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Flight-Test Estimation of Aircraft Aerodynamic Characteristics—Russian Experience

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Introduction

ADVANCED and innovative flight-test techniques are necessary to demonstrate, verify, and validate new concepts and for further progress in aeronautical engineering. Likewise, accurate determination of aerodynamic characteristics from flight-test data is equally important and required in several applications, for example, for envelope expansion and to tune the highly augmented systems. Such information is also needed for calculations and simulations while performing flight tests to forecast characteristics and improve flight safety.[1,2] Data obtained from wind-tunnel tests are not always reliable, and sometimes it is difficult to simulate specific flight conditions in a wind tunnel. Dynamic behavior at high angles of attack is an example of the former case, whereas the latter is the case with flight modes in which the thrust level significantly affects the aerodynamic characteristics. Therefore, in many applications it becomes necessary to determine or verify the aerodynamic coefficients against flight-test data. Powerful identification methods are required to derive aircraft motion models from flight-test data.[3,4]

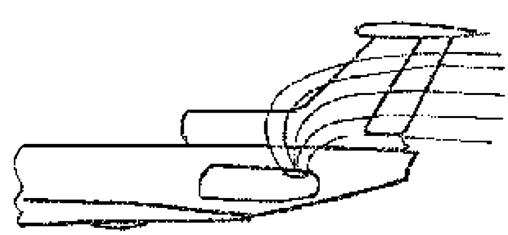
Identification methods allow development of models valid over a wide range of flight conditions and all flight configurations. Well-established estimation methods are widely applied to determine the aerodynamic coefficients of an aircraft from flight tests.[3–5] This paper presents briefly the experience gathered at the Gromov Flight Research Institute, Russia, in the area of estimation of aerodynamic characteristics of aircraft from flight tests.

Two types of procedures are adopted to derive models, namely, partial and complete estimation. The partial estimation involves determination of individual aerodynamic characteristics in terms of the moment or force coefficients and their derivatives, coefficient ratios, or trim curves, that significantly influence the aircraft response, but cannot always be reliably measured in wind-tunnel tests. For example, the degree of directional stability upon thrust reversal or the nonlinear variation in the pitching-moment coefficient at high angles of attack that is typical of stall and spin, resulting from flow breakdown or destroyed vortex flow. The second procedure of complete estimation is used during flight tests, when all, or almost all, aerodynamic coefficients are to be determined. Complete estimation is used, for example, to obtain data to tune the variable stability systems on in-flight simulators with adjustable stability and controllability parameters. In each case system identification has proved to be a useful practical tool to derive aircraft models of adequate fidelity from flight test data. In this paper, three characteristically different applications are presented to bring out the practical value of estimation methods in conjunction with flight tests.

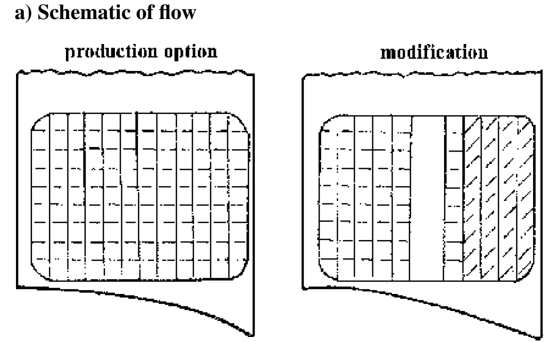
Aircraft Variable Stability Systems

The variable stability system (VSS) enables the replication of the dynamics and optimization of the systems of any other flight vehicle under realistic flying environment on a test vehicle that serves as an in-flight simulator (IFS).[6] In the present case Tu-154 IFS is used to investigate the performance of a recoverable space airplane "Buran." To be able to simulate a landing approach flight path, it was necessary to reverse the side engines thrust during the flight. As seen in Fig. 1a, thrust reversal results in flow deceleration in the fin-rudder area, and thereby deteriorates significantly the Tu-154 IFS aerodynamic performance. This necessitated resetting the variable stability system. As it is difficult to simulate the flight conditions with engine trust reversal in a wind tunnel, the aerodynamic coefficients had to be determined from flight-test data. For that purpose, a special flight-test program was performed on a Tu-154 IFS with engine thrust reversal using three types of reversible grates; the production version and one modified version are shown in Fig. 1b. The program involved special test maneuvers at three different airspeeds, mainly exciting the lateral-directional motion through aileron and rudder inputs typically developed for parameter estimation purposes.

