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X-31A System Identification Using Single-Surface Excitation at High Angles of Attack

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Parameter identification of the X-31A experimental aircraft was conducted throughout the envelope expansion using mainly pilot input maneuvers. The quality of the identification results, especially in the high-angle-of-attack regime, suffered from high correlations between the aircraft controls and states as well as from insufficient sideslip excitation. These problems are caused by the high feedback gains used in the flight control system to control the basically unstable airplane. Therefore, in 1994–1995 a dedicated flight test program using single surface excitation for parameter identification at high angles of attack was conducted. The results prove that identification of highly augmented aircraft benefits considerably from this technique. This article presents the realization of the single-surface excitation using the X-31A flutter test box. Also, the flight test program, the applied evaluation methods, and the identification models are discussed. Selected identification results from the single-surface excitation tests are presented and compared to those obtained from the pilot input maneuvers.

Nomenclature

b = reference span
C_D, C_L = coefficients of drag and lift
C_l, C_m, C_n = coefficients of roll, pitch, and yaw moment
C_X, C_Y, C_Z = coefficients of longitudinal, lateral, and vertical force
$\bar{c}$ = reference chord
F = engine gross thrust
p, q, r = roll, pitch, and yaw rates
$\bar{q}$ = dynamic pressure
S = reference area
V = true airspeed
x_{thac} = distance from thrust impact point to aerodynamic center
α = angle of attack
β = angle of sideslip
δ_a, δ_r = aileron (differential trailing-edge flap) and rudder deflections
δ_{can}, δ_e = canard and elevator (symmetric trailing-edge flap) deflections
σ, κ = thrust vector deflections in pitch and yaw

Superscript
$*$ = trim value

Introduction

THE X-31A poststall experimental aircraft was developed within the enhanced fighter maneuverability (EFM) program to demonstrate the tactical advantage of a fighter aircraft operating in the poststall region.[1,2] Two fighter-type X-31A aircraft were built by Rockwell International and Daimler–Benz Aerospace (Dasa, formerly MBB) under contract to the U.S. Advanced Research Projects Agency (ARPA) and the German Ministry of Defense (GMoD). Since their maiden flight in 1990, both X-31A experimental aircraft have flown more than 500 flights. The concept of enhanced fighter maneuverability in the poststall flight regime by utilizing thrust vectoring and the resulting tactical advantage have been demonstrated impressively.[3]

The X-31A (Fig. 1) is an aerodynamically unstable delta wing aircraft. The primary aerodynamic control surfaces for the longitudinal axis are symmetrical trailing-edge flaps and canard. Differential trailing-edge flaps provide roll control and a conventional rudder is used for directional control. The aircraft is powered by a single F404-GE-400 engine. A movable inlet provides adequate airflow to the engine at high angles of attack (AOA). In addition to the aerodynamic control surfaces, a three-paddle thrust vectoring (TV) system is mounted around the engine exhaust nozzle. The TV system allows thrust de-

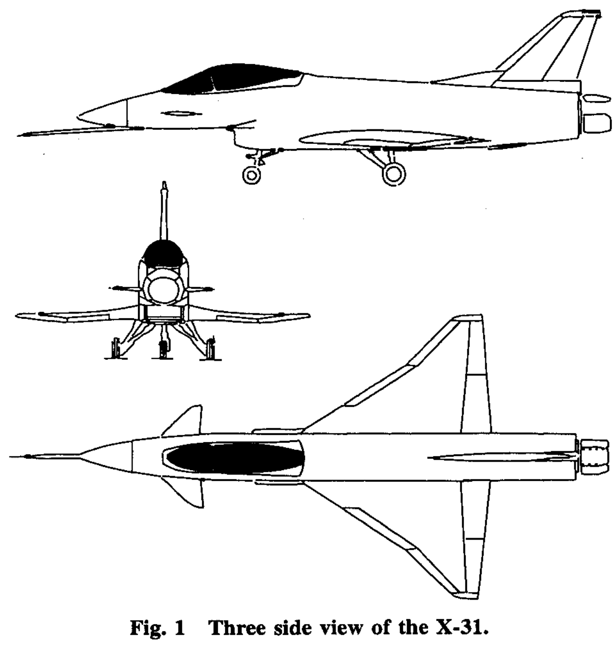

Fig. 1 Three side view of the X-31.

