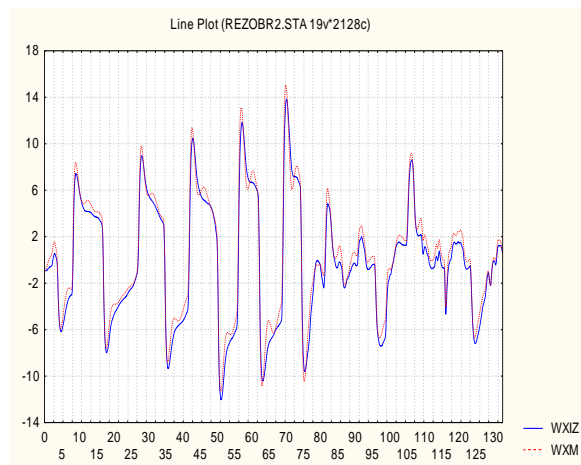


Figure 5. Measured and simulated roll angular rate after adjustment of the aerodynamic data.

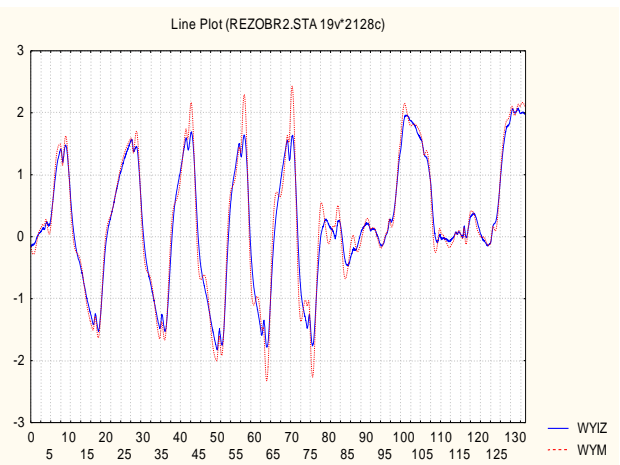


Figure 6. Measured and simulated yaw angular rate after adjustment of the aerodynamic data.

Thus, through identification we have obtained that the interceptors' efficiency is 10...20% of a priori values drawn from wind tunnel experiments. So the technology of identification enables to adjust the initial data bank of aerodynamic coefficients.

Another example of lateral parameter identification appears in figure 7. In this case, coherence of identification estimates and the appropriate coefficients from wind-tunnel aerodynamic data bank is rather high.

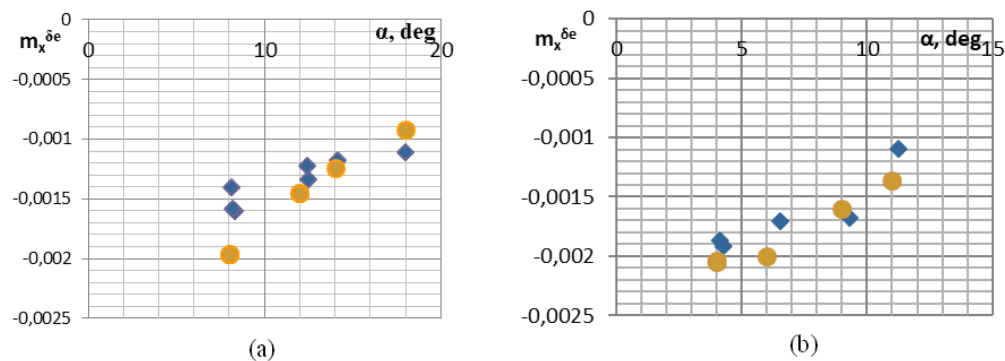


Figure 7. Comparison of aileron efficiency $m_x^{\delta e}$ estimated by identification (blue) and wind-tunnel aerodynamic data, where (a) the take-off configuration and (b) landing configuration.

Acknowledgments

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