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Identification of Speed Brake, Air-Drop, and Landing Gear Effects from Flight Data

R. V. Jategaonkar,* W. Mönnich,† D. Fischenberg,‡ and B. Krag§
DLR, German Aerospace Research Establishment, 38108 Braunschweig, Germany

Applying system identification methodology, an aerodynamic database covering the entire operational flight envelope, was estimated from Transall flight data. This paper emphasizes the modeling and identification of some of the Transall specific operational characteristics such as the ramp door and dropping of heavy loads. In addition, aerodynamic effects because of speed brakes and landing gear are determined applying a nonlinear maximum likelihood parameter estimation method. The identification results indicate that the speed brakes function as pure drag generators only for the retracted landing flaps. For extended landing flaps, applying speed brakes affects the aircraft pitching motion. The landing gear is found to affect both the longitudinal and lateral–directional aircraft motion. Opening of the ramp door results in an effectively enlarged fuselage, affecting mostly the lateral–directional motion. It is demonstrated that the load dropping can be adequately modeled by properly accounting for the variations in the aircraft mass characteristics.

Introduction

AT the German Aerospace Research Establishment (DLR), a major project on the development of an aerodynamic database from Transall flight data was completed in the recent past.[1,2] A ground-based flight simulator incorporating this database has been built by Thomson Training and Simulation. The simulator, to be used for pilot training by the German Air Force, must faithfully replicate the aircraft flight dynamics and all of the functional characteristics over the entire operational envelope. It is generally known that the fidelity of simulation depends to a large extent on the accuracy of the mathematical model and on the database representing the aircraft. Hence, an accurate flight-validated aerodynamic database is considered a prerequisite.

Although the wind-tunnel measurements of the Transall, made in the 1960s, are still available, this wind-tunnel-generated database is considered unsuitable for a modern flight simulator, being unable to meet the level D quality standards of the Federal Aviation Administration.[3] System identification methodology, which has found widespread application in the aerospace community during the last two decades, provides an alternative approach to estimate aerodynamic derivatives from flight data.[4–6] It has also been applied in the recent past to generate databases suitable for flight simulators.[7–9]

The C-160 Transall data gathering project was aimed at determining the flight-validated aerodynamic database suitable for a simulator and to generate validation test data for simulator checkout and acceptance. A detailed description of the program and that of the complete aerodynamic modeling is not within the scope of this paper. Attention is restricted to modeling and identification of some of the Transall specific operational characteristics, such as opening the ramp door and the dropping of heavy loads. In addition, the aerodynamic effects because of speed brakes and landing gear are determined from flight tests. A brief description of the flight tests carried out to enable estimation of these specific effects is provided. Emphasis is placed on clearly showing the influence of neglecting these effects on the aircraft dynamics, which would play an important role in pilot training, and on the acceptance of the simulator by the pilots as a device representing truly the Transall aircraft. Parameter estimation has been carried out applying a nonlinear maximum likelihood parameter estimation method. Instead of providing numerical values of the identified parameters and their accuracies, typical results obtained are presented as a comparison between measured aircraft responses and those predicted by using the model determined for each configuration investigated in this paper.

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*Scientist, Institute of Flight Mechanics, Lilienthalplatz 7. Senior Member AIAA.

†Scientist, Institute of Flight Mechanics, Lilienthalplatz 7. Affiliate Member AIAA.

‡Scientist, Institute of Flight Mechanics, Lilienthalplatz 7.

§Head, Fixed Wing Aircraft Branch, Institute of Flight Mechanics, Lilienthalplatz 7.

Test Aircraft

The C-160 Transall is a military transport aircraft capable of carrying troops, casualties, freight, supplies, and vehicles, and serves the needs of the German Air Force. It is powered by twin turboprop Rolls Royce Tyne engines with four-bladed propellers. Each engine is capable of generating 70,000-N thrust. The maximum takeoff and landing weight is 51,000 kg, and the maximum cruising speed at an altitude of 16,000 ft is 277 kn (513 km/h). The cantilever high wing has an area of 160 m^2 with a span of 40 m. The overall length is 32.4 m. The horizontal tail area is 43.8 m^2 (Ref. 10).

Apart from the conventional control surfaces, i.e., elevator, rudder, and ailerons, the C-160 is equipped with hydraulically operated air brakes mounted inboard on the wings and spoilers mounted outboard forward of the flaps on each wing. The spoilers are designed to improve the aileron effectiveness and are deflected proportionally for aileron deflections greater than 3 deg and less than 10 deg. For aileron deflections greater than 10 deg the spoilers are deflected to the maximum limit of 45 deg. The underside of the upswept rear fuselage lowers to form a loading ramp. The tricycle landing gear is retractable. Each main unit is composed of two pairs of wheels in tandem and the twin-wheel nose unit is steerable. A typical aircraft chosen from the C-160-fleet was instrumented to measure and record onboard a total of 91 parameters (Fig. 1). The flight measurements sampled at a rate of 50 Hz were recorded on a removable hard disk for off-line processing.[11]