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flection up to 15 deg and is used to augment pitch and yaw control during low-speed and poststall flight.

The Institute of Flight Mechanics of DLR participates in the X-31A project as a member of the international flight test team. Besides contributions to the handling qualities analysis, its main task is the identification of aerodynamic parameters from flight test data. This system identification is necessary to validate and update the aerodynamic database of the X-31A from wind-tunnel measurements and supplemental calculations. If significant deviations of the aircraft aerodynamics from the database predictions are identified, they have to be incorporated into the simulation model. This might in turn also require modifications of the flight control system gains.

Background

In preparation of X-31A parameter identification (PID) from flight-test data, first a study was conducted applying PID to simulated data in the conventional and also in the poststall regime.[4] The objectives of this study were to investigate the applicability of PID methods, to define adequate model structures, and to specify suitable control inputs. The obtained results indicated two areas where problems could be expected during flight-test data evaluation: 1) the open-loop aircraft is aerodynamically unstable and is only flown in closed-loop configuration and 2) the integrated flight control system causes correlations between the aircraft states and controls.

The instability leads to divergence or even to an overflow in the integration of the state equations when the well-known maximum likelihood (ML) output error method is applied for parameter estimation. The problem can be overcome by using either estimation algorithms that stabilize the numerical integration (ML output error method with artificial stabilization and ML filter error method), or estimation algorithms that avoid numerical integration (regression algorithm and ML output error method in the frequency domain).[5-8]

The study also showed that separate inputs to the individual control surfaces, bypassing the flight control system, are required to reduce the correlations between the motion variables and to provide accurate estimates for the effectiveness of the individual control surfaces. DLR therefore suggested using the capabilities of the flutter test box (FTB) for parameter identification purposes to overcome these problems.[9]

In 1991, flight tests using the unmodified flutter test box for PID were conducted at 20- and 25-deg angle of attack. The results showed that all derivatives could be identified independently from these tests and that the uncertainty levels of the results were very small.[10] But no major deviations, either from the wind-tunnel data or from the values identified from pilot input maneuvers, were found for these flight conditions. Therefore, using the flutter test box for parameter identification purposes was stopped at that time.

Much more parameter identification was conducted mainly during envelope expansion into the poststall regime. Because of the lack of dedicated PID maneuvers, data from pilot generated maneuvers designed for handling qualities investigations had to be used for identification. As expected, several important parameters could not be identified independently from these maneuvers.[6-8] For example, canard effectiveness had to be kept at its prediction for parameter identification throughout the whole envelope.

A need was felt for demonstrating the possible improvement in parameter estimates from using single-surface excitation, especially at high angles of attack. This finally led to a series of dedicated PID test flights.

Single-Surface Excitation

Realization

One of the two X-31A aircraft can be equipped with a flutter test box that allows to separately excite all aerodynamic control surfaces. This excitation capability has been used to the advantage of parameter identification. DLR designed and built a signal generator card that fits into the existing flutter test box. Instead of sinusoidal excitation signals like, e.g., sweeps that are used for flutter tests, the DLR card generates PID signals like normal and improved doublets and 3211 multistep signals.[11] Rockwell manufactured a new amplifier card that allows larger excitation amplitudes necessary for parameter identification at high AOA. The surface deflection limits in the tests were 7.1 deg for the canard, 11.8 deg for the trailing-edge flaps, and 7.8 deg for the rudder.

