PRACTICAL ASPECTS OF MODELING AIRCRAFT DYNAMICS FROM FLIGHT DATA

Kenneth W. Iliff and Richard E. Maine
Ames Research Center
Dryden Flight Research Facility
Edwards, California

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The purpose of parameter estimation, a subset of system identification, is to estimate the coefficients (such as stability and control derivatives) of the aircraft differential equations of motion from sampled measured dynamic responses. Model structure determination, which is another aspect of systems identification, is discussed elsewhere.

Statement of Aircraft Parameter Estimation Problem

Estimate the coefficients (parameters) of the aircraft differential equations of motion from sampled measured dynamic responses

In the past, the primary reason for estimating stability and control derivatives from flight tests was 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 knowledge of these new flight regimes increased, 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 previously required.

Uses of Flight-Determined Estimates

- Correlation studies
- Handling qualities documentation
- Design compliance
- Simulation
  - Flight planning (envelope expansion)
  - Pilot training
- Control system design
  - Linear analysis
  - Nonlinear simulation
  - Pilot in the loop

The maximum likelihood estimator is used to obtain the stability and control derivatives from flight data. This is done by minimizing the cost function $J(\xi)$ where the unknown derivatives to be estimated are in the vector ξ. The term J is the weighted outer product of the difference between the measured response and the computed response, based on the current value of ξ. For the stability and control derivative problem, we can assume the state and measurement equations are linear, although they need not be for maximum likelihood estimators in general.

Maximum Likelihood Estimator

State Equation

$$\dot{x} = Ax + Bu + \eta$$

Observation Equation

$$z_i = Cx_i + Du_i + n_i$$

Minimize Cost Function

$$J(\zeta) = \sum_{i=1}^{N} [z_i - \tilde{z}_i(\zeta)]^* R^{-1} [z_i - \tilde{z}_i(\zeta)] + \tfrac{1}{2} N \ln |R|$$

