Engineering Notes

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Two Complementary Approaches to Estimate Downwash Lag Effects from Flight Data

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Introduction

VALIDATION of the wind-tunnel and analytical estimates of the aerodynamic derivatives with estimates from flight test data is an important application of the system identification methodology. Reliable and accurate estimates of a large number of aerodynamic derivatives are obtained from flight data using the maximum likelihood method, although, routinely, explicit accounting for certain unsteady aerodynamic effects such as downwash and sidewash interferences pose difficulties. Recent advances in both parameter estimation methods and in flight test techniques have provided a new impetus for modeling and identification of such unsteady interference effects in aircraft dynamics.[1-3]

This Note addresses in some depth the problem of accounting for downwash lag effects in aircraft parameter estimation from flight data. One possibility of including such an effect is to proceed from the fundamental and to model the forces acting on the wing and tail plane separately. In such a case it becomes possible to estimate explicitly the downwash angle and also to include the lag effect. It leads, however, to a model that is nonlinear in parameters and necessarily requires an estimation program capable of handling nonlinear model postulates. The other approach is a simplification based on linearization. It leads to the first-order approximation of aerodynamic derivatives with respect to translational acceleration. The derivatives due to the body-fixed translational acceleration in the vertical direction are equivalent in the stability axis to those with respect to the rate of change of angle of attack. The second approach was first investigated in Ref. 1 to estimate from flight data the pitching moment derivatives with respect to pitch rate and rate of change of angle of attack of a highly maneuverable aircraft with large roll angle capabilities.

A parameter estimation program capable of handling linear as well as nonlinear system models is used here to compare the two approaches of accounting for the downwash. Further, an attempt is made to investigate the possibility of using the linearized approach to estimate separately the two pitch damping derivatives from flight tests with a larger aircraft having limited roll angle capabilities.

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Downwash Effects

In the theory of aircraft flight mechanics, it is well known that the most significant effect of the wing on the tail is the downward deflection of the flow, which could be aerodynamically modeled as a downwash angle ϵ. Such effects are present even under the assumption of quasisteady flow and need to be properly accounted for. Conventionally, as a first-order approximation, the downwash angle is assumed to be proportional to the wing angle of attack and is represented as a constant derivative $\partial\epsilon/\partial\alpha$. Any instantaneous change in the wing angle of attack, say, in response to control surface deflection, leads to an immediate variation in the flow pattern or downwash generated at the wing trailing edge. The modified flow, however, reaches the tail after a time interval $\Delta t = r_H^*/V$, where V is the airspeed and r_H^* is the tail length. Thus, the effective angle of attack at the tail is changed only after a time delay of Δt s. This so-called downwash lag effect can be mathematically expressed as $(\partial\epsilon/\partial\alpha)\ \alpha(t-\Delta t)$. In the context of estimation of aerodynamic derivatives from flight data, two approaches are possible to account for the downwash lag effect.

Linearized Aerodynamic Model

In this approach, the downwash lag effect is approximated through derivatives with respect to the translational acceleration in the vertical direction. In the stability axis, as already pointed out, they become derivatives due to $\dot{\alpha}$, the rate of change of angle of attack.[1] The Taylor series expansion of the lift force and pitching moment results in an aerodynamic model that is linear in parameters. Typically,

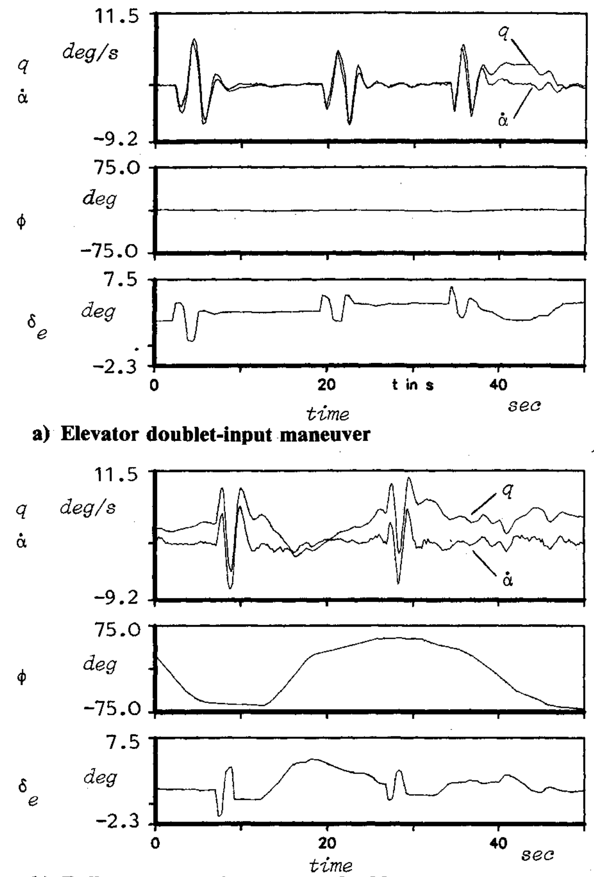
$$C_L = C_{L_0} + C_{L_\alpha}\alpha + C_{L_{\delta e}}\delta_e + C_{L_q}\frac{q\bar{c}}{V} + C_{L_{\dot{\alpha}}}\frac{\dot{\alpha}\bar{c}}{V} \tag{1a}$$

