Uses of Parameter Estimation in Flight Test

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An overview of the experience gained at the NASA Dryden Flight Research Facility in aircraft parameter estimation is presented and the ways in which this experience is used in flight test are explained. Some of the reasons for the current importance of parameter estimation in most modern aircraft test programs are discussed, and three examples from projects underway at Dryden are used to illustrate how parameter estimation of stability derivatives can be integrated into a flight-test program.

Nomenclature

a_Y = lateral acceleration, g
C_ℓ = coefficient of rolling moment
C_m = coefficient of pitching moment
C_n = coefficient of yawing moment
$C_{n_{\beta_{dyn}}}$ = directional dynamic stability
C_Y = coefficient of side force
g = acceleration due to gravity, ft/s^2
L_{YJ} = rolling moment due to yaw jet, ft-lb/jet
M = Mach number
p = roll rate, deg/s
q = pitch rate, deg/s
$\bar{q}$ = dynamic pressure, psf
r = yaw rate, deg/s
Re = Reynolds number
t = time, s
V = velocity, ft/s
α = angle of attack, deg
β = angle of sideslip, deg
δ_a = aileron deflection, deg
δ_{DE} = differential elevon deflection, deg
δ_r = rudder deflection, deg
δ_{sp} = differential spoiler deflection, deg
ϕ = bank angle, deg

Subscripts

$p,r,\alpha,\beta,$
$\delta_a,\delta_{DE},$
δ_r, δ_{sp} = derivatives with respect to indicated quantity

Introduction

In the past, the primary reason for estimating stability and control derivatives from flight tests was in order to make comparisons with wind-tunnel estimates. As aircraft became more complex and as flight envelopes were expanded to include flight regimes that were not well understood, new requirements for the derivative estimates evolved. For many years, the flight-determined derivatives were used in simulations to aid in flight planning and in pilot training. The simulations were particularly important in research flight-test programs in which an envelope expansion into new flight regimes was required.

Parameter estimation techniques for estimating stability and control derivatives from flight data became more sophisticated to support the flight-test programs. As more was learned about these new flight regimes, more complex aircraft were flown. Much of this increased complexity was in sophisticated flight-control systems. The design and refinement of the control system required higher fidelity simulations than were required previously.

As a consequence of this requirement, a more complete knowledge of the flight-determined stability and control derivatives was necessary. Almost all of today's high-performance aircraft have very complex control systems to make up for their deficiencies in basic aerodynamic characteristics. Consequently, most flight-test programs for these aircraft require a complete flight-determined set of stability and control derivatives. The determination of the derivatives requires the use of parameter estimation techniques.

The Dryden Flight Research Facility has developed a maximum likelihood parameter estimation program called MMLE3 (Ref. 1), which was used for all of the analysis in this paper. MMLE3 analyzes small perturbations about steady-state conditions; other procedures need to be developed and applied where small perturbation assumptions do not hold. This paper presents an overview of Dryden Flight Research Facility's experience in aircraft parameter estimation and a discussion of how this experience is used in flight test.

Examples of Parameter Estimation in Flight Test

The Ames/Dryden Flight Research Facility has been involved in the estimation of stability and control derivatives with the maximum likelihood estimator since 1966. Since that time Dryden analysts have successfully applied maximum likelihood estimators to over 40 different aircraft configurations. Some of the experience gained through these applications is documented in Refs. 2 and 3. More recent applications have concentrated on estimating stability and control derivatives to assist in designing or refining control systems.

Three of the most recent applications are the F-14, highly maneuverable aircraft technology (HiMAT), and the Space Shuttle. The application to these programs is discussed in detail below. All three of these programs have made and still make extensive use of high-fidelity, pilot-in-the-loop simulations which are initialized using the best wind tunnel data available. The flight-test program is designed to enable data to be obtained for refining the simulator model; however, it should be noted that proved parameter estimation techniques work only when aircraft can be flown about some steady-state condition.

The definition of how the simulator model is enhanced depends on the aircraft involved in the flight-test program. The F-14 flew several flights specifically to define the stability and control derivatives over a large range of angles of attack because the control refinement was addressing the high-angle-of-attack regime. The HiMAT flew several flights with a

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positive static margin so that derivatives could be obtained to design a control system for flight at a negative static margin. The Space Shuttle entered from space on the most conservative trajectory to allow assessment of those characteristics before an envelope expansion was begun. Once the flight data are obtained and analyzed, the simulator is updated to assist in the control-system design and further flight planning. Even when flight results agree with wind tunnel predictions, they assist in expanding the flight envelope because the results increase the confidence in the simulation.

The next three sections discuss in detail the procedure mentioned above. All of the stability and control estimates presented in these sections were obtained using the maximum likelihood estimator program MMLE3 (Ref. 1).

F-14

The F-14 is a twin-engine, high-performance fighter that has a variable wing-sweep capability. The F-14 program addressed improving the handling qualities of the airplane at high angles of attack by incorporating a number of control-system techniques. The program and some of the results are described in detail in Refs. 4 and 5. The first part of the program was dedicated to obtaining flight-determined stability and control derivatives. The flight conditions covered the subsonic envelope of the F-14—the complete trimmed angle-of-attack range for Mach numbers of 0.9 and below.