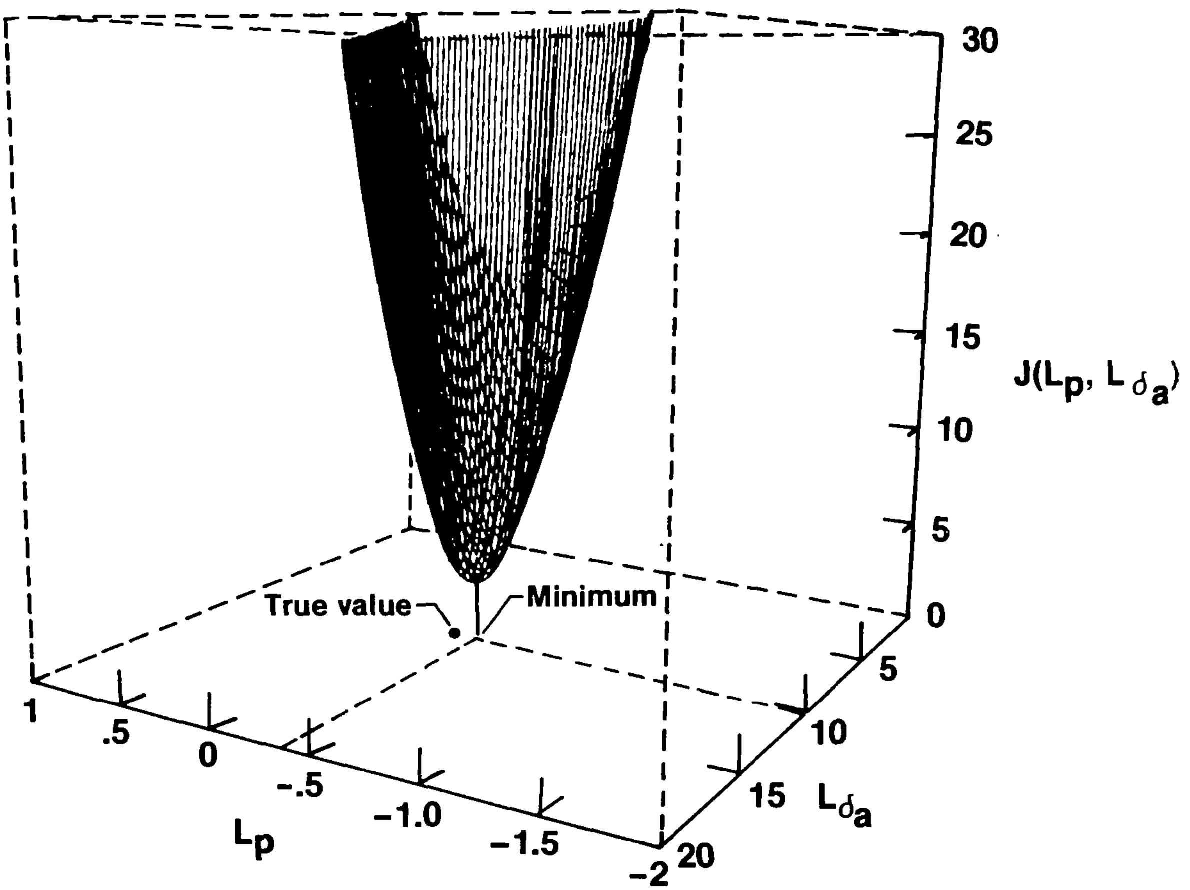
Where

$\tilde{z}_i$ is computed estimate of z_i

ζ is vector of unknowns

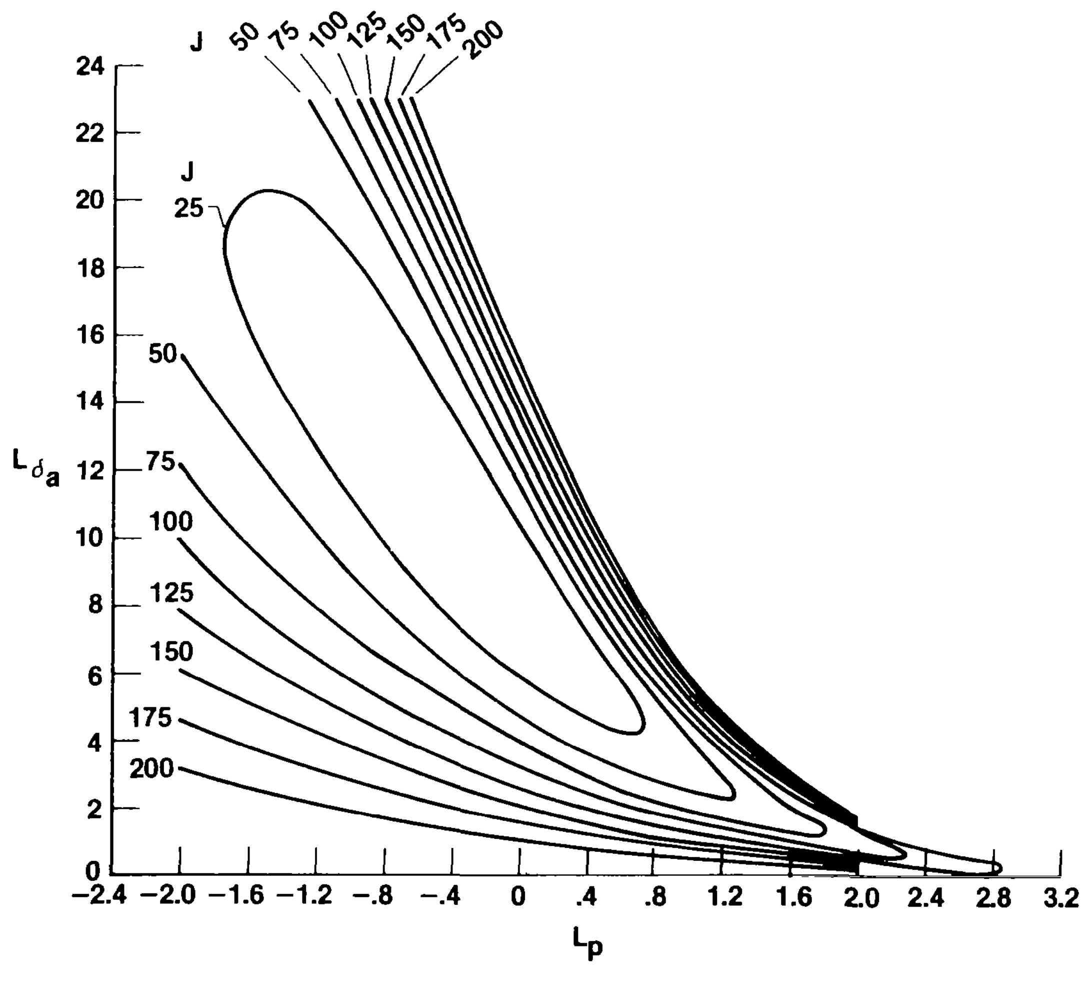
If we look at the case where the vector of unknowns ξ contains only the roll-damping and the roll-control power, we can see some of the essential features of the minimization of the cost function. The cost function is shown here as a function of these two unknowns for a set of simulated data with added measurement noise. The minimum is shown, as well as the true value used in simulation. The reason for the difference is the measurement noise. This is also true for the case of real-flight data, where the measurement error may also be caused by modeling error. The maximum likelihood estimate is at the minimum of the cost function.