The flight-test data were processed using the least-squares method, assuming a linear coefficient model.[3–5] Figure 2 shows the derivatives of the yawing-moment and side-force coefficients



a) Schematic of flow



b) Reversible grates

Fig. 1 Flow around fin-rudder caused by thrust reversal.

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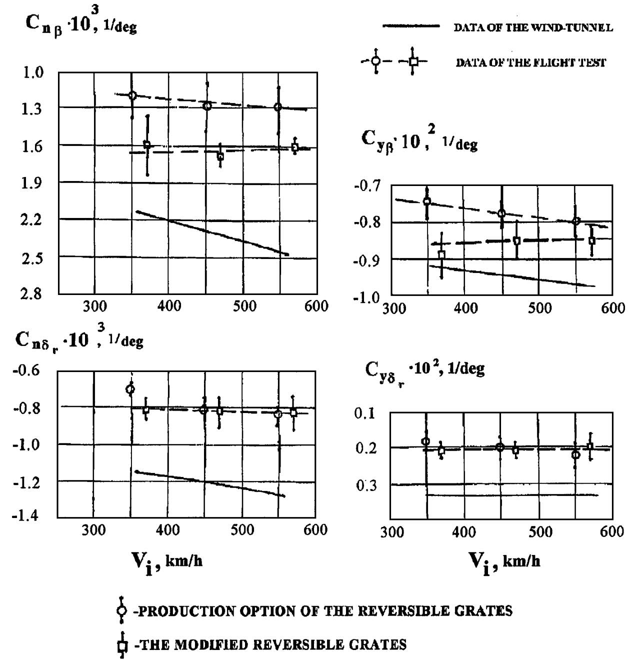

Fig. 2 Estimates of lateral-directional derivatives for two types of reversible grates.

for the two types of reversible grates. Wind-tunnel test data for a flight without engine thrust reversal are also shown on the same figure for comparison and bring out clearly the significant influence of the thrust reversal in flight.

The results presented show that the modified reversible grates reduced the influence of thrust reversal on the aerodynamic characteristics, particularly seen from the derivatives $C_{n\beta}$ and $C_{y\beta}$. The flight estimated characteristics diminished the effect of the deployment of the thrust reverse on the gain ratios in the rudder channel of the VSS. The obtained data were used to calculate the gain ratios and tune up the VSS on the Tu-154 IFS with engine thrust reversal.

Another application deals with estimating the aerodynamic coefficients at higher angles of attack and using this information to determine the factors that degrades the stability and controllability in these modes. Such information is helpful in developing measures for eliminating such factors, using both design features and automation. In the specific case, wind-tunnel testing of a heavy transport aircraft demonstrated peculiarities in the variation of the pitching moment, which resulted in a decrease in the stability and controllability at higher angles of attack. Specifically, the aircraft exhibited a longitudinal instability, whose onset and intensity strongly depended on the Mach number and in a loss of the pitch damping while the angle of attack is increasing.

To verify these results, aerodynamic characteristics were estimated from the data of special flight tests performed on this aircraft at angles of attack up to 12 deg. A methodology based on a combination of the modified stepwise regression method and the adaptive model method together with a spline approximation of nonlinear dependencies and an analysis of a set of statistical criteria (multiple correlation coefficient, F criteria) was applied.[3,7] Figure 3 shows the estimated pitching-moment coefficients, elevator efficiency, and damping derivative. These moment characteristics were determined from multiple test maneuvers under identical conditions. The figure also shows the coefficients calculated using the least-squares method from data obtained by splitting these modes into a single-degree angle-of-attack subintervals and using the linear model.

The estimates derived from the different maneuvers correlate with the ones obtained from the subinterval data. In addition, Fig. 3 shows trim dependency calculation based on the estimated coefficients, trim points obtained during the aircraft flight tests, and elevator effectiveness values calculated from trim dependencies obtained in flight tests with various positions of the center of gravity of the aircraft.