In many instances the flight data agreed with the wind tunnel predictions. Figure 1 (from Ref. 4) shows the comparison of C_{n_β} vs α from flight and wind tunnel estimates. The symbols designate the estimate and the vertical bar the uncertainty level (Cramér-Rao bound). The agreement is good although some disagreement can be seen above an angle of attack of 25°; nevertheless, the same trends are seen for both the flight and wind tunnel data.

Figure 2 (from Ref. 4) shows the flight-determined C_{ℓ_p} vs α for low Mach number (<0.55) and for a Mach number of 0.9. There was some uncertainty in the accuracy of the wind tunnel predictions of C_{ℓ_p} because the tunnel model configuration was different from the flight configuration. These flight data agreed with the trends found in the tunnel and, with the proper interpretation, even the magnitudes were in fair agreement. Figure 3 (from Ref. 4) shows the flight-determined values of C_{ℓ_β} vs α compared with the results of two different sets of wind tunnel results. There was some concern about the disagreement of the two sets of wind tunnel results before flight. At angles of attack above 15 deg the flight data lie in between the sets of tunnel data.

A last example from the F-14 shows how the wind tunnel and flight estimates fit together in improving a simulation. After the lateral-directional derivatives were put in the simulation, it was noted that the resulting simulated lateral-directional motions from a longitudinal-stick snap maneuver were inconsistent with the flight response. Since the F-14 program was primarily a lateral-directional investigation, the longitudinal derivatives in the simulation had not been updated with the flight-determined values. When the flight-determined longitudinal derivatives were included in the simulation, the stick snap response agreed more closely with that in flight. Investigation of the inconsistency uncovered a large discrepancy between the wind tunnel and flight-determined values of C_{m_α}. This can be seen in Fig. 4, where flight-determined C_{m_α} is compared with the wind tunnel estimates of C_{m_α} for the untrimmed condition at constant elevon position and for the slope at the trimmed condition. Further investigation showed that the untrimmed values of C_{m_α} at a constant elevon position had been put in the simulation and that the predicted trimmed value of C_{m_α} was in excellent agreement with flight estimates.

These examples of C_{ℓ_p}, C_{ℓ_β}, and C_{m_α} show how flight data, in addition to providing a primary source of estimates, can be used to help interpret wind tunnel data; with this same interpretation, these data can then be used to improve the simulation at points away from steady-state flight data. Sometimes wind tunnel data are available but have been discounted or overlooked, and flight data can give new credence to these wind tunnel data.

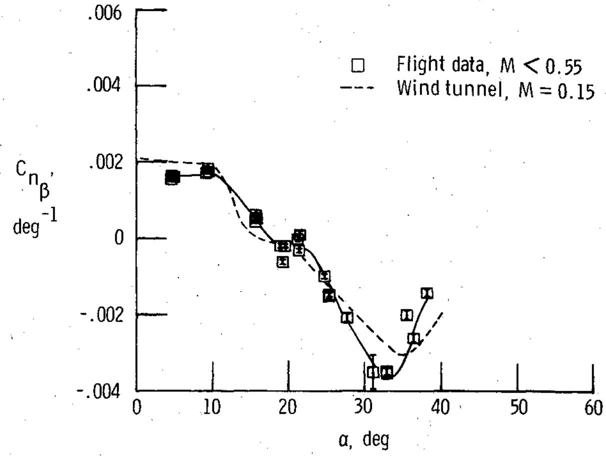

Fig. 1 Comparison of flight-derived estimates of static directional stability with wind tunnel data.

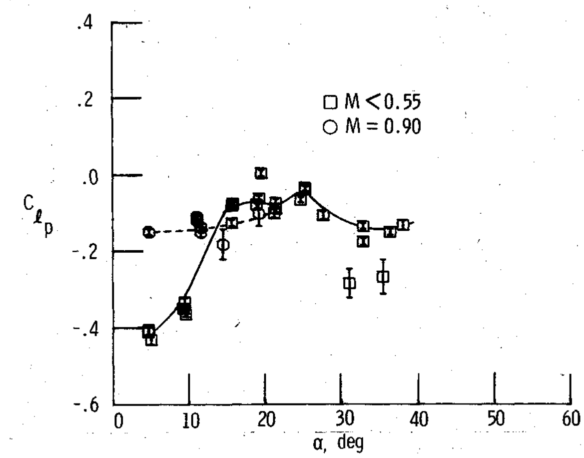

Fig. 2 Summary of flight-derived estimates of roll damping for $M<0.55$ and $M=0.9$.

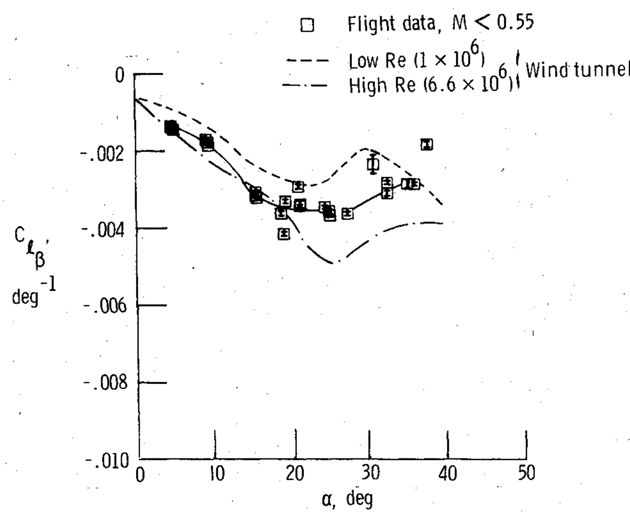

Fig. 3 Comparison of flight-derived estimates of dihedral effect with two sets of wind tunnel data.