Cost Function Surface Near Minimum



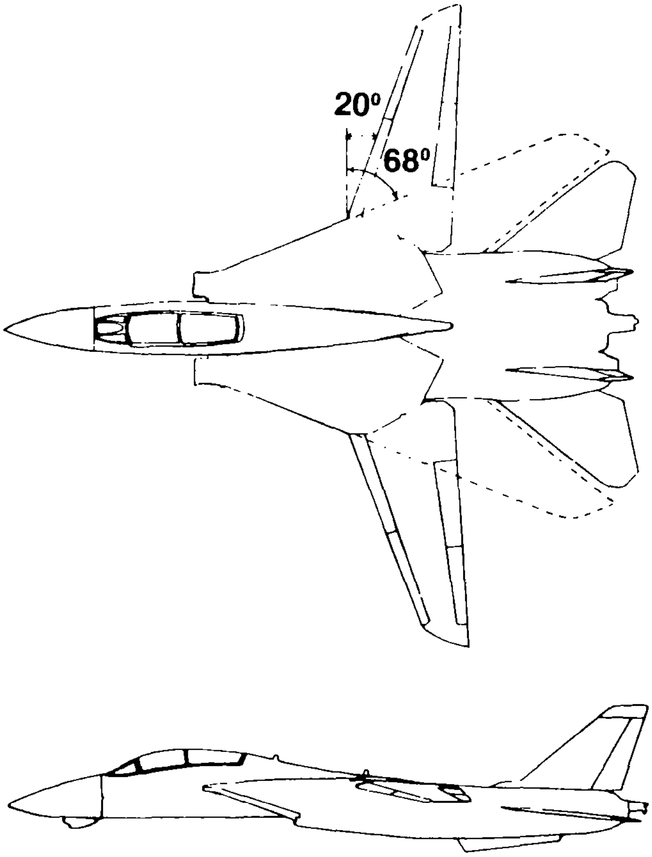
If we slice through the surface at constant values of the cost function, we can depict the cost function with isoclines. If we are far from the minimum (lowest isocline value), the isoclines are not elliptical. As we approach the minimum, the isoclines become more closely elliptical or nearly quadratic. Most minimization techniques take advantage of the quadratic nature of the cost function near the minimum.

Cost Function Isoclines



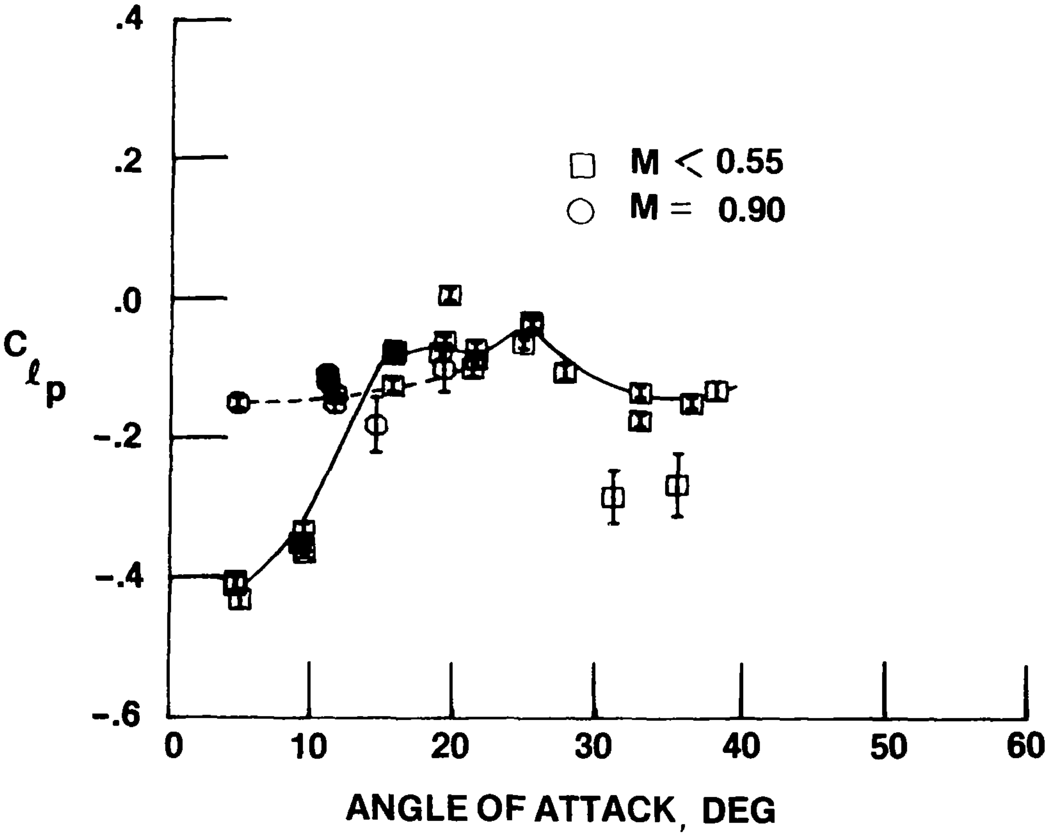
The F-14 is a twin-engine, high-performance fighter aircraft that has variable wing sweep capability. The F-14 program addressed improvement of airplane handling qualities at high angles of attack by incorporating a number of control system techniques. The first part of the program was dedicated to obtaining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