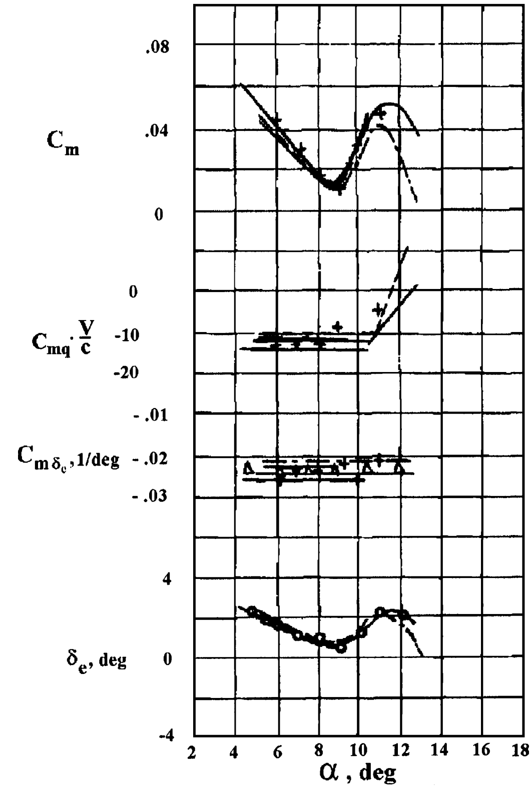

Fig. 3 Pitching-moment characteristics of a heavy transport aircraft: ——, adaptive method; - - - -, modified stepwise regression; ○, flight test; △, flight-test calculation with use of trim dependencies; and +, subinterval splitting method.

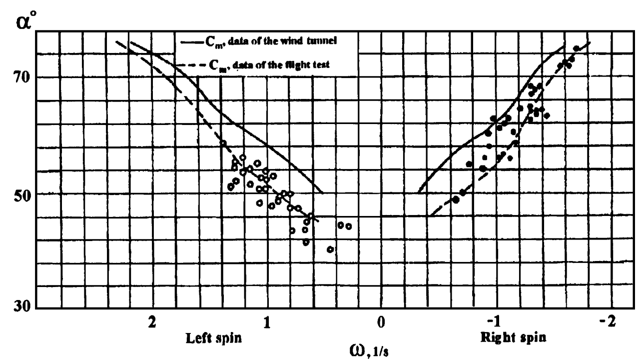

Fig. 4 Trim curves of spin correction.

An analysis of all presented results shows a good agreement and suggests that the obtained moment characteristics comply with those of the real aircraft. The obtained results demonstrate the special constructive measures that need to be taken to ensure acceptable stability and controllability characteristics.

Spin Flight-Test Data

Stall and spin, inertial autorotation, and flying at very high Mach numbers are critical modes of flight operation. Application of estimation methods to spin flight data is presented here. One of the most important aerodynamic characteristics that affects the aircraft trim under spin is the pitching-moment coefficient and its relation to the angle of attack. Figure 4 shows the trim curves for the angle of attack, $\alpha = f(\omega)$, for left and right spins. The curves were calculated from the pitching-moment dependency $C_m(\alpha)$; wind-tunnel tests are shown in solid lines, and those determined from flight tests shown as dashed lines. The same figure also shows the experimental points in circles that correspond to the equilibrium spin modes. Figure 4 shows clearly that the corrected aerodynamic data result in trim curves, $\alpha = f(\omega)$, that better comply with the experimental data shown as circles. This examples brings out the application of estimation methods to investigate complex phenomenon and the resulting nonlinear aircraft motion.

Simplified Engineering Estimation Methods in Prototypes Flight Tests

Engineering estimation methods allow quick determination of fundamental force and moment coefficients, and because of their simplicity they have been used on a broad basis in the important practical applications as early as in prototype flight tests.

During prototype aircraft flight testing, the coefficients are estimated in the operational as well as ultimate area of flight envelope. Knowledge about these coefficients is necessary to set the tolerances on the aircraft weight and balance and also the limits on Mach number and altitude. In addition, the estimated coefficients are used during flight tests to calculate corrections to the trim curve for random deviations of the weight and the center of gravity from designated values and to allow for any deviation from the steady flight of aircraft. In such cases, relatively simple, so-called engineering, estimation methods are used.[5,8] Such a procedure is applied to calculate the maneuver point $\bar{x}_n$ and maneuver margin σ_n.

In the classical well-known procedure to find the maneuver point, the slopes of the trim curves $d\delta_e/dn_z$ are determined for several positions of the center of gravity $\bar{x}_T$ and plotted as a function $d\delta_e/dn_z = f(\bar{x}_T)$. The point where the resulting line crosses the abscissa axis determines the maneuver point $\bar{x}_n$. The difference between the position of the center of gravity and the maneuver point $(\bar{x}_T - \bar{x}_n)$ equals the aircraft maneuver margin σ_n.