The F-14 flight data shown here improved the simulation over a large part of the envelope. Since the F-14 high-angle-of-attack program also required examination of responses of

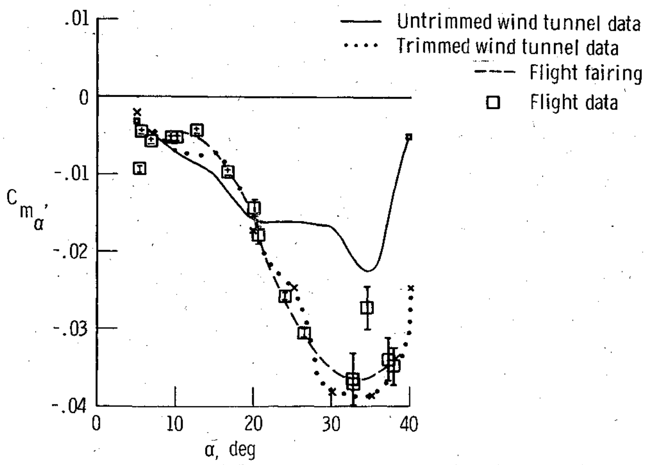

Fig. 4 Comparison of flight and wind tunnel estimates for C_{m_α}.

a much more transient nature, more tedious and time-consuming fine tuning of the simulation was required for flight at other than near the trimmed conditions. Some of this work is described in Ref. 6. With the resulting simulation, the proposed control-system techniques being investigated were further refined; the result was a more efficient demonstration in flight.

The preceding is an example of the value of flight-test parameter estimation in improving the handling qualities of an aircraft through the use of control-system improvements.

HiMAT

The highly maneuverable aircraft technology (HiMAT) vehicle is a remotely piloted research vehicle with advanced close-coupled canards, wing-type winglets, and provisions for variable leading-edge camber. It is made of advanced composite materials to allow for aeroelastic tailoring and minimum weight. It is to be flown with a relaxed static margin because the wing deformation then results in a desirable camber shape at high load factor and because the trim drag is reduced.

The HiMAT vehicle is described in Refs. 7 and 8. The vehicle was designed to fly with a sustained 8-*g* turn capability at a Mach number of 0.9 at 25,000 ft and to demonstrate flight supersonically to a Mach number of 1.4. In order to attain the Mach 0.9 condition, it is predicted that the vehicle needs to be flown at a 10% mean aerodynamic chord (MAC) negative static margin (unstable). The philosophy for testing HiMAT is somewhat different from that for production aircraft. Flight-determined stability and control derivatives were to be relied on in order to keep the wind tunnel program to a minimum. The original simulation data base contained the wind tunnel data supplemented with some computed characteristics.

The flight-test philosophy was to fly the vehicle in a stable condition to obtain stability and control derivatives with the control feedbacks set to zero. While these data were being gathered, a control system suitable for unstable flight was being designed based on wind tunnel tests. Then, with the flight-determined derivatives, the simulator could be updated and the control system adjusted for this update so that the vehicle could be flown safely at a negative static margin. Stability and control maneuvers were performed at Mach numbers from 0.4 to 0.92, angles of attack up to 10 deg, and altitudes from 15,000 to 45,000 ft. A complete set of stability and control characteristics was obtained for both the longitudinal and lateral-directional degrees of freedom. Reference 9 contains a summary of the stability and control analysis results. Some of the figures for lateral-directional derivatives from Ref. 9 are used in the following discussion. Because the values of the HiMAT derivatives are classified, the data are plotted on unlabeled vertical axes; nevertheless,

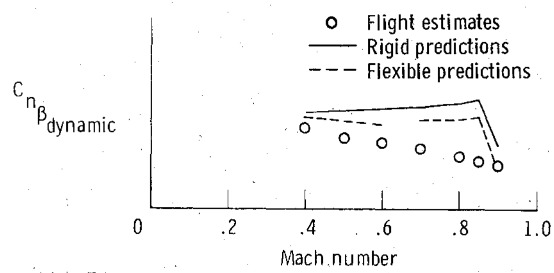

Fig. 5 Comparison of flight and predicted estimates for directional dynamic stability at $\alpha = 4$ deg as a function of Mach number.

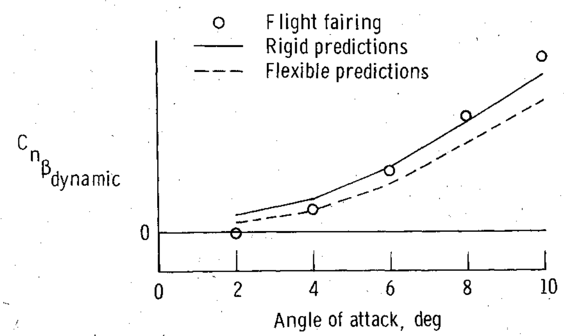

Fig. 6 Comparison of flight and predicted estimates for directional dynamic stability as a function of angle of attack at a Mach number of 0.9.

an assessment of predicted and flight-determined derivatives still can be made. All of the derivatives, predicted and flight-determined, are corrected to 0% MAC. For the flight conditions flown to date, there were no aeroelastic effects noted in the flight data.