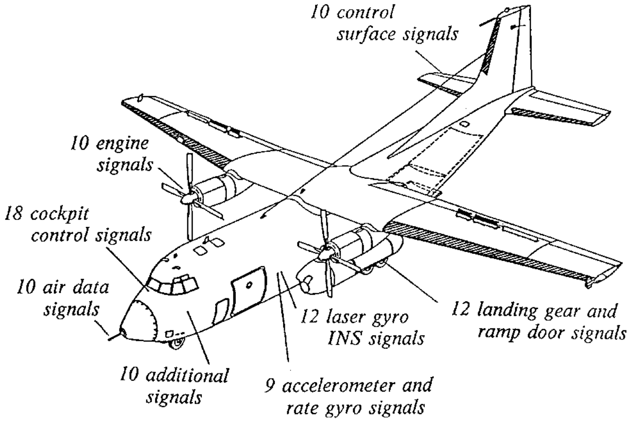

Fig. 1 Instrumented C-160 Transall aircraft.

Flight Test Program

A comprehensive flight test program consisting of calibration flights, system identification maneuvers, ground tests, sound recordings, and validation tests was carried out with the instrumented C-160 aircraft at the German Air Force Flight Test Center.[2] The flight maneuvers suitable for parameter estimation were flown at four different altitudes of 2000, 8000, 16,000, and 26,000 ft and at five different speeds at each altitude, thus spanning the operational envelope. Five flap positions of 0, 20, 30, 40, and 60 deg, and for each flap position three locations of c.g., namely, extreme forward [23% mean aerodynamic chord (MAC)], nominal (28% MAC), and extreme aft (33% MAC), were investigated.

At each chosen flight condition, the system identification maneuver was initiated from a trimmed level flight. The maneuver sequence consisted of a multistep elevator input exciting the short period motion, an elevator pulse exciting the phugoid motion, a bank-to-bank maneuver exciting the rolling motion, followed by a rudder input exciting the yawing motion. The bank-to-bank maneuver consisted of a small aileron input (less than 3 deg) followed by a larger aileron input that automatically draws out the spoilers. This sequence is necessary to ensure separate identification of aileron and spoiler derivatives. The previous standard maneuver sequence was augmented with a thrust input maneuver to enable determination of thrust effects. In addition, whenever permissible, a level turn maneuver with superimposed elevator doublets in the banked position was carried out, providing more information to accurately estimate the downwash parameters. The aforementioned flight maneuvers, covering the bulk of the flight test time, provide a basis for the determination of a basic aerodynamic model. This set of data was augmented with stall approaches during which the pilot carefully applied the elevator, aileron, and rudder doublets, thus exciting the aircraft's characteristic motion with a steadily increasing angle of attack until the stall boundary. Similarly, flight maneuvers were carried out with single engine flights. All of the system identification maneuvers were flown manually by the test pilot.

To investigate the ramp door influence, a typical flight condition of 130 kn at 8000 ft was selected. At this flight condition the ramp door was fully opened. Starting from a level flight the flight maneuvers for system identification were carried out, exciting the longitudinal and lateral–directional motion with elevator, aileron, and rudder inputs as described earlier. At the end of the test sequence, the ramp door was closed before proceeding to the next test.

To enable modeling of aerodynamic effects because of speed brakes, flight tests were carried out at 8000 ft, 110 kn for a 30-deg flap deflection; at 8000 ft, 100 kn for a 60-deg flap deflection; and at 16,000 ft, 195 kn for the retracted landing flaps. Starting from a horizontal level flight, the test sequence consisting of applying 40% of speed brakes, holding for a couple of seconds, and retracting the speed brakes was carried out. The tests were also repeated by applying maximum, i.e., 100%, of speed brakes. No specific flight maneuvers were carried out while the brakes were applied.

To enable the modeling of aerodynamic effects because of the landing gear, flight maneuvers with extended landing gear were carried out at 16,000 ft with 120, 140, and 160 kn. Once again, starting from a horizontal level flight, the system identification maneuver sequence was applied. To facilitate direct evaluation, the same test sequence was repeated at the same flight conditions with retracted landing gear. This procedure was also followed for the ramp door and speed brake tests.

Two load-drop tests were carried out in the test area of the German Flight Test Center, in the first run dropping a load of 4600 kg and in the second of 4000 kg. The load was anchored on the loading rails in the front portion of the cabin. By opening the ramp door fully, a small parachute is let out that pulls the load out. The load rolls on the rails until the end of the loading ramp and drops out over the ramp door edge. Since the load must land in the specified test area, the pilot orients the aircraft appropriately depending upon the wind. The ramp door is then closed before proceeding to the next test.