$$C_m = C_{m_0} + C_{m_\alpha}\alpha + C_{m_{\delta e}}\delta_e + C_{m_q}\frac{q\bar{c}}{V} + C_{m_{\dot{\alpha}}}\frac{\dot{\alpha}\bar{c}}{V} \tag{1b}$$

In the past, many of the investigations were necessarily restricted to models linear in parameters, mainly because the available estimation programs were capable of handling only the linear system models.[4] Although algorithmically it is feasible to estimate the translational derivatives $C_{L_{\dot{\alpha}}}$ and $C_{m_{\dot{\alpha}}}$, the linearization results in a correlation problem and affects the independent estimation of these derivatives. In typical flight maneuvers employed in estimating the longitudinal derivatives, the pitch rate q is highly correlated $\dot{\alpha}$ (see Fig. 1a). This is clear from the $\dot{\alpha}$ equation[1]:

$$\dot{\alpha} = -\frac{\bar{q}S}{mV}C_L + q + \frac{g}{V}(\cos\theta\ \cos\phi\ \cos\alpha + \sin\theta\ \sin\alpha)$$
$$-\tan\beta(p\ \cos\alpha + r\ \sin\alpha) \tag{2}$$

In the conventional longitudinal maneuvers, the variations in roll angle ϕ are minimal. Since the lift coefficient C_L is a linear function of α, q, and δ_e, the first two terms in Eq. (2) yield a linearly dependent $\dot{\alpha}$ component. To overcome this linear dependence, special flight maneuvers are required. An independent component of $\dot{\alpha}$ can be generated through the gravity term, i.e., the third term on the right side of Eq. (2).



a) Elevator doublet-input maneuver

b) Roll maneuver with elevator doublet

Fig. 1 Correlation between pitch rate q and rate of change of angle of attack $\dot{\alpha}$.

The magnitude of the contribution of this term depends on the excursions in the pitch angle θ or roll angle ϕ. In addition, simultaneous variation in the airspeed V can be be used to augment the contribution. Figure 1b clearly indicates that a typical roll maneuver carried out removes the correlation between the variables q and $\dot{\alpha}$.[1,5] The variable $\dot{\alpha}$ is not directly measured in flight but is obtained by numerical differentiation only for the qualitative comparison.

For large aircraft, large pitch angle excursions may pose practical difficulties. On the other hand, roll maneuver is easy to carry out and also provides necessary separation of q and $\dot{\alpha}$. Reference 1 demonstrates successful estimation of the two pitch damping derivatives from a 180-deg (inverted position) roll maneuver with a highly maneuverable aircraft, indicating possible limitation to large aircraft. The current investigation attempts to validate the wind-tunnel estimates for the specific test aircraft and to establish the possibility of estimating such derivatives for larger aircraft with limitations on the possible maximum roll angle as well as load factor.

Two-Point Aerodynamic Model

For a conventional aircraft with wing and horizontal tail, the lift and drag forces can be assumed to be working at two points, namely the neutral points of the wing and of the tail. Knowing the forces, the moments can be computed readily, since the lever arms are generally known. In a general case, the lift and pitching moment acting on an aircraft can be represented as[3,6]:

$$C_L = C_{L_0} + C_{L_{\alpha W}}\alpha(t) + \frac{S_H}{S} \times \left\{ C_{L_{\alpha H}}\left[\alpha(t) - \frac{\partial\epsilon}{\partial\alpha}\alpha(t-\Delta t) + i_H + \tan^{-1}\frac{qr_H}{V}\right] + K_{\delta_e}\delta_e \right\}$$