Figure 5 shows flight-determined directional dynamic stability, $C_{n_{\beta_{dyn}}}$, vs Mach number at $\alpha = 4$ deg compared with the rigid and flexible predictions. Flight estimates are about the same as the predictions at Mach numbers of 0.4 and 0.9, but differ significantly in between. In Fig. 6, $C_{n_{\beta_{dyn}}}$ is plotted vs α at $M = 0.9$. This figure shows that the vehicle is slightly unstable in the lateral-directional axes at the lower angles of attack. Because these data are plotted for 0% MAC, this instability will be considerably greater and over a wider angle-of-attack range if the center of gravity is moved aft by 10% MAC. The derivatives C_{Y_β} and C_{ℓ_p} agreed with predictions; however, C_{n_r} was twice the predicted value, C_{n_p} was the opposite sign, and C_{ℓ_r} was a small fraction of the predictions. The rolling moments due to aileron, $C_{\ell_{\delta_{DE}}}$, agreed fairly well with the rigid predictions; $C_{n_{\delta_r}}$ was 25% less than predicted; and both $C_{n_{\delta_a}}$ and $C_{n_{\delta_{DE}}}$ showed a positive increment over prediction. The derivative $C_{l_{\delta_r}}$ was about twice that predicted. Since there were so many large differences between flight-determined and the minimal wind tunnel set, it was decided to completely re-evaluate the lateral-directional control laws designed for the unstable configuration, using the flight data instead of the wind tunnel data used in the original design. Some of the reasons for this can be seen in Fig. 7 in which the control derivatives $C_{n_{\delta_{DE}}}$ and $C_{n_{\delta_r}}$ are plotted against angle of attack at a Mach number of 0.9. These differences between flight and prediction meant the simulator had to be extensively revised.

The HiMAT vehicle program is a technology demonstration program and is, therefore, only required to demonstrate the technology at specific design points. A technology demonstration is quite different from many programs, such as that of the F-14 just discussed, because only certain steady-state requirements have to be demonstrated. Therefore all of the points that needed to be flown were near steady-state points for which flight-determined derivatives already existed. The approach taken to update the

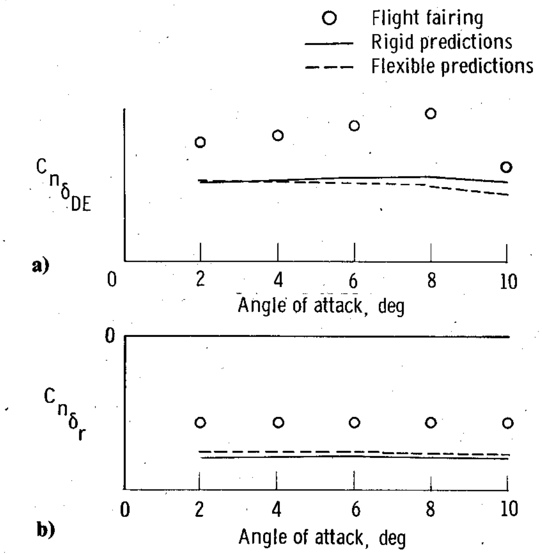

Fig. 7 Comparison of $C_{n\delta_{DE}}$ and $C_{n\delta_r}$ as a function of angle of attack at a Mach number of 0.9. a) Differential elevon yawing moment coefficient. b) Rudder yawing moment coefficient.

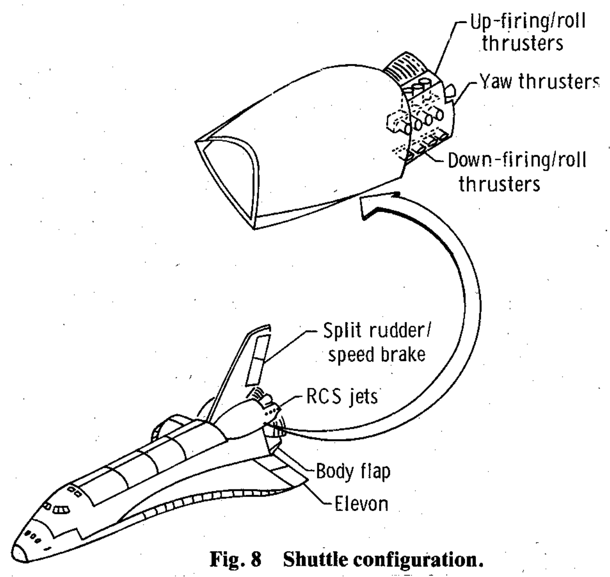

Fig. 8 Shuttle configuration.