The neutral point $\bar{x}_n^V$ and static margin σ_V are determined during flight tests in the same way. If trim dependencies have been obtained in flight tests as a function of flight speed for two to three positions of the center of gravity (see Fig. 5), then the elevator efficiency coefficient can be determined. The elevator efficiency parameter can be determined as a function of Mach number (see Fig. 5). If flight tests have been made for a single position of the center of gravity, then the derivatives of the aerodynamic force and moment coefficients are calculated using the method of free oscillations.[5] Applications of parameter estimation methods to determine such characteristics from flight data have also been reported in the literature.[9]

Yet another simplified procedure, called angular acceleration method, is based on a graphical analysis of angular accelerations to determine the moment coefficients $C_m(\alpha)$ for an arbitrary aircraft motion with a nonlinear dependency.[5] This method is used most frequently in testing aircraft at high angles of attack, when a strictly defined maneuver is hard to perform and the characteristics are inherently nonlinear.

In the present case, dependency of the pitching-moment coefficient C_m and of the elevator efficiency parameter on the angle of attack is determined from flight data (see Fig. 6). During flight tests

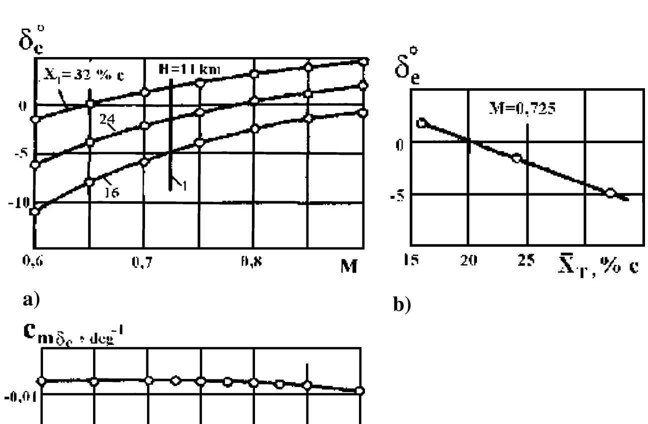

Fig. 5 Determination of elevator effectiveness parameter: a) cutting the trim dependencies by vertical lines, b) elevator deflections vs center of gravity, and c) elevator effectiveness vs Mach number.

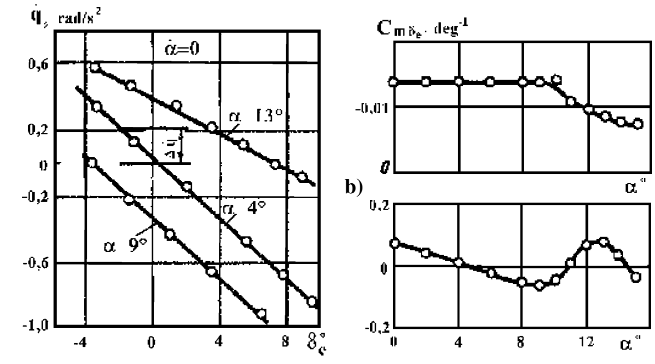

Fig. 6 Determination of pitching-moment characteristics by angular acceleration method: a) pitch acceleration, b) elevator effectiveness, and c) pitching-moment coefficient.

at high Mach numbers, it is important to know the level of static directional stability of the aircraft $C_{n\beta}$ because its absolute value normally decreases as the Mach number increases, and when the characteristics are unfavorable the aircraft can lose directional stability, which could be very dangerous.

To determine the static directional stability during flight tests, a control pulse is applied to the rudder, and the resulting lateral oscillations of the aircraft are recorded. Processing the recorded flight-test data yields the period of free lateral oscillations, which is used to calculate the value of the static directional stability.[5] The described method of calculating the directional stability is quite simple; however, as it is approximate it can only be used at low levels of the lateral stability, that is, when the aircraft motion is nearly two dimensional.

Conclusions

Estimation of aerodynamic characteristics from flight tests has been used at the Gromov Flight Research Institute, Russia, to help make decisions about expanding flight conditions with regard to the angle of attack, Mach number, and position of the center of gravity. Another application is to obtain such information for tuning automatic systems and simulating aircraft motion. In particular, estimation from flight-test data is used in those cases where the flight conditions are difficult to simulate in a wind-tunnel or the wind-tunnel results are not reliable enough. Estimation method is also applied to analyze the spin flight data. When flight testing prototypes, relatively simple engineering estimation methods are applied to determine some aerodynamic coefficients and their derivatives. The results are used to revise the restrictions established for the aircraft or to calculate various corrections during flight tests, for example, corrections for a deviation of the weight or the center of gravity from the designated values, or for a deviation of the aircraft motion from the stable flight. The three different types of examples presented the paper bring out the practical value of the estimation methods and the importance of models derived from flight tests.

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