Using the flutter test box is one very simple possibility to realize single-surface excitation. An alternative would be to use the flight control computers for input signal generation. Using the FTB has the advantage that troubleshooting is limited to a very small area and even changing the signals requires only reprogramming of the signal generator card. Disadvantages are that the flutter test box does not provide for excitation of the thrust vector vanes or for any more sophisticated input sequences involving several control surfaces. Also, additional monitoring and limiting functions are required to prevent aircraft damage from FTB malfunction, especially at higher dynamic pressures. For the X-31A, this monitoring is incorporated in the flight control system.

Test Points and Maneuvers

The tests with single-surface excitation were conducted as a proof of concept and not to identify a full aerodynamic model of the X-31A. Tests were therefore primarily conducted at high angles of attack where the data scatter and uncertainty levels of the PID results from pilot input maneuvers were largest.

In the initial two flights, test points from 25- to 50-deg AOA, in 5-deg increments, were flown. After the evaluation showed promising results, even for the higher angles of attack where the excitation amplitudes were relatively small, single-surface excitation maneuvers were conducted up to 70-deg AOA in a third flight. Rudder excitation tests were only performed up to 45-deg AOA at this time because the aerodynamic data set predicted zero rudder effectiveness above that angle of attack. To prove repeatability of the results, the lateral–directional points between 35- and 55-deg AOA were repeated in a fourth flight. With additional monitoring capabilities implemented in the flight control software, single-surface excitation tests at higher dynamic pressures (corresponding to 10-, 15-, and 20-deg AOA) were conducted in a fifth flight.

The amplitude settings for the direct control inputs from the FTB were selected so that for the longitudinal motion the variation in angle of attack was below 5 deg and the load factor variation was below 1 g. For the lateral–directional axis the limits were 3 deg in sideslip and 15 deg in roll angle. The length of the time intervals for the multistep signals were adjusted to excite the higher frequency eigenmotions of the aircraft. The frequencies had been determined from eigenvalue analysis of the linearized simulation model. The longitudinal inputs (canard and symmetric trailing-edge flaps) were preceded by pilot pitch doublets to ensure sufficient aircraft excitation at high angles of attack in spite of the limited FTB commands. The pilot inputs were also necessary to get a higher variation in thrust vector deflection as the TV_{vanes} cannot be excited by the flutter test box. For similar reasons, the lateral–directional inputs (rudder and differential trailing-edge flaps) were preceded by yaw/roll doublets.

To clearly bring out the advantage of single-surface excitation, the corresponding results are compared in this article to those derived from pilot input maneuvers. Two kinds of pilot generated maneuvers were used: 1) doublets at specific trim angles of attack and 2) randomly distributed pitch and yaw/roll doublets during level deceleration from 6- to 70-deg AOA and following acceleration back to 6-deg AOA. These maneuvers had been requested by NASA Langley for parameter identification purposes.

Evaluation

Models

The following aerodynamic model was used for the longitudinal motion:

$$C_D = C_{D0} + C_{D\alpha}(\alpha - \alpha^*) + C_{Dq}q(\bar{c}/2V) + C_{D\delta_e}\delta_e + C_{D\sigma}\sigma(F/\bar{q}S) \quad (1)$$

$$C_L = C_{L0} + C_{L\alpha}(\alpha - \alpha^*) + C_{Lq}q(\bar{c}/2V) + C_{L\delta_e}\delta_e + C_{L\sigma}\sigma(F/\bar{q}S) \quad (2)$$

$$C_m = C_{m0} + C_{m\alpha}(\alpha - \alpha^*) + C_{mq}q(\bar{c}/2V) + C_{m\delta_e}\delta_e + C_{m\delta_{\text{can}}}(\delta_{\text{can}} - \delta^*_{\text{can}}) + C_{m\sigma}\sigma(F/\bar{q}S) \quad (3)$$

The longitudinal thrust vector derivatives are related via,[12]

$$C_{D\sigma} = -C_{Z\sigma}\sin\alpha \quad (4)$$

$$C_{L\sigma} = -C_{Z\sigma}\cos\alpha \quad (5)$$

$$C_{m\sigma} = -C_{Z\sigma}x_{\text{thac}}/\bar{c} \quad (6)$$

with the pitching moment derivative $C_{m\sigma}$ being the parameter determined from identification.