Basic Aerodynamic Model

Estimation of an aerodynamic model valid over the entire operational envelope is an iterative procedure. Focusing the attention on flights in the normal flight regime, several configurations covering five landing flap positions and three different c.g. locations were analyzed. Considering small excursions around a trim point enabled the estimation of primary derivatives neglecting angle of attack and Mach number dependencies or other nonlinear effects. Such point identifications, carried out for each flight condition tested, yielded a bulk of estimation results from which the structure of the global comprehensive model could be assessed. For example, the dihedral effect, derivative $C_{l\beta}$, estimated from several flights at four landing flap positions, is shown in Fig. 2.[12]

The collated results of point identification were analyzed to determine the structure of the aerodynamic model that was valid over a broader range. For example, it could easily be deduced that the lift-curve slope $C_{L\alpha WB}$ is a function of Mach number, the downwash parameter $\partial\varepsilon_H/\partial\alpha$, is a nonlinear function of angle of attack, and the elevator control effectiveness $C_{L\eta}$ is a nonlinear function of angle of attack and also of the elevator deflection.[12] The dihedral effect for each landing flap, as seen from Fig. 2, can be modeled as a linear function of angle of attack. Based on such deductions, the aerodynamic model was formulated to cover the complete range of angle of attack and Mach numbers flown in the tests. From the six-degree-of-freedom equations of motion, the aerodynamic derivatives were estimated by combining several flight conditions in a single run. For example, this multipoint identification included 75 flight maneuvers with 55,000 data points amounting

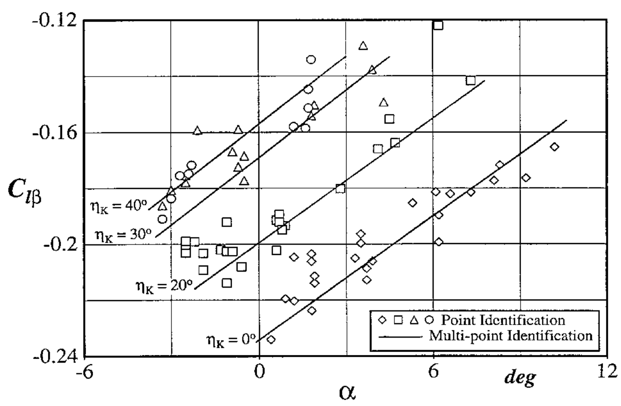

Fig. 2 Dihedral effect (derivative $C_{l\beta}$).

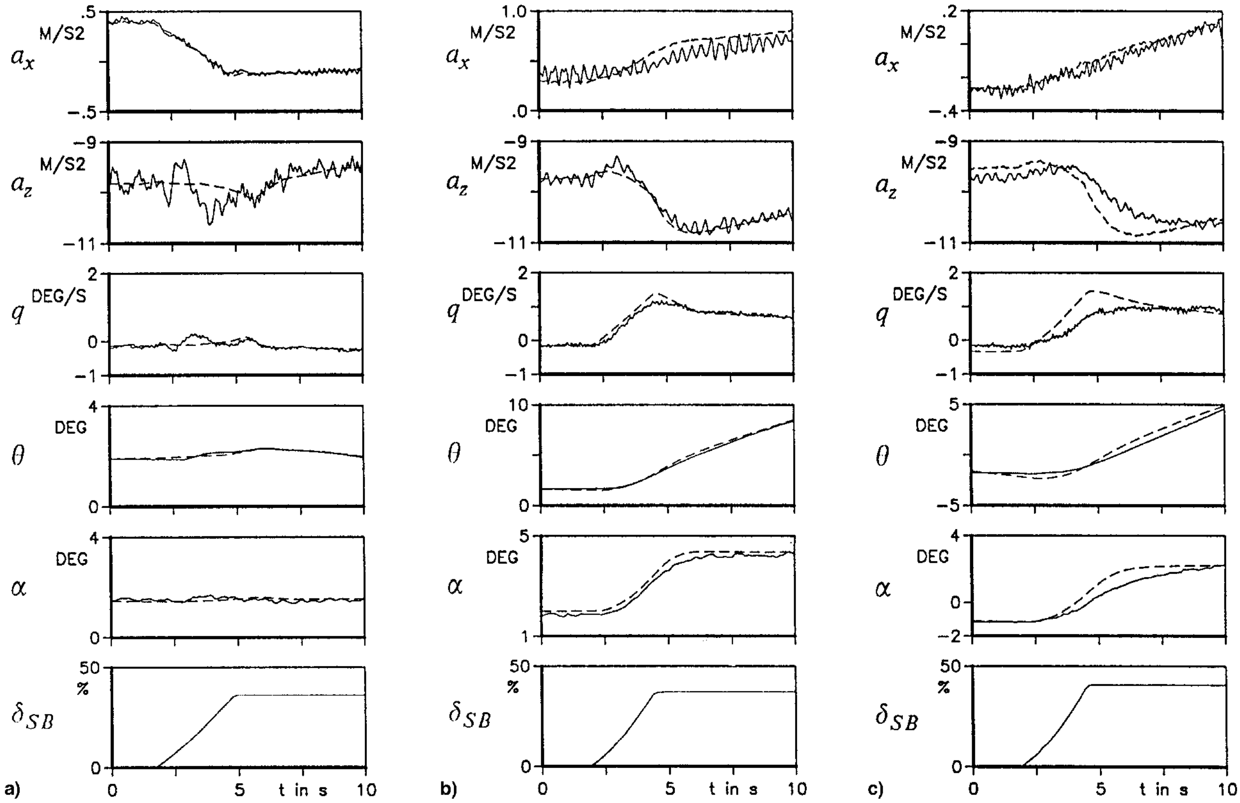

Fig. 3 Identification of aerodynamic effects caused by speed brakes (——, flight measured; ----, estimated). Landing flap = a) 0, b) 30, and c) 60 deg.