$$C_m = C_{m_0} - \frac{r_H^*}{\bar{c}}\frac{S_H}{S} \times \left\{ C_{L_{\alpha H}}\left[\alpha(t) - \frac{\partial\epsilon}{\partial\alpha}\alpha(t-\Delta t) + i_H + \tan^{-1}\frac{qr_H}{V}\right] + K_{\delta_e}\delta_e \right\} + C_{m_{qW}}\frac{q\bar{c}}{V} \tag{3}$$

where the subscript W refers to the wing/body combination and H to the horizontal tail, S and S_H denote the wing and tail areas, $\bar{c}$ the mean aerodynamic chord, δ_e the elevator deflection, and i_H the trim angle. The lever arms r_H and r_H^* are, respectively, the distances from the center of gravity and from the neutral point of the wing to the neutral point of the tail. For the sake of clarity, in Eq. (3) only α is shown to be a function of time, although the other variables are also time-dependent.

The two-point aerodynamic modeling necessarily leads to a more complex nonlinear-in-parameter model. The use of such a model to estimate the lift derivatives separately for the wing and tail requires an estimation program capable of handling nonlinear system models as well as a provision to generate delay in a specified variable, in the present case α. Both of these options are available in the estimation program used in these investigations.[7] This approach, although requiring more advanced estimation programs, provides physically more realistic representation of the aerodynamics and accounts for the downwash effects explicitly through the derivative $\partial\epsilon/\partial\alpha$ and a delay Δt. Thus, it overcomes the need for special flight maneuvers otherwise necessary to remove correlation between the motion variables.

Equivalent linear derivatives, if required, say, for comparison purposes, may be obtained from the estimated lift curve slope of the tail plane $C_{L_{\alpha H}}$ and downwash parameter $\partial\epsilon/\partial\alpha$ by simple recomputations. For example,

$$C_{m_q} = -\left(C_{L_{\alpha H}}\frac{S_H}{S}\frac{r_H^*}{\bar{c}}\right)\frac{r_H}{\bar{c}} + C_{m_{qW}} \tag{4a}$$

$$C_{m_{\dot{\alpha}}} = -\left(C_{L_{\alpha H}}\frac{S_H}{S}\frac{r_H^*}{\bar{c}}\frac{\partial\epsilon}{\partial\alpha}\right)\frac{r_H}{\bar{c}} \tag{4b}$$

Flight Tests

The DLR test aircraft called ATTAS (Advanced Technologies Testing Aircraft System) is a medium-size twin-jet short-haul 44-passenger aircraft modified and instrumented for the research purposes of in-flight simulation.[8] The aircraft, with a span of 21.5 m, wing area of 64 m^2, and full-fuel takeoff weight in the range of 20 tons, has maximum roll angle capability up to about 90 deg, and the maximum safe load factor is 2.8 g for the retracted landing flaps. To investigate estimation of C_{m_q} and $C_{m_{\dot{\alpha}}}$, a flight test program was carried out at an altitude of 5000 m and indicated aispeed of 200 kt. Apart from the conventional maneuvers to excite the longitudinal and lateral directional motion with rapidly changing 3-2-1-1 multistep inputs,[4] five roll maneuvers were carried out. The first four roll maneuvers were with the bank angles of 20 , 40, 50, and 60 deg, respectively. In these maneuvers, the variations in airspeed were minimal. In the fifth maneuver, the 60-deg roll is combined with acceleration and deceleration, i.e., airspeed variation. Elevator doublets were also applied in the banked position to maximize the information. During the complete maneuver, one must ensure that the load factor is within the allowable safe limits. Although the conventional multistep inputs were generated from the onboard computer and applied automatically, roll maneuvers requiring more coordination and continuous monitoring were carried out manually by the test pilot.

Data Analysis and Results

The onboard recorded flight data was analyzed off-line using the maximum likelihood estimation program for nonlinear systems.[7] Although detailed analysis of all of the test maneuvers has been carried out,[8] only typical results required to demonstrate estimation of downwash effects are presented here. Five roll maneuvers were analyzed separately to find the effect of the roll angle on the estimates of $C_{m_{\dot{\alpha}}}$ and C_{m_q}. In each case, roll maneuver is combined with the conventional multistep input maneuvers, exciting separately the longitudinal and lateral directional motion.

The results of the analysis based on the linearized model of Eq. (1) indicate that it was not possible to estimate separately the derivatives C_{m_q} and $C_{m_{\dot{\alpha}}}$ from the roll maneuver with 20-deg bank angle. The other roll maneuvers with more than 40-deg bank angle provided uncorrelated estimates of these two derivatives, which appeared physically meaningful and also compared well with wind-tunnel predictions. The estimates obtained from the accelerated and decelerated 60-deg roll maneuver are provided in Table 1. In Fig. 2, the agreement between the measured and estimated time responses of typical motion variables is seen to be good. The first segment corresponds to the multistep elevator input and the second to the roll maneuver with elevator doublet input. For the purpose of illustration, only short records are shown.