For the lateral–directional motion the following aerodynamic model was used:

$$C_Y = C_{Y0} + C_{Y\beta}\beta + C_{Yp}p(b/2V) + C_{Yr}r(b/2V) + C_{Y\delta_a}\delta_a + C_{Y\delta_r}\delta_r + C_{Y\kappa}\kappa(F/\bar{q}S) \quad (7)$$

$$C_l = C_{l0} + C_{l\beta}\beta + C_{lp}p(b/2V) + C_{lr}r(b/2V) + C_{l\delta_a}\delta_a + C_{l\delta_r}\delta_r \quad (8)$$

$$C_n = C_{n0} + C_{n\beta}\beta + C_{np}p(b/2V) + C_{nr}r(b/2V) + C_{n\delta_a}\delta_a + C_{n\delta_r}\delta_r + C_{n\kappa}\kappa(F/\bar{q}S) \quad (9)$$

The two thrust vector derivatives are not independent but related through

$$C_{n\kappa} = C_{Y\kappa}x_{\text{thac}}/b \quad (10)$$

with the moment derivative $C_{n\kappa}$ being the parameter to be estimated.

Methods

Prior to the estimation of the aerodynamic derivatives, a flight-path reconstruction[6] was carried out to assure flight test data compatibility. The aerodynamic derivatives were then identified by matching the aerodynamic coefficients via regression. Although the coefficients are not directly measured they can easily be computed from other measurements, essentially from the linear and angular accelerations.

For the evaluation of the single-surface excitation maneuvers, the different inputs for each trim AOA were combined. Therefore, the 3211 inputs to the canard and symmetric trailing-edge flaps were evaluated together with the corresponding pitch doublets in one identification run for the longitudinal motion. Similarly, the 3211 inputs to rudder and asymmetric trailing-edge flaps were combined with the yaw/roll doublets for the lateral–directional axis. The corresponding results are labeled separate surface in the plots.

The pilot-generated doublets at specific trim AOA were evaluated separately for each angle of attack. For comparison purposes, the full aerodynamic model was identified from these doublet maneuvers, even though this sometimes yields physically meaningless values because of correlation problems. In the plots, these results are referred to as single maneuver.

The pilot doublet maneuvers during the level deceleration and accelerations were evaluated via data partitioning.[13] Data from all randomly distributed doublets of different flights are first put together. An option in the PID program code enables cutting out all data for a given angle-of-attack range, which are then evaluated together. For the current evaluation, the whole angle-of-attack range was partitioned into 5-deg intervals, the corresponding results are labeled data partitioning.

Results

Longitudinal Motion

When X-31A parameter identification is conducted using data from pilot-generated maneuvers, control surface deflections and aircraft states are always correlated because of the flight control laws. In the longitudinal motion correlations between canard deflection and angle of attack, as well as between symmetric trailing-edge flap deflection and vertical thrust deflection, are generated. This is illustrated by the time histories from a pitch doublet shown in the left part of Fig. 2.

These correlations are eliminated by single-surface excitation. A 3211-sequence commanded directly to the canard

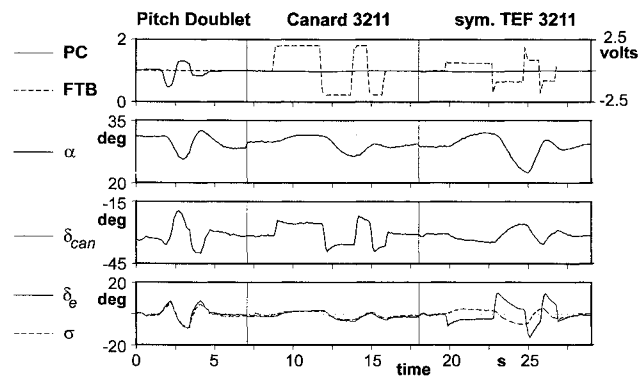

Fig. 2 Time histories of longitudinal PID maneuvers.