to about 2200 s of flight data at 16 flight conditions for the landing flap of 0 deg. The estimates of the dihedral effect obtained from such a comprehensive model are shown in Fig. 2 by solid lines. The multipoint identification procedure was repeated separately for each flap position. In each case, a nonlinear maximum likelihood method was applied to estimate the aerodynamic derivatives.[13–15]

Modeling of Speed Brake Effects

The aerodynamic effects caused by the speed brakes are modeled as incremental changes in the lift, drag, and pitching moment coefficients, i.e., as $\Delta C_{L\mathrm{SB}}$, $\Delta C_{D\mathrm{SB}}$, and $\Delta C_{m\mathrm{SB}}$ (the subscript SB denoting speed brakes). Flight tests during which 40% brakes were applied is taken as a typical case for evaluation. Based on the aforementioned comprehensive aerodynamic model, the previous incremental effects are identified separately for three landing flaps, namely, $\eta_K = 0$, 30, and 60 deg. This identification yields the estimated responses shown by the dashed lines in Fig. 3, which are compared with the flight measurements shown by the solid lines, where a_x is the longitudinal acceleration, a_z is the vertical acceleration, q is the pitch rate, θ is the pitch angle, α is the angle of attack, and δ_{SB} is the speed brake deflection. The braking effect is clearly observed from the reduction in a_x for $\eta_K = 0$ deg. Variations in the heave and pitching motion as seen from a_z and q, respectively, are negligible. The speed brakes, as seen in Fig. 4, consist of lower and upper flaps on each wing and are deflected symmetrically. As such, they primarily work in a classical sense as a drag-inducing device.

A closer look at the response match for $\eta_K = 0$, 30, and 60 deg in Fig. 3, however, shows some discrepancies. A time lag between the flight measurements and the estimated responses is clearly seen, this time lag increasing with the increasing flap deflection. These discrepancies are modeled as a downwash

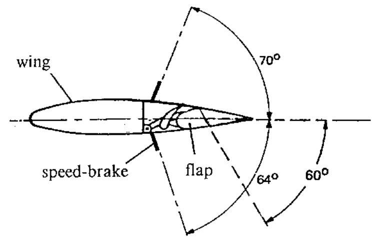

Fig. 4 Speed brake and flap configuration.

generated by the speed brakes. Accounting for the transit time effect, the angle of attack at the tail is now given by

$$\alpha_H = \alpha + i_H - \left[\frac{\partial \varepsilon_H}{\partial \alpha}\alpha(t - \tau_\alpha) + \frac{\partial \varepsilon_H}{\partial C_S}C_S(t - \tau_{\mathrm{CS}}) + \frac{\partial \varepsilon_H}{\partial \delta_{\mathrm{SB}}}\delta_{\mathrm{SB}}(t - \tau_\alpha)\right] \tag{1}$$

where α is the angle of attack at the wing, i_H is the horizontal tail setting angle, C_S is the thrust coefficient, δ_{SB} is the speed brake deflection, ε_H is the downwash angle, and τ_α and τ_{CS} represent the transit time, i.e., the time taken for any flow changes generated at the wing and at the propeller, respectively, to reach the tail. The downwash parameters $\partial\varepsilon_H/\partial\alpha$ and $\partial\varepsilon_H/\partial C_S$ are known from the foregoing step of basic aerodynamic model identification. The downwash parameter $\partial\varepsilon_H/\partial\delta_{\mathrm{SB}}$ is required to be estimated from flight data.

This model postulate yields the responses shown in Fig. 5. Compared to Fig. 3, the improved match for q, a_z, and θ, particularly for the 30- and 60-deg landing flap, clearly demonstrates appropriateness of the formulated model. The parameter $\partial\varepsilon_H/\partial\delta_{\mathrm{SB}}$ was found to be zero for $\eta_K = 0$ deg, as was to be expected from Fig. 3a. The estimates for the other two flap