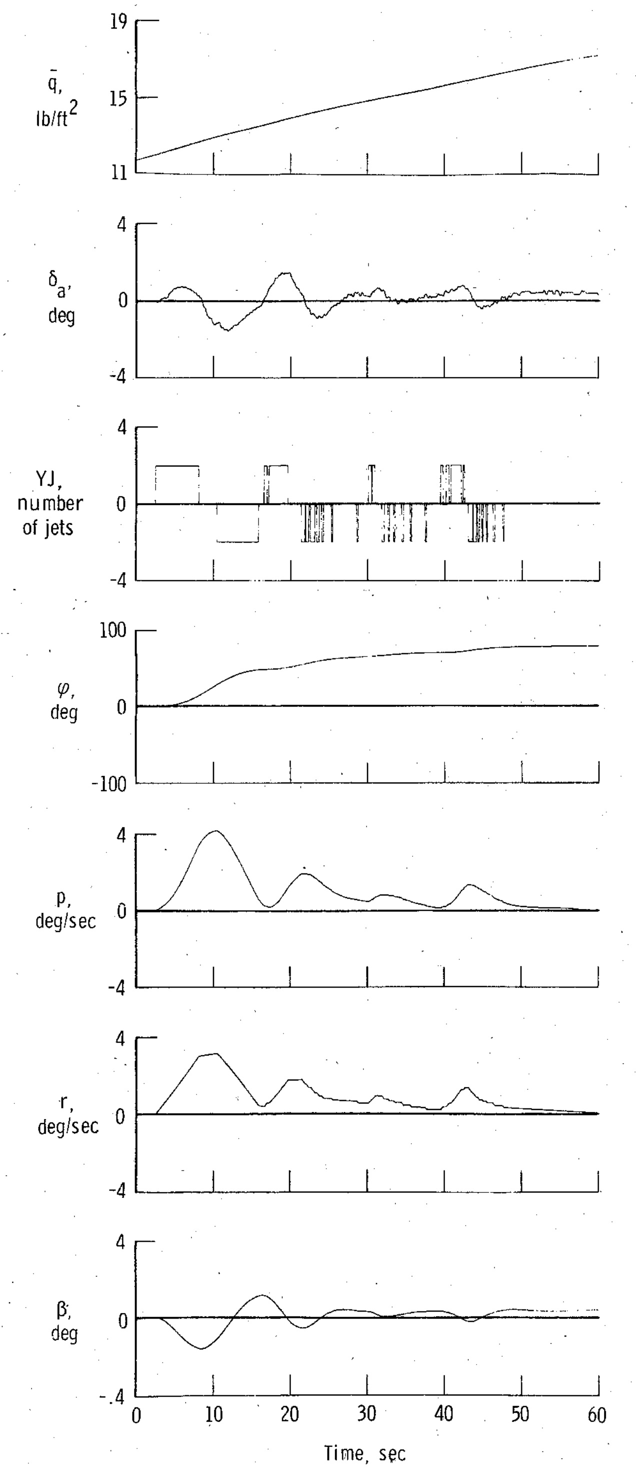

Fig. 9 Predicted bank maneuver at a Mach number of 24 for STS-1.

simulator was to disregard all of the predicted data and to use only the slope data from flight test. The knowledge that the aircraft exhibited no significant aeroelastic effects permitted the re-evaluation of the unstable control-system design to be simplified from the original design effort.

The control laws designed for the unstable configuration were more complex than the rate-feedback system used for gathering stability and control derivatives. The new control laws included 1) adding an a_Y feedback to improve the closed-loop directional dynamic stability, 2) adding an interconnect between the lateral stick and rudder to improve the lateral control characteristics, 3) changing the various feedback gains to improve the damping characteristics, and 4) locking the aileron surface to eliminate the adverse yaw and the possibility of a predicted surface-buzz problem at the higher Mach numbers. This design of the lateral-directional control system was the result of an extensive study of possible control systems using both the simulator and linear analysis techniques. When the new control system was designed, it was implemented on the HiMAT and was flown again with a positive static margin. Control-surface doublets were made on this flight and the responses compared with the simulator-derived responses. The comparison was excellent, giving confidence that the vehicle could be tested with the center of gravity aft of the neutral point.

The benefits of flying the vehicle with a relaxed static stability were proved in flight when a 0.4-g improvement in sustained-g capability was realized by changing the center of gravity location from the neutral point to 5% MAC aft of the neutral point. When the vehicle was flown with a 5% MAC negative static margin, a sustained turn of about 7.8/g was achieved. Based on these numbers, the HiMAT vehicle should be able to demonstrate a sustained 8.0-g turn capability with the 10% MAC negative static margin.

In the case of the HiMAT vehicle, the flight-test parameter estimation became the sole method of defining the stability and control derivatives. A control-system design for the