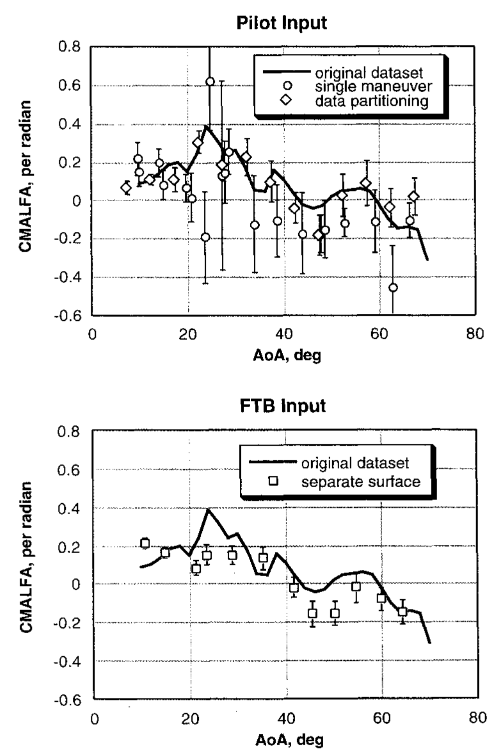

Fig. 3 PID results: longitudinal stability.

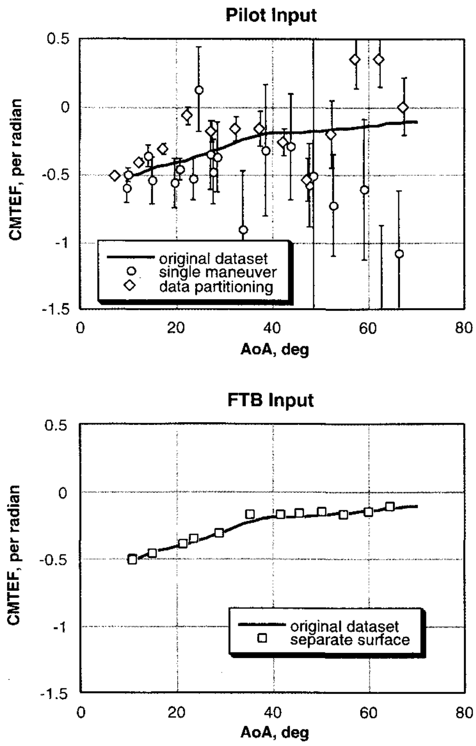

Fig. 4 PID results: symmetric trailing-edge flap effectiveness.

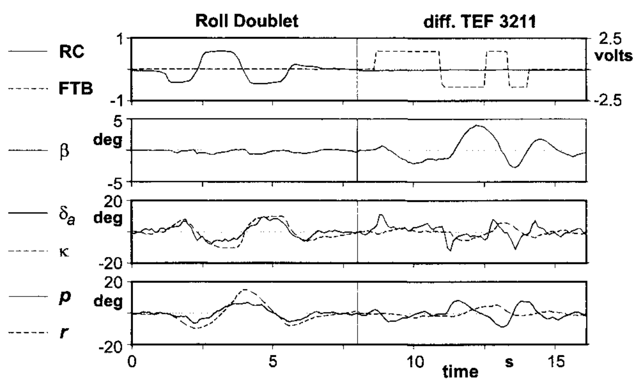

Fig. 5 Time histories of lateral-directional PID maneuvers.

avoids the correlation of this signal with angle of attack. Similarly, separate excitation of the symmetric trailing-edge flaps eliminates the correlation between trailing-edge flap and thrust vector deflection, as can also be seen in the time histories of Fig. 2.