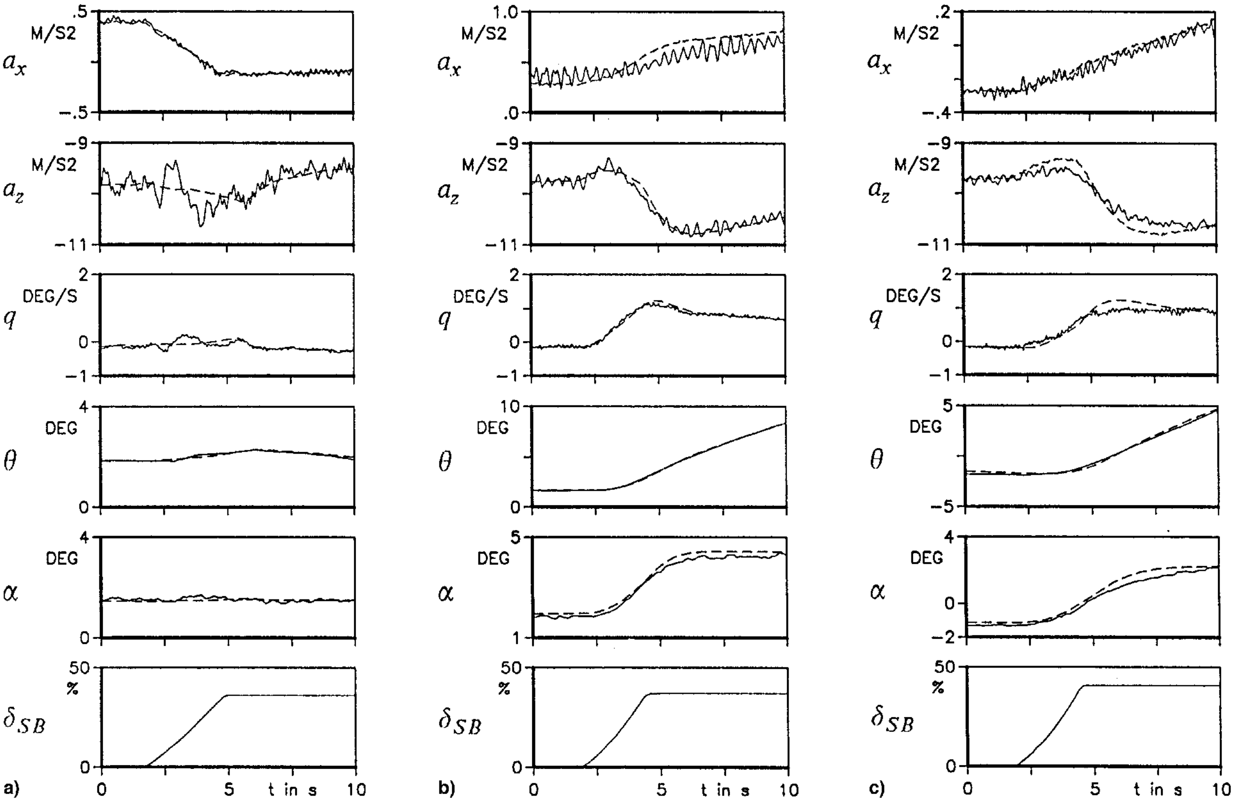

Fig. 5 Influence of downwash lag caused by speed brakes (——, flight measured; ----, estimated). Landing flap = a) 0, b) 30, and c) 60 deg.

positions were found to be almost linearly dependent on the flap deflection.

Modeling of Ramp Door Aerodynamics

Applying the basic aerodynamic model identified for the clean configuration, the flight maneuvers with the ramp door open are analyzed. First, no additional aerodynamic parameters for the ramp door influence were estimated. This yields the estimated responses pertaining to the lateral–directional motion shown in Fig. 6a, where a_y is the lateral acceleration, p is the roll rate, r is the yaw rate, ϕ is the roll attitude, β is the sideslip angle, ξ is the aileron deflection, and ζ is the rudder deflection. A noticeable difference in the estimated responses compared to the flight measurements is observed from the variables β, r, and a_y. The damping of the yawing motion also appears to be affected.

To account for these effects additional derivatives $C_{n\beta LT}$, C_{nrLT}, and $C_{Y\beta LT}$ were introduced, the subscript LT denoting the ramp door. Estimation of these aerodynamic derivatives from the maneuvers with the ramp door open posed no difficulties. They were estimated with very low standard deviations. The resulting model responses shown in Fig. 6b match the flight measured data very well. The computed responses in Fig. 6b were obtained from the model where only the three aforementioned parameters were estimated, whereas the remaining parameters were fixed on their values from the basic aerodynamic model. The identified incremental derivatives represent the effects of an enlarged fuselage as a result of opening the ramp door, which is the underside of the upswept fuselage. It is known that the body and the tail primarily contribute to the weathercock stability, i.e., to the derivative $C_{n\beta}$. Although the important contributions to the damping-in-yaw, derivative C_{nr}, are from the wing and the vertical tail, the large bodies are also known to contribute to this derivative.[16,17]

Load Drop Test

Accurate knowledge about the aircraft mass characteristics, such as weight, moments of inertia, and c.g., is necessary for accurate parameter estimation, because the inaccuracies in the moments of inertia, for example, directly affect the nondimensional moment derivatives, whereas any errors in the mass cause proportional errors in the force derivatives.[5] This is particularly true in the case of load-drop tests. Load dropping leads not only to a sudden reduction in the overall weight, but also to significant variations in the c.g. position and of the moments of inertia caused by the changing load distribution as the load is pulled out from its anchored position in the front cabin part to the rear edge of the ramp door before dropping out. In the tests carried out, a 4600-kg load, which is about 10% of the overall weight, moves over a length of 10 m in approximately 1.5 s before falling out.