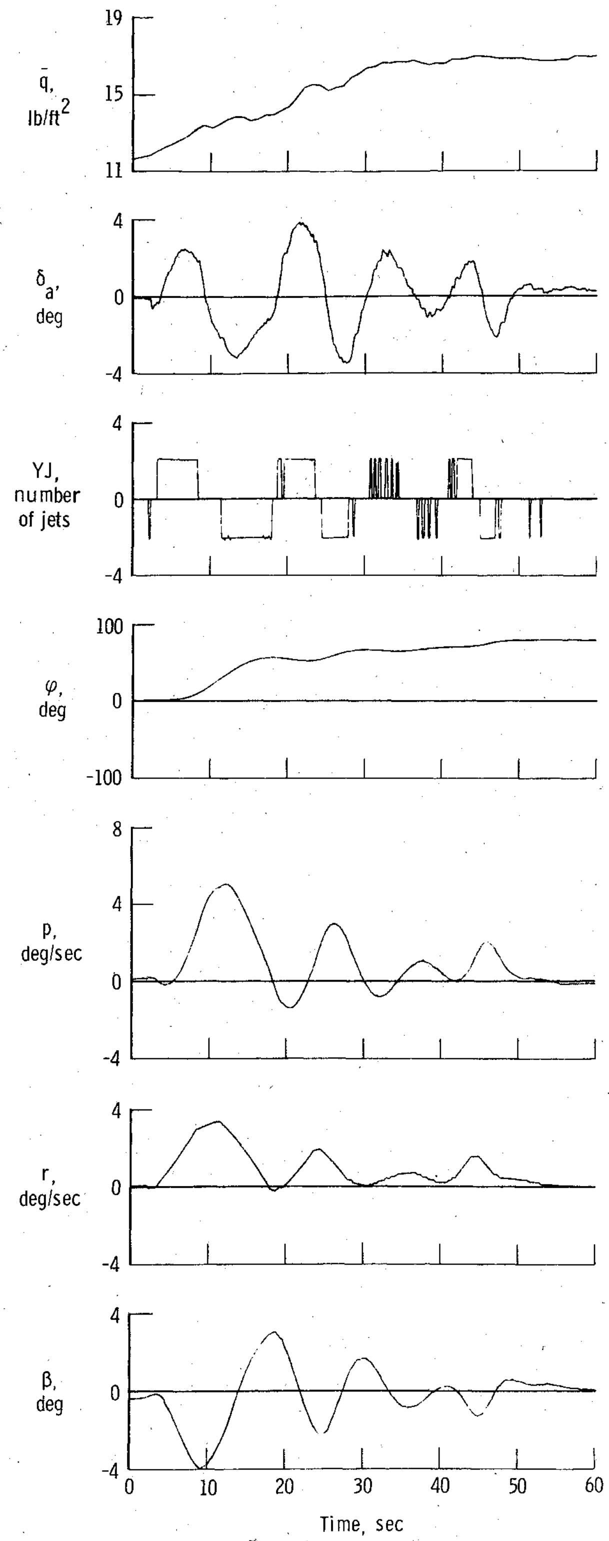

Fig. 10 Actual bank maneuver at a Mach number of 24 on STS-1.

unstable configuration was defined before flight-test results were available. The adequacy of the design was demonstrated on the simulation updated with flight data. The resulting control system enabled the vehicle to be flown with a 5% MAC negative static margin and shows promise of permitting flight with a 10% MAC negative static margin to attain the design point.

Space Shuttle

The Space Shuttle is a large double-delta-winged vehicle designed to enter the atmosphere and land horizontally. The entry control system consists of 12 vertical reaction control system (RCS) jets (six up-firing and six down-firing) and 8 horizontal RCS jets (four left-firing and four right-firing), 4 elevon surfaces, a body flap, and a split rudder surface. The locations of these devices are shown in Fig. 8. The vertical jets and the elevons are used for both pitch and roll control. The jets and elevons are used symmetrically for pitch control and asymmetrically for roll control.

The two preceding examples showed how parameter estimation can be used in an incremental flight-test program; i.e., a progressive expansion of the flight envelope to obtain data in the more certain areas first and later in the more challenging or hazardous areas. However, the Space Shuttle program could not be approached in this manner because the vehicle had to demonstrate safely most of its flight envelope on the first flight, which included very hazardous flight regimes. The subsonic flight and landing characteristics had been demonstrated in the eariler approach and landing tests (ALT) program, but the hypersonic, peak heating, and transonic regions were largely unexplored for a vehicle of this type. Probably the only approach available for a Shuttle-type vehicle is that described below.

First, extensive wind tunnel tests were performed and then those data were incorporated into high-fidelity simulations. As previously stated, no matter how carefully wind tunnel tests are performed there are usually some discrepancies between the predictions and demonstrated flight characteristics. Therefore, uncertainties were defined for each stability and control derivative; these uncertainties, called "variations" in Ref. 11, to a large extent were based on previous discrepancies between predictions and flight.[12]

In preparation for the first flight, the control-system engineers developed a control system that was to provide satisfactory closed-loop vehicle characteristics for deviations from predictions that fell between the variations that had been defined. After flight data had been obtained, the flight estimates of the stability and control derivatives would be used to reduce the preflight variations. This reduction then would allow the control engineers to refine the control system and, therefore, improve the Shuttle's handling qualities. In addition, the flight-determined derivatives would be used to determine if configuration placards (limitations on the flight envelope) could be modified or removed.

Some of the stability and control results obtained from the first three flights are contained in Refs. 13 and 14. One of the interesting examples of where parameter estimation played an important role in the Shuttle program occurred during the first energy management bank maneuver on the first entry of the Shuttle (STS-1). The computed response to the automated control inputs with the predicted stability and control derivatives is shown in Fig. 9. It should be noted that the control inputs shown here (and for all other simulation comparisons) are the closed-loop commands from the Shuttle control laws. The maneuver was to be made at a velocity of 24,300 ft/s and at a dynamic pressure of about 12 psf.

The actual maneuver from STS-1 that occurred at this flight condition is shown in Fig. 10. The flight result in Fig. 10 shows a more hazardous maneuver than was predicted. At this flight condition the excursions have to be kept small. The flight maneuver resulted in twice the sideslip peaks predicted and in a somewhat higher roll rate than predicted. Also, there was more yaw jet firing than was predicted and the motion was more poorly damped than predicted. It is obvious from comparing the predicted vs actual maneuver that the stability and control derivatives are significantly different than predicted. It is fortunate that the control-system design philosophy discussed earlier had been used for the Shuttle. Although the flight maneuver resulted in excursions greater than planned, the control system did manage to damp out the oscillation in less than 1 min. With a less conservative design approach, the resulting entry could have been substantially worse.