F-14 AIRPLANE CONFIGURATION



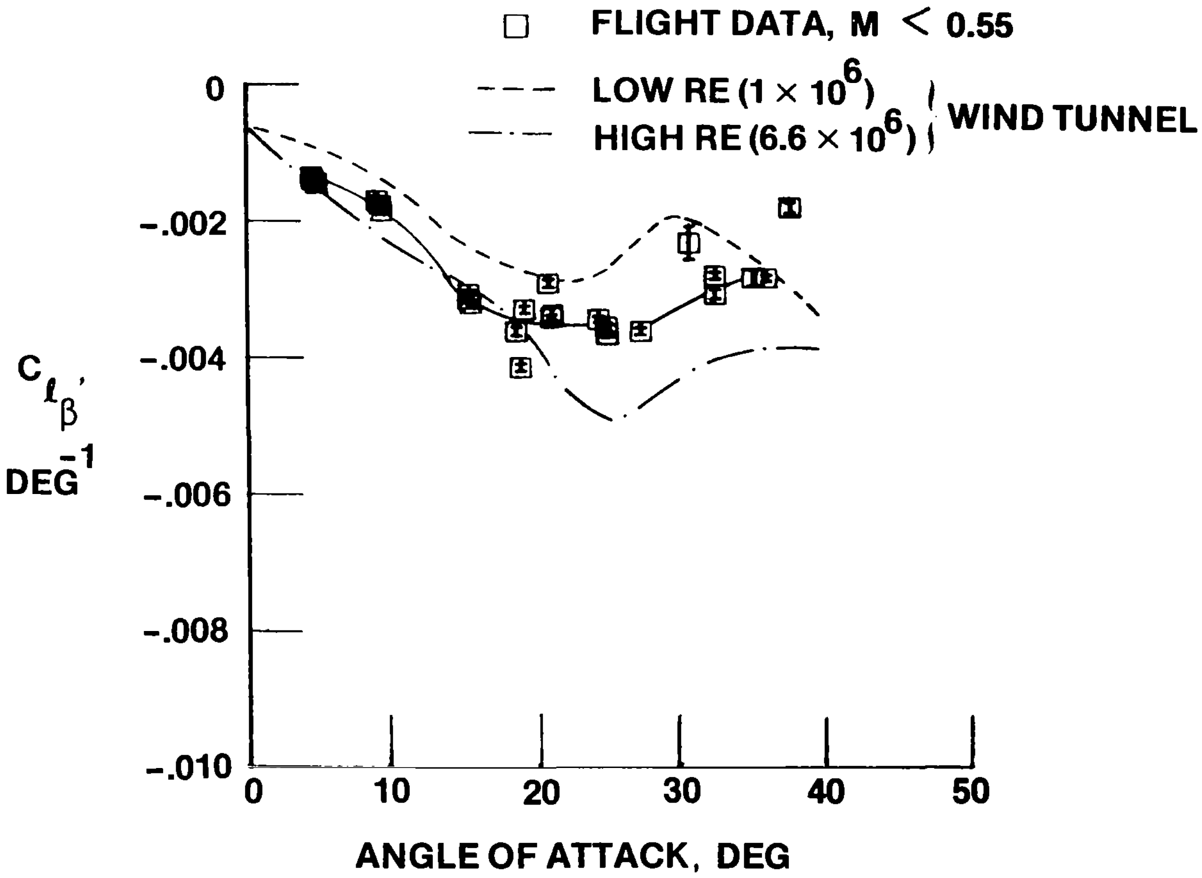
This figure shows the flight-determined damping in roll (C_{ℓ_p}) as a function of angle of attack (α) for low Mach numbers (<0.55) and for a Mach number of 0.9. There was some uncertainty in the accuracy of the wind tunnel predictions of C_{ℓ_p} because the tunnel model configuration was different from the flight configuration. These flight data agreed with the trends found in the tunnel; with the proper interpretation, even the magnitudes were in fair agreement.