Knowing 1) the initial position x_0 of the load, 2) the time point t_0 at which the load is unlatched and begins to move on the rails, and 3) the time point t_{out} at which the load drops out of the aircraft, the actual location of the load at any time during the maneuver can be determined.

Assuming a constant acceleration at which the load is pulled out, the pulling acceleration a_{pull} is obtained as

$$a_{\text{pull}} = \frac{2(x_R - x_0)}{(t_{\text{out}} - t_0)^2} \tag{2}$$

where x_R is the rear edge of the ramp door from where the load drops out. This is a fixed distance known from the aircraft geometry. The actual position of the load x at any time t ($t_0 < t < t_{\text{out}}$) during the maneuver is then given by

$$x = x_0 + \tfrac{1}{2} a_{\text{pull}}(t - t_0)^2 \tag{3}$$

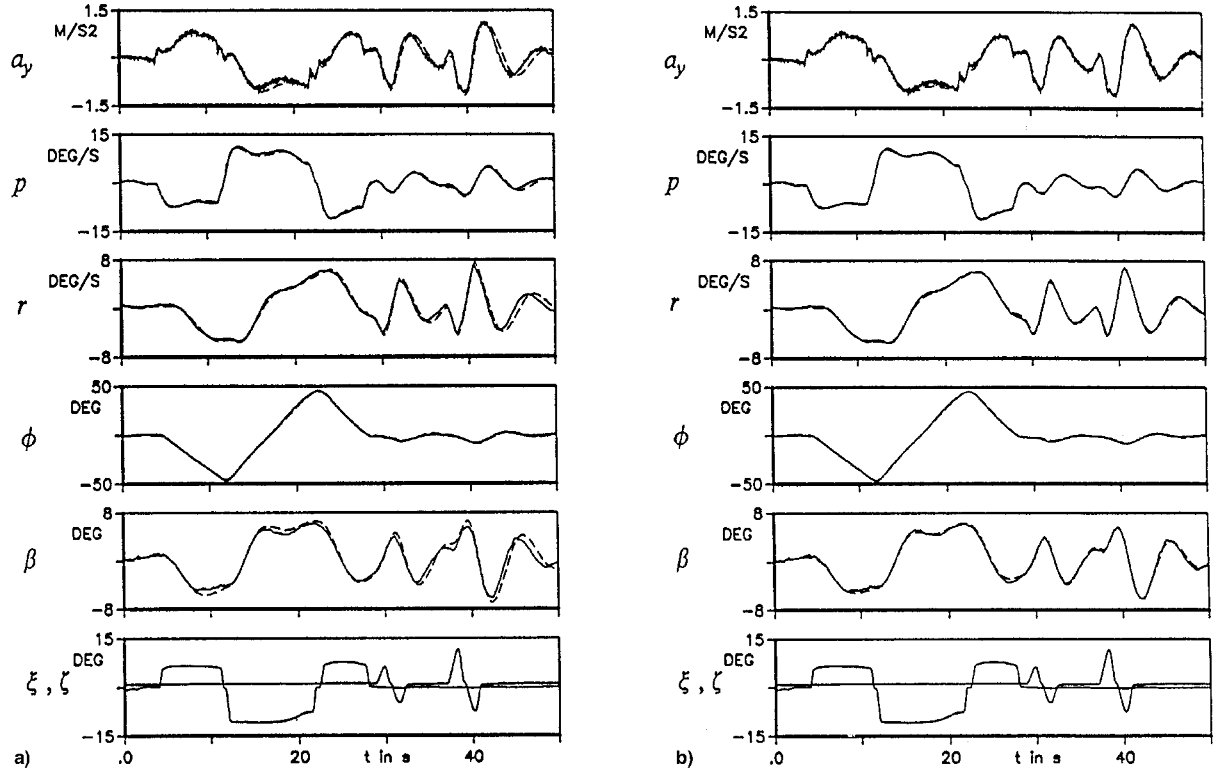

Fig. 6 Identification of lateral-directional motion with ramp door open (——, flight measured; - - - -, estimated): a) neglecting and b) accounting for ramp door effects.