Longitudinal Stability

The parameter identification results for the longitudinal stability (Fig. 3) from single-surface excitation and data partitioning are close to the predictions and have small uncertainty levels (five times standard deviation in all plots). In contrast, the single maneuver evaluation results show large scatter and error bounds, caused by correlation of this parameter with canard effectiveness and the other pitching moment derivatives including thrust vector effectiveness.

Trailing-Edge Flap Effectiveness

The PID results from single maneuver evaluation for the poststall regime (above 30-deg AOA) show large scatter and error bounds (Fig. 4) caused by correlation mainly with thrust vector effectiveness. Data partitioning yields smaller error bounds than single maneuver evaluation, but some unrealistic (positive) identified values indicate that the results still suffer from the same correlation problems. Only fixing thrust vector effectiveness at its predicted value would enable the identification of the trailing-edge flap effectiveness from pilot input maneuvers in the poststall regime. In contrast, the trailing-edge flap effectiveness could be identified with little scatter and very small error bounds from the single-surface excitation tests, yielding values close to the predictions.

Lateral–Directional Motion

For the lateral–directional motion, roll stick deflection commands roll around the velocity vector so that roll and yaw rate

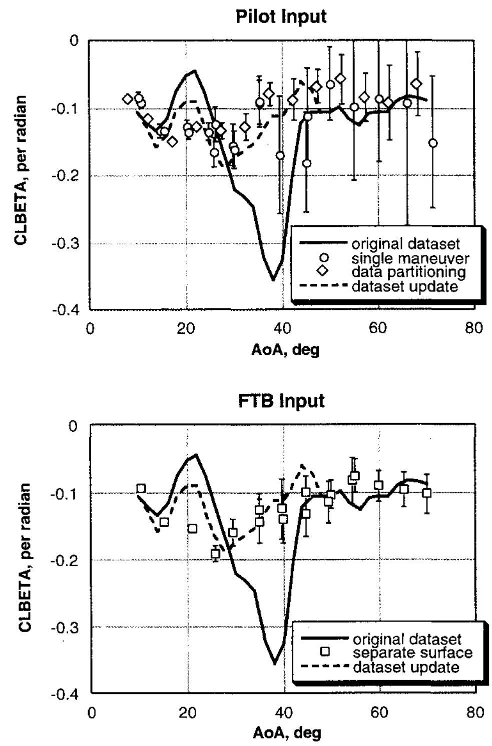

Fig. 6 PID results: dihedral coefficient.

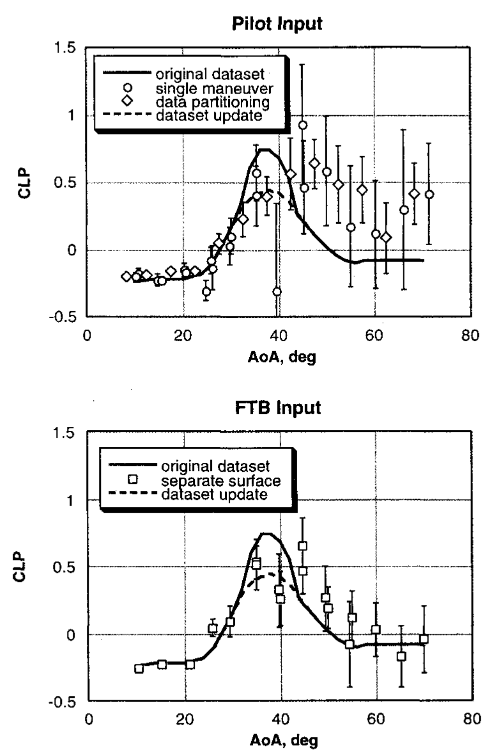

Fig. 7 PID results: roll damping.