DAMPING-IN-ROLL ESTIMATES



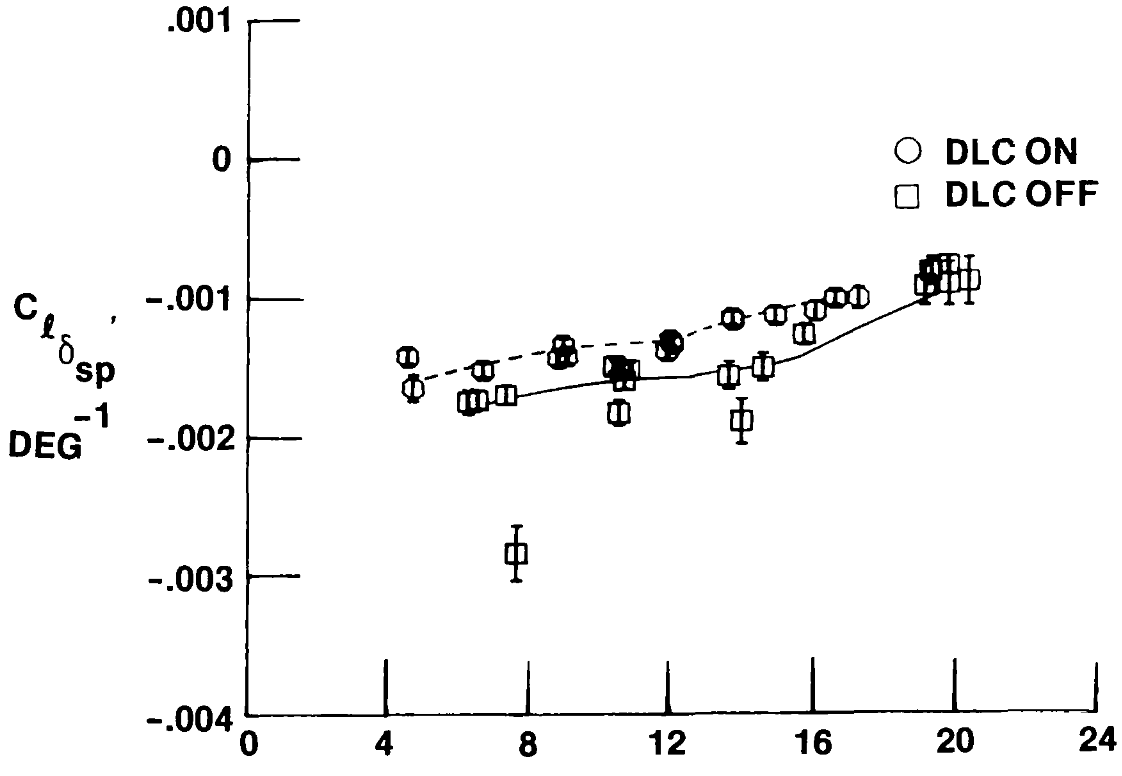
This figure shows the flight-determined values of dihedral effect (C_{ℓ_β}) as a function of α compared with the results of two different sets of wind tunnel results. There was some concern about the disagreement of the two sets of wind tunnel results before flight. At low angles of attack, the three sets of estimates are in fair agreement; however, at angles of attack above 15°, the flight data lie between the sets of tunnel data.

DIHEDRAL EFFECT ESTIMATES



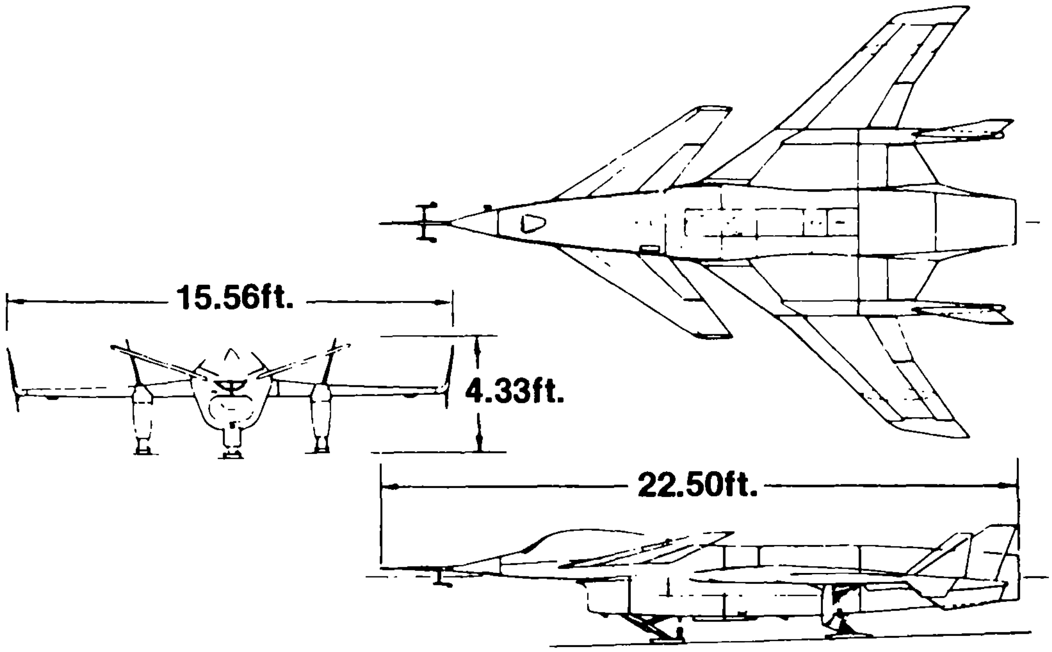
The F-14 data in this figure show the sensitivity with which we can determine stability and control derivatives. Rolling-moment coefficient as a result of differential spoiler deflection ($C_{\ell_{\delta_{sp}}}$) is shown as a function of angle of attack. It is apparent that there is about 10 percent to 20 percent more effectiveness with the direct lift control (DLC) off. The difference between DLC on and DLC off is a small configurational change. With the DLC on, the spoilers are positioned 4° above the wing contour; with the DLC off, the spoilers are positioned along the wing contour. Therefore, the 4° change in position results in a significant change in spoiler effectiveness, demonstrating the sensitivity with which the parameter estimation method can detect changes in vehicle characteristics that result from changes in configuration.