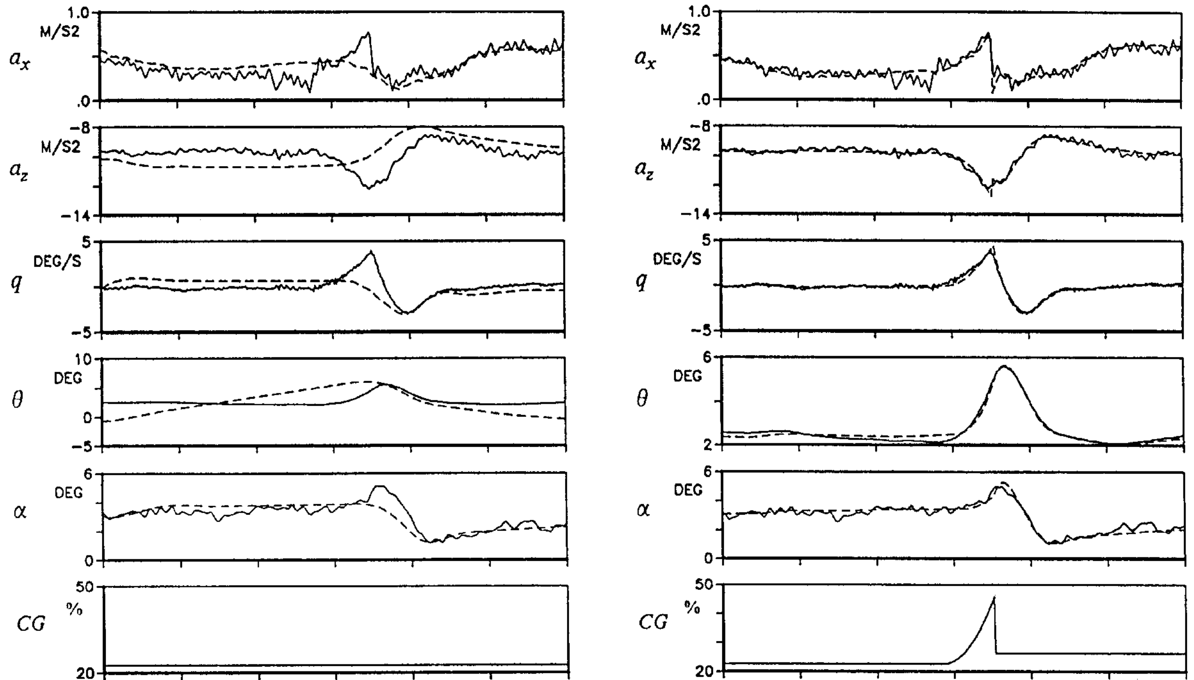

Fig. 7 Identification of 4600-kg load drop test (——, flight measured; - - - -, estimated): a) neglecting and b) accounting for changes in mass characteristics.

Having determined the actual position of the load at any time t during the maneuver, the c.g. location can be determined from the c.g. nomogram based on an index computation.[1] As suggested by the simulator manufacturer, the aircraft mass characteristics data without any modifications including the c.g. nomogram supplied by the aircraft manufacturer has been used in the present case to compute the location of the c.g., although knowing the aircraft mass, the mass of the moving load, and the position of the load, the c.g. can be computed by other methods as well.

Based on the comprehensive model incorporating the incremental effects because of the ramp door, the 4600-kg load drop test is analyzed in two steps. In the first step, the aircraft mass characteristics throughout the length of the test are held constant at the initial values, i.e., those at the start of the run, thus neglecting the variations in the c.g. and the moments of inertia.