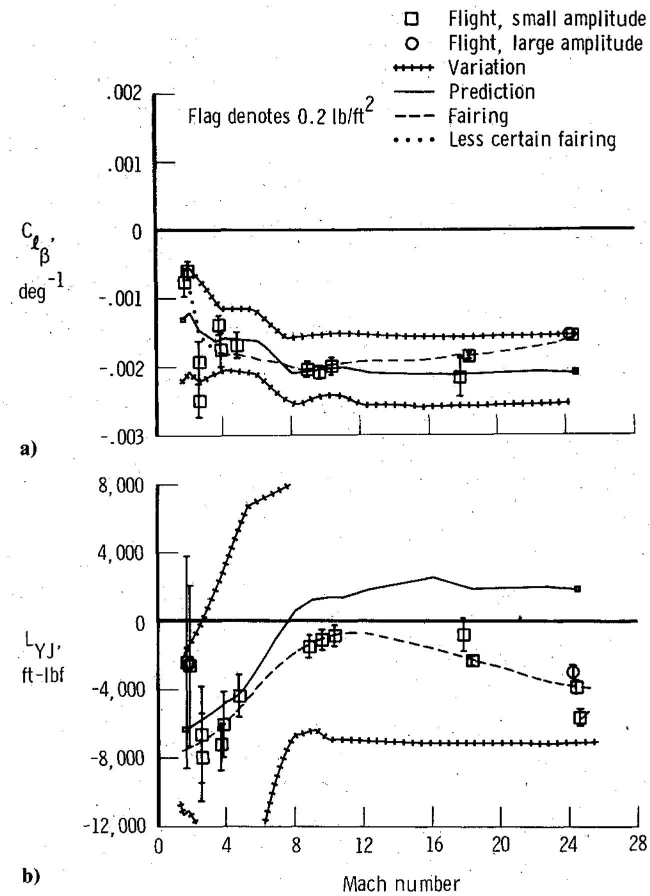

Fig. 11 Space Shuttle estimates: a) $C_{\ell\beta}$ and b) L_{YJ}.

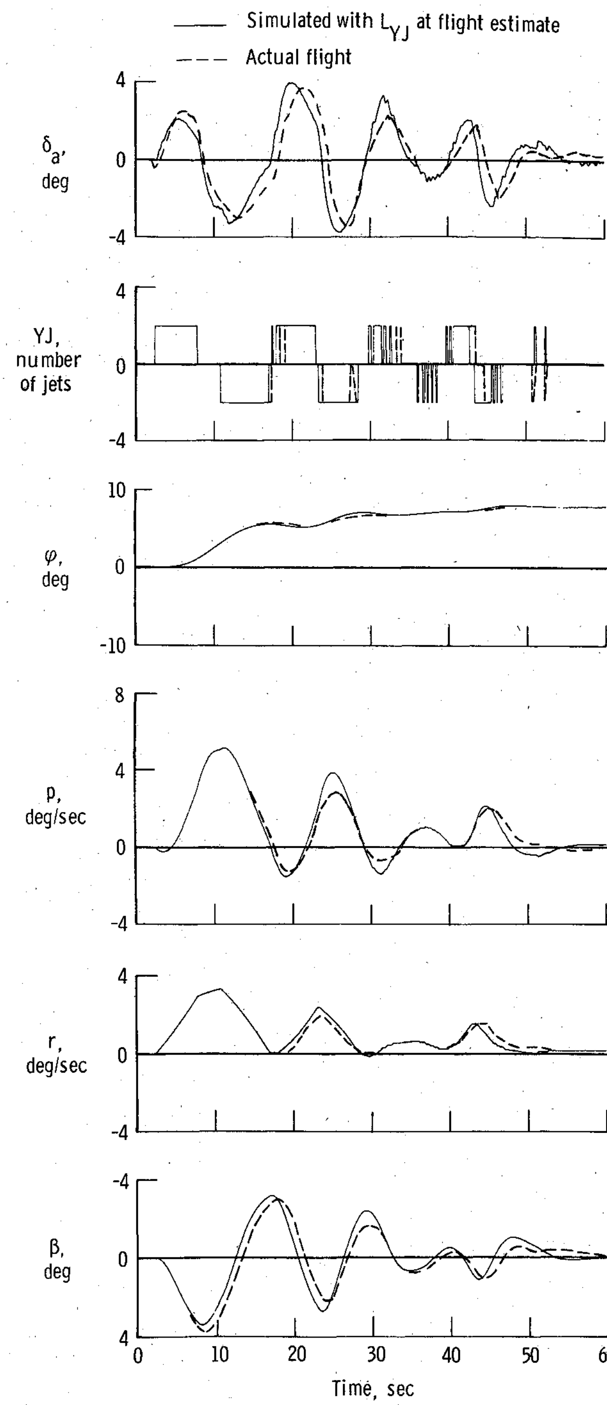

Fig. 12 Comparison of simulated bank maneuver with L_{YJ} at a flight-estimated value with the STS-1 bank maneuver.