DIFFERENTIAL SPOILER EFFECTIVENESS ESTIMATES



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. The flight-test philosophy was to fly the vehicle in a stable condition, with the control feedbacks set to zero, to obtain stability and control derivatives. 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 0.40 to 0.92, at angles of attack up to 10°, and at altitudes from 15,000 ft to 45,000 ft. A complete set of stability and control characteristics was obtained for both the longitudinal and lateral-directional degrees of freedom.

HiMAT RPRV BASELINE CONFIGURATION



The HiMAT vehicle is constructed of advanced composite materials to allow for aeroelastic tailoring and to minimize 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 the time drag is reduced. The vehicle was designed to fly with a sustained 8-g turn capability at a Mach number of 0.9 and an altitude of 25,000 ft, and to demonstrate supersonic flight to a Mach number of 1.4. To attain the Mach 0.9 condition, it is predicted that the vehicle must be flown at a 10-percent mean aerodynamic chord (MAC) negative static margin (unstable). The philosophy for testing HiMAT is somewhat different from that for testing production aircraft. Flight-determined stability and control derivatives are to be relied on to keep the wind tunnel program to a minimum. The original simulation data base contained the wind tunnel data, supplemented with some computed characteristics.

HiMAT TECHNOLOGY DEMONSTRATION

VEHICLE CONCEPT
  - REMOTELY PILOTED
  - CLOSE-COUPLED CANARD
  - ADVANCED COMPOSITES
  - AEROELASTICALLY TAILORED
  - NEGATIVE STATIC MARGIN

DESIGN POINT DEMONSTRATION
  - SUSTAINED 8-G CAPABILITY
  - SUPERSONIC FLIGHT TO MACH OF 1.4

The results of the flight test program showed that damping in yaw (C_{n_r}) was twice the predicted value, yawing moment with respect to roll rate (C_{n_p}) was the opposite sign, and rolling moment with respect to yaw rate (C_{ℓ_r}) was a small fraction of the predicted value. Rudder effectiveness ($C_{n_{\delta r}}$) was 25 percent of the prediction, rolling moment due to rudder deflection ($C_{\ell_{\delta r}}$) was twice the prediction, and both yawing moment with respect to aileron deflection ($C_{n_{\delta a}}$) and yawing moment with respect to elevon deflection ($C_{n_{\delta_{DE}}}$) were more positive than the prediction. Using the value found from flight data, the control system was changed markedly from the original control system, which was based on data from the limited wind tunnel program.

FLIGHT TO PREDICTION COMPARISON (LATERAL-DIRECTIONAL)

(MINIMAL WIND TUNNEL PROGRAM)

DAMPING

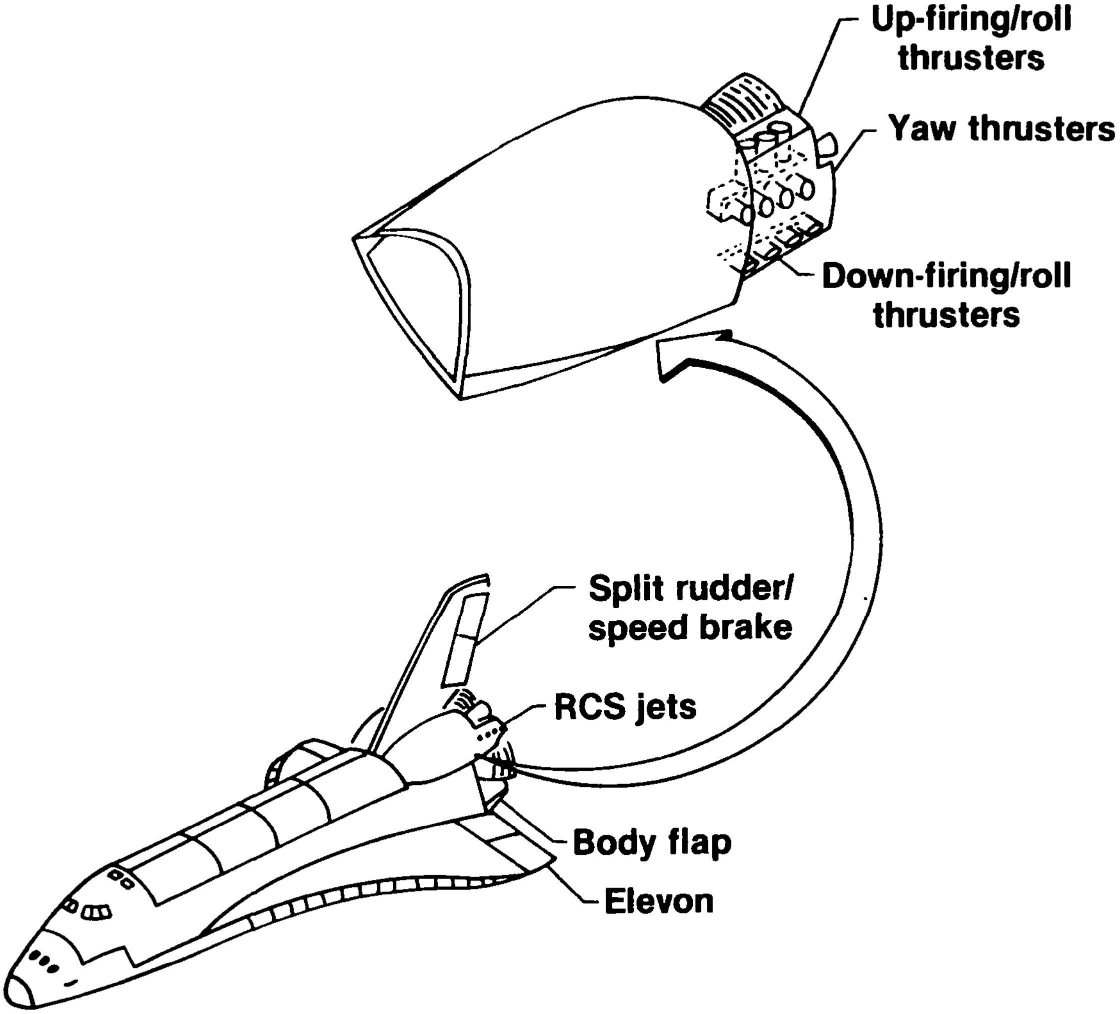
C_{n_r}	TWICE PREDICTION
C_{n_p}	OPPOSITE SIGN OF PREDICTION
C_{l_r}	SMALL FRACTION OF PREDICTION