Table 1 Identifiability of aerodynamic parameters

Parameter	SM	DP	SS
C_{D0}	+	+	+
$C_{D\alpha}$	+	+	+
C_{Dq}	Fixed	+	+
$C_{D\delta_e}$	−	−	+
C_{L0}	+	+	+
$C_{L\alpha}$	+	+	+
C_{Lq}	Fixed	+	−
$C_{L\delta_e}$	+	−	+
C_{m0}	+	+	+
$C_{m\alpha}$	+	+	+
C_{mq}	−	−	+
$C_{m\delta_e}$	+	−	+
$C_{m\delta_{can}}$	Fixed	−	+
$C_{m\sigma}$	Fixed	−	+
C_{Y0}	+	+	+
$C_{Y\beta}$	−	−	−
C_{Yp}	−	−	−
C_{Yr}	Fixed	−	−
$C_{Y\delta_a}$	−	+	+
$C_{Y\delta_r}$	−	+	+
C_{l0}	+	+	+
$C_{l\beta}$	+	+	+
C_{lp}	−	−	+
C_{lr}	Fixed	+	+
$C_{l\delta_a}$	+	+	+
$C_{l\delta_r}$	−	+	+
C_{n0}	+	+	+
$C_{n\beta}$	−	−	+
C_{np}	Fixed	−	+
C_{nr}	−	+	+
$C_{n\delta_a}$	+	+	+
$C_{n\delta_r}$	+	+	+
$C_{n\kappa}$	Fixed	+	+

Note: SM, single maneuver; DP, data partitioning; SS, separate surface; +, high-quality; and −, low-quality estimates.

are always correlated. Strong correlations are also present between differential trailing-edge flap deflection and yaw axis thrust vectoring (see left part of Fig. 5). In addition, the flight control system keeps sideslip close to zero. This makes the identification of sideslip derivatives difficult, if not impossible.

As can be seen from the time histories in the right part of Fig. 5, direct excitation of the differential trailing-edge flaps eliminates the previously mentioned correlations and also creates much larger sideslip angles.

Dihedral Coefficient

The upper part of Fig. 6 illustrates that identification results from pilot input maneuvers suffer from correlations and insufficient sideslip excitation. The identified values of the dihedral coefficient show large scatter and uncertainty levels. In contrast, PID results from single-surface excitation obviously show a clear trend and have much smaller error bounds. The error bounds at very high angles of attack are smallest for the flutter test box inputs because these maneuvers create the largest variation in sideslip angle.

When the aerodynamic database for the X-31A was updated for AOA up to 50 deg in 1993, only PID results from pilot input maneuvers were available. Despite their poor quality, these results did not confirm the large negative $C_{l\beta}$ values for AOA between 30–45 deg predicted by wind-tunnel tests, and the database for the dihedral coefficient was changed as shown.

Roll Damping

The identified roll damping (Fig. 7) from single maneuver evaluation allows no reasonable comparison to the predictions because of large scatter and error bounds. Only fixing C_{lr} (rolling moment because of yaw rate) would yield reasonable roll damping results from these maneuvers. From single-surface excitation experiments it is possible to identify the two derivatives, C_{lp} and C_{lr}, independently. However, the uncertainty levels are still relatively large. This can be observed for all damping parameters and is probably caused by the artificial damping of the unstable aircraft by the flight control system. The roll damping identified from flutter test box input tests shows a strong variation in the 35- to 55-deg AOA region, which was confirmed by test point repetition. Above 50-deg AOA, the results from data partitioning indicate positive (undamped) C_{lp}, unlike the single-surface excitation results.

Table 1 gives an overview of the identifiability of all aerodynamic parameters extracted from different maneuvers for the longitudinal and lateral–directional motion, respectively. The + denotes high-quality estimates (low scatter and small uncertainty levels), and the − denotes low-quality estimates. In the case of pilot-induced maneuvers, reasonable estimates can be obtained only when some parameters are fixed on their predictions. The lateral–directional derivatives with respect to rudder deflection were estimated only up to 40-deg AOA.