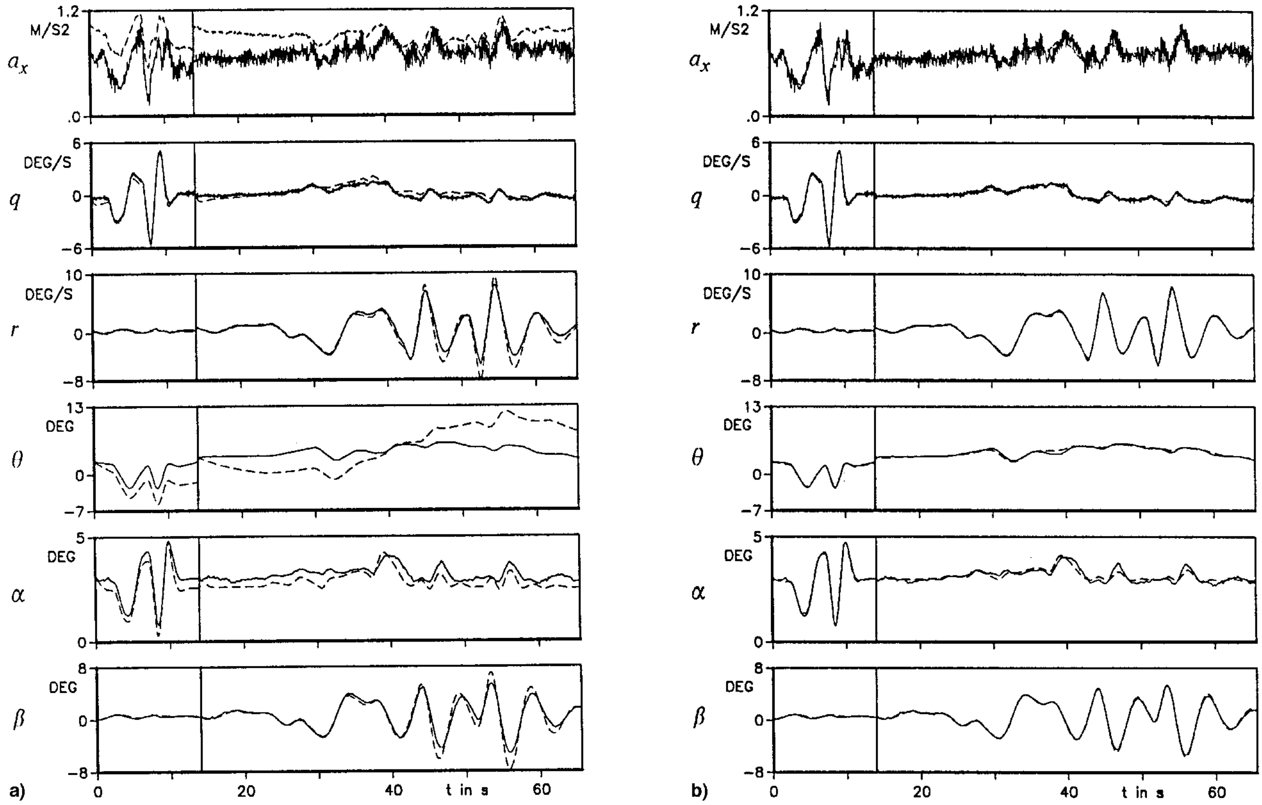

Fig. 8 Identification of aircraft motion with extended landing gear (——, flight measured; ----, estimated): a) neglecting and b) accounting for landing gear effects.

This yields the response match between the model prediction and flight measurements shown in Fig. 7a, where *CG* is the center of gravity position and the other variables have been previously defined. The match for all of the variables is far from being acceptable. In the second step, changes in the aircraft mass characteristics were accounted for according to Eqs. (2) and (3). This yields the response match shown in Fig. 7b. The agreement between the model prediction and flight measurements is found to be very good. The c.g., as seen from Fig. 7b, varies from 23% to about 45% just at the time of load dropping out and then falls suddenly to about 25%.

For level flights, the permissible limits for the forward and aft locations of the c.g. are 20 and 36%, respectively. It is interesting to point out here that during this load drop test the location of the c.g. just at the time of load falling out of the aircraft is about 45%. Such extreme c.g. locations, however, are only momentarily reached, for example, less than a second as seen from Fig. 7b.

Landing Gear Aerodynamic Effects

Once again, following the general approach adopted in the aforementioned cases, the modeling and identification of aerodynamic effects because of the landing gear is carried out stepwise. Proceeding from the basic aerodynamic model identified for the clean configuration, the flight maneuvers with extended landing gear are analyzed. The basic model yields the estimated responses for some typical motion variables shown in Fig. 8a. The discrepancies in a_x are demonstrative of additional drag being induced. Some minor deviations in q are also observed. In the case of the lateral–directional variables, the predicted β and r show some discernible differences compared to the flight measurements.

The basic aerodynamic model is augmented with additional parameters, namely, incremental changes in the lift, drag, and pitching moment coefficients, i.e., ΔC_{LLG}, ΔC_{DLG}, and ΔC_{mLG}, the subscript LG denoting the landing gear. Furthermore, the derivatives $C_{n\beta LG}$ and $C_{Y\beta LG}$ were introduced to model the influence on the lateral–directional motion. As expected, the identified value of ΔC_{DLG} suggests increased drag. The positive value of the derivative $C_{n\beta LG}$ indicates increased weathercock stability. The two derivatives $C_{Y\beta LG}$ and $C_{n\beta LG}$ are adequate to model the influence of the landing gear on the lateral–directional motion. Attempts to estimate increased yaw damping because of landing gear did not lead to any improvements in the response match, whereas a destabilizing effect of the landing gear on the pitching motion, as indicated by a positive value of the pitch damping derivative C_{mqLG}, is identified. Estimation of the aforementioned aerodynamic derivatives from the maneuvers with extended landing gear posed no difficulties, whereby the remaining parameters were fixed on their values from the basic aerodynamic model. The landing gear parameters were estimated with very low standard deviations. The resulting model responses shown in Fig. 8b match the flight measured data very well.

Concluding Remarks

The system identification methodology has been applied to model and identify from Transall flight data the incremental aerodynamic effects of secondary importance caused by speed brakes, ramp door, and landing gear. The flight-determined aerodynamic model is augmented with a suitable model for aircraft mass characteristics to cater for heavy load drops. By way of comparison, the effects of neglecting the incremental aerodynamic effects and variations in the mass characteristics on the model response compared to the flight measurements are brought out. Such effects play an important role in the pilot training of Transall specific operations on a simulator currently being built.

Acknowledgments

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