CONTROL

$C_{n_{\delta_r}}$	25% LESS THAN PREDICTION
$C_{l_{\delta_r}}$	TWICE PREDICTION
$C_{n_{\delta a}}$	AND $C_{n_{\delta_{DE}}}$ MORE POSITIVE THAN PREDICTION

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 eight horizontal RCS jets (four left-firing and four right-firing), four elevon surfaces, a body flap, and a split rudder surface. The locations of these devices are shown in this figure. 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.

Shuttle Configuration



The flight-determined stability and control derivatives are used to update and improve simulations, refine the control system, modify flight envelope restrictions (placards), and improve flight procedures.

Uses of Estimates From Shuttle

Improve simulation

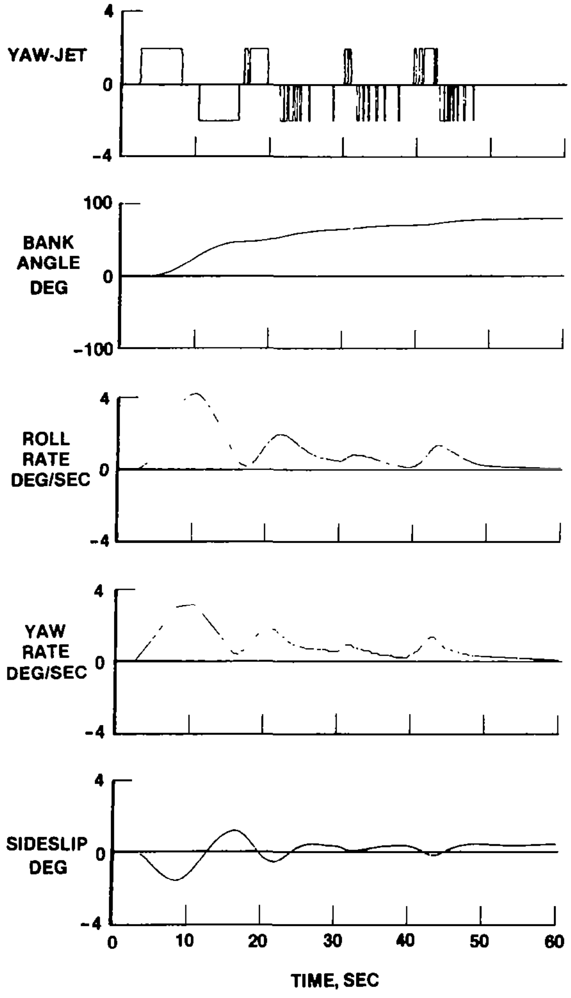
Control system refinement