Conclusions

Parameter identification of the X-31A was carried out using pilot input and single-surface excitation maneuvers. The results indicate the following:

1) Single maneuver evaluation is unusable, especially at high angles of attack. The high correlation of the input and state variables lead to correlations in the corresponding derivatives.

2) Data partitioning overcomes most of the problems of single-maneuver evaluation by combining a large amount of information from many single maneuvers. This reduces the correlation problems somewhat and improves the estimates of all derivatives, especially the stability and damping derivatives.

3) Single-surface excitation gives by far the best estimates for the control surface effectiveness parameters because of direct uncorrelated excitation of the corresponding control surfaces. The reduced correlations of the motion variables also improve the estimates of all other derivatives. For the lateral–directional motion, all sideslip derivatives benefit from the higher variation in sideslip at high angles of attack.

In conclusion, a combination of data partitioning and separate surface excitation would be the best solution. This would require tests with single-surface inputs (which would have to be scaled with dynamic pressure), applied continuously during variation of angle of attack.

Acknowledgments

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References

[1]Dornheim, M. A., "X-31 Flight Tests to Explore Combat Agility to 70 Deg. AoA," *Aviation Week & Space Technology*, March 11, 1991, pp. 38–41.

[2]Ross, H., *X-31 Enhancement of Aerodynamics for Maneuvering Beyond Stall*, CP-497, AGARD, 1991 (Paper 2).

[3]Eubanks, E., Gütter, R., and Lee, B., "X-31 CIC Flight Test Results," *Workshop on Full Envelope Agility*, 4-PWR SM TG, Eglin AFB, March 1995, pp. 31–47.

[4]Plaetschke, E., Rohlf, D., and Saliaris, C., "X-31A Aerodynamic Model Identification from Simulated Data—Part 1: Conventional Flight Test Point C5, Part 2: Post Stall Flight Test Point P2," DLR-IB 111-90/11 and DLR-IB 111-90/19, 1990.

[5]Kaletka, J., and Fu, K.-H., "Frequency-Domain Identification of Unstable Systems Using X-31A Aircraft Flight Test Data," AIAA Paper 93-3635, Aug. 1993.

[6]Rohlf, D., Plaetschke, E., and Weiss, S., *X-31A System Identification Applied to Post-Stall Flight—Aerodynamics & Thrust Vector-*

ing, CP-548, AGARD, 1994 (Paper 14).
[7]Weiss, S., Rohlf, D., and Plaetschke, E., "Parameter Identification for X-31A at High Angles of Attack," *Fourth High Alpha Conference*, Vol. 1, Paper 7, NASA-CP-10143, NASA Dryden Flight Research Center, July 1994.
[8]Plaetschke, E., Weiss, S., and Rohlf, D., "Identification at High Angles of Attack Applied to X-31A Flight Test Data," *DLR-Mitt. 93-14*, 1993, pp. 181–198.
[9]Rohlf, D., "X-31A System Identification—Implementation of Computer Generated Input Signals," DFVLR-IB 111-88/45, Nov. 1988.
[10]Plaetschke, E., and Weiss, S., "Identification of Aerodynamic Parameters from Pilot and FTB Inputs for AoA up to 30 Deg," DLR-IB 111-91/40, June 1991.
[11]Koehler, W., and Wilhelm, K., "Auslegung von Eingangssignalen für die Kennwertermittlung," DFVLR-IB 154-77/40, Dec. 1977.
[12]Plaetschke, E., and Weiss, S., "Identification of Thrust Vector Effectiveness from X-31A Flight Test Data," *Zeitschrift für Flugwissenschaft und Weltraumforschung*, Vol. 17, Aug. 1993, pp. 235–238.
[13]Klein, V., "Estimation of Aircraft Aerodynamic Parameters from Flight Data," *Progress in Aerospace Science*, Vol. 26, 1989, pp. 1–77.