The obvious way to assess the problem with the first bank maneuver was to compare the flight-determined stability and control derivatives with the predictions. Of all of the derivatives obtained from STS-1, the two important ones that differed most from predictions at the flight condition being discussed were $C_{\ell\beta}$ and L_{YJ}; the latter is the rolling moment due to a single yaw jet firing. Since the entry tends to decrease monotonically in Mach number, the derivatives can be portrayed best as functions of the guidance system Mach number, which is $V/1000$. Figure 11a shows $C_{\ell\beta}$ vs guidance Mach number, and Fig. 11b shows L_{YJ} vs guidance Mach number. Only the estimates from STS-1 are shown in these figures. The prediction is shown by the solid line and the variations by the hatched lines. The symbols designate the estimates and the vertical bars the uncertainties. The dashed line is the fairing of the flight data.

When only the large change in $C_{\ell\beta}$ was entered into the simulation data base, the maneuver looked very much like the original prediction (Fig. 9); however, as expected, the frequency of the oscillations was changed to be more representative of the actual flight frequencies seen in Fig. 10. The effect of changing only L_{YJ} from the predictions on the simulator is shown with the flight response in Fig. 12. These two time histories are very close, considering that the other differences between the flight-determined and predicted derivatives have been ignored.

From these illustrations it is apparent that the primary problem with the initial bank maneuver was the poor prediction of L_{YJ}. The control-system software is very complex; it cannot be changed and verified between STS missions, so an interim approach was taken to keep this large excursion from occurring on future flights. The flight-determined derivatives were put into the simulation data base and the Shuttle pilots practiced performing the maneuver manually to try to attain a smaller response within more desirable limits. The maneuver was performed manually on STS-2 through STS-4. Figure 13 shows the manually-flown maneuver from STS-2. The maneuver appears to be much better behaved because p, r, and β are now within the desired limits. The maneuver does not look like the original predicted response because the derivatives and the input are different and the basic control system remains unchanged. Since the response variables are kept low and the inputs are slower and smaller, the flight responses on STS-2 through STS-4 do not show a tendency to oscillate. The flight control software was altered for STS-5 to make an input similar to the manual maneuver flown on STS-2 (Fig. 13). The resulting response on STS-5 was similar to that from STS-2.

The maneuver discussed above is only one of those that are going to result in control refinements. In the near future, the software will be updated for all flight conditions, based on the

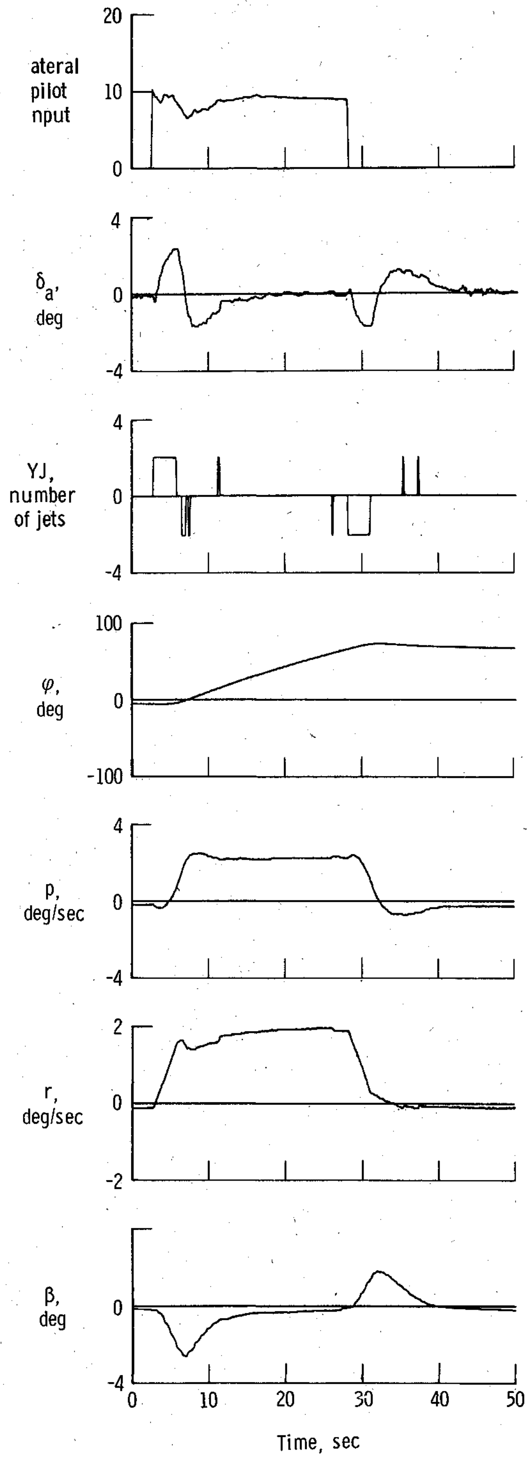

Fig. 13 Manual bank maneuver at a Mach number of 24 from STS-2.

flight-determined stability and control derivatives determined to date.

Parameter estimation techniques are being applied to the highly complex Space Shuttle vehicle, and the results of this application will significantly affect the control system design, placard modification, and flight procedures used in general.

Concluding Remarks

Parameter estimation techniques play an important role in flight tests at the NASA Ames/Dryden Flight Research Facility. These techniques were used in the F-14 program to effect control system changes that improved its handling qualities at high angles of attack. The same techniques provided the primary source of information for the refinement of the control system for the HiMAT vehicle at negative static margin. The energy management maneuvers have been redefined for the Space Shuttle, based on simulations using flight-determined stability and control estimates. Moreover, parameter estimation techniques are being relied upon for future control-system design, placard modification or removal, and flight procedures in general for the Space Shuttle.

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