The analysis has been repeated using the two-point aerodynamic model, Eq. (3). Although this approach does not necessarily require special flight tests, in order to compare the results with linearized model, the same set of time records including a roll maneuver were analyzed. Since the downwash effect is implicitly modeled, the roll maneuver with only a 20-deg bank angle provided an estimate of the downwash parameter $\partial\epsilon/\partial\alpha$, which agreed well with the estimates from the other roll maneuvers with larger bank angles. From the estimated $C_{L_{\alpha H}}$ and $\partial\epsilon/\partial\alpha$, the equivalent linear pitch damping derivatives C_{m_q} and $C_{m_{\dot{\alpha}}}$ are computed, using Eq. (4). These values compare well with the estimates from the linearized model and wind-tunnel prediction (see Table 1). The match between the flight-measured and estimated responses was essentially the same as in Fig. 2. Table 1 also provides other pitching moment derivatives. The elevator control effectiveness, $C_{m_{\delta e}}$, as estimated by both of the models, is found to be a little higher in flight than the wind-tunnel prediction.

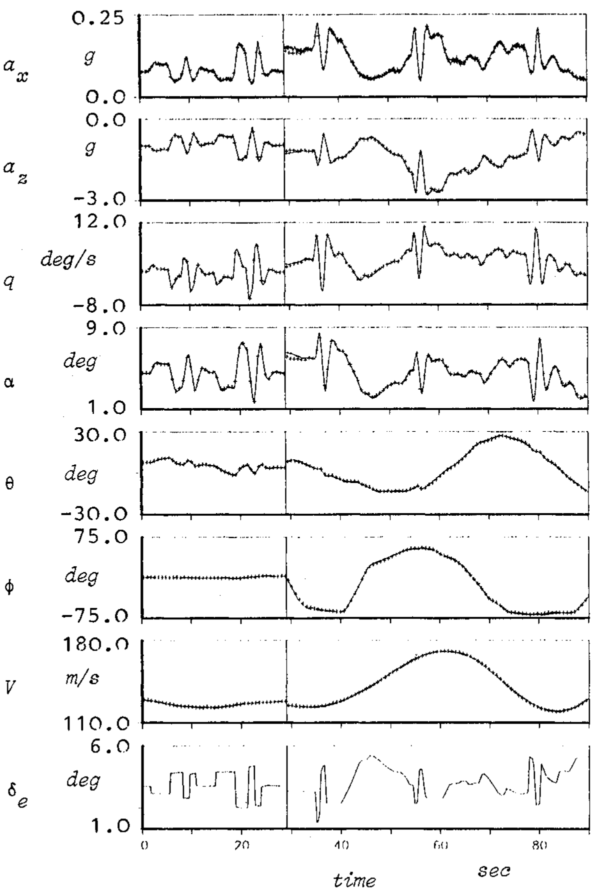


Fig. 2 Flight-measured (———) and estimated (+ + + +) responses for an elevator multistep input maneuver and a roll maneuver with elevator doublet input.

Table 1 Pitching moment derivatives

Parameter	Wind-tunnel prediction	Estimates obtained from: Linearized model	Two-point model[a]
C_{m_α}	−1.07	−1.18	−1.12
$C_{m_{\delta e}}$	−1.40	−1.66	−1.68
C_{m_q}	−8.67	−7.86	−9.03
$C_{m_{\dot{\alpha}}}$	−4.65	−5.23	−4.59

[a] Recomputed estimates.

Concluding Remarks

This Note compares the two approaches to account for the downwash lag effect in the estimation of aerodynamic derivatives from flight data. The equivalent pitching moment derivatives estimated from flight data by the two methods and the wind-tunnel predictions agreed well. The linearized approach based on the Taylor series requires special flight maneuvers to remove the correlation between the motion variables. The roll maneuvers with more than 40-deg bank angle yielded uncorrelated estimates of the two pitch damping derivatives. The two-point aerodynamic model, based on the forces acting on the wing and tail, accounts explicitly for the downwash lag effect through a constant derivative and time delay. It requires, however, a more advanced parameter estimation program, capable of handling general nonlinear systems, but eliminates the need for special flight maneuvers. In this sense, the more complex approach may provide an alternative to account for the downwash effects for large aircraft with limited roll angle capabilities.

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