Modify placard

Improve flight procedures

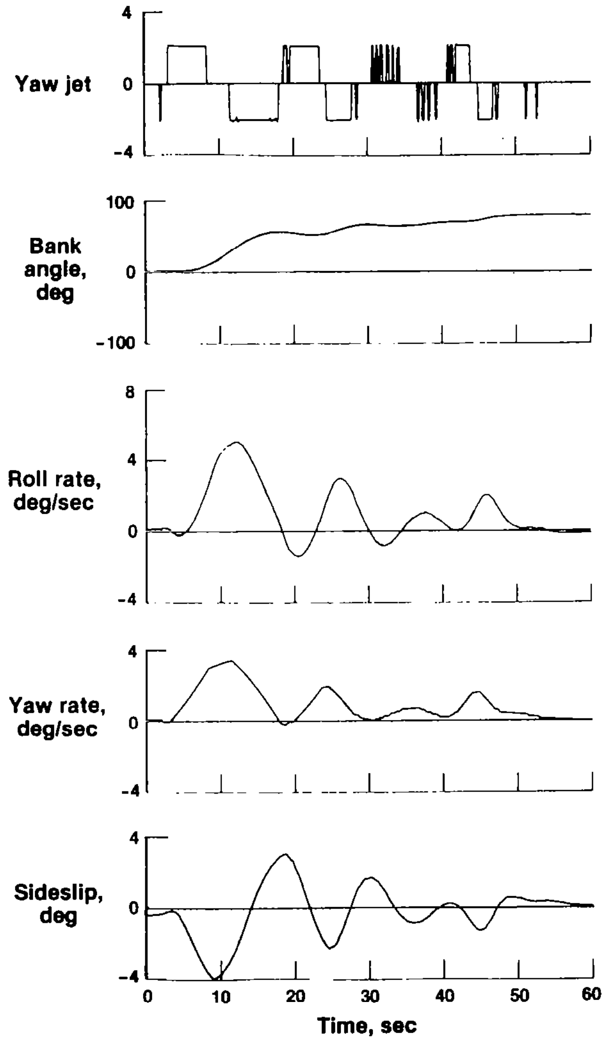
One of the interesting examples of where parameter estimation played an important role in the Shuttle program occurred during the first energy management bank maneuver on the first entry of the Shuttle (STS-1). The computed response to the automated control inputs with the predicted stability and control derivatives is shown in this figure. The control inputs shown here are the closed-loop commands from the Shuttle control laws. The maneuver was to be made at a velocity of 24,300 ft/sec and at a dynamic pressure of about 12 lb/ft^2.

PREDICTED BANK MANEUVER FOR STS-1



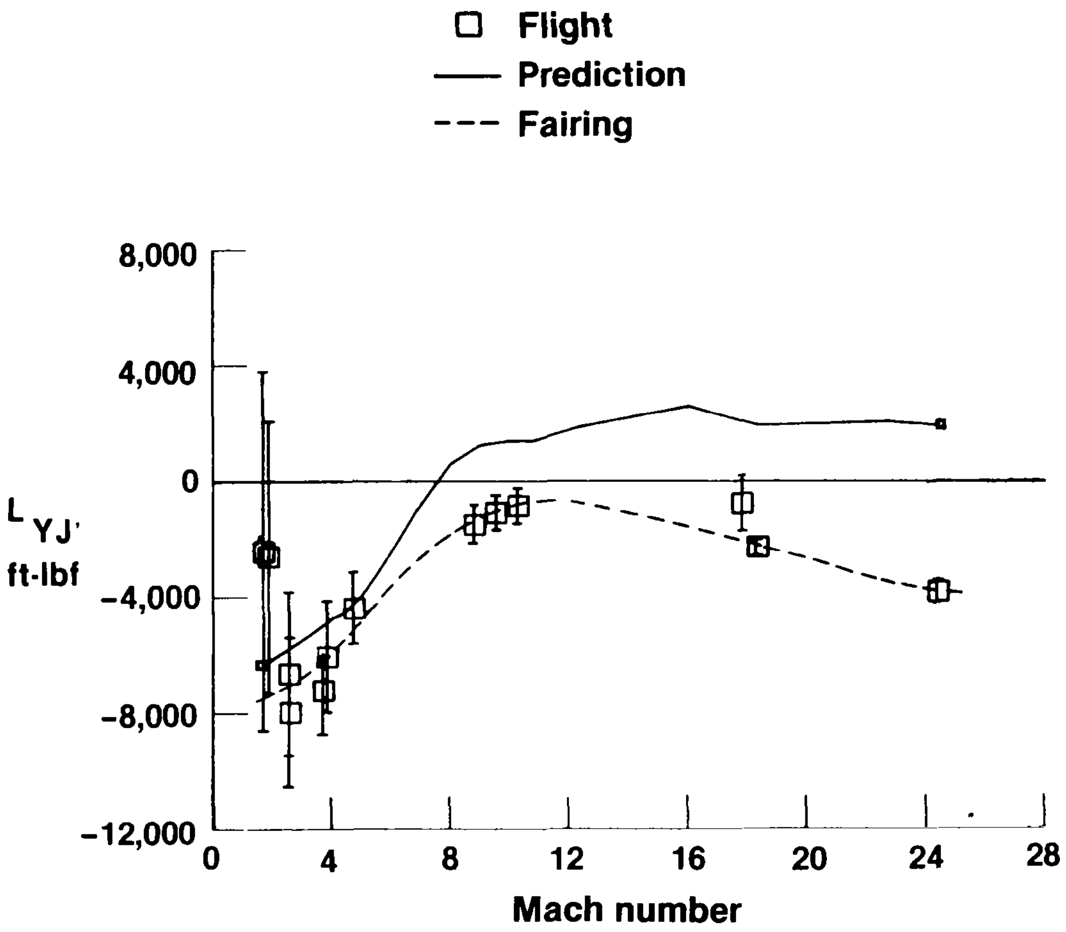
The actual maneuver from STS-1 that occurred at this flight condition is shown in this figure. The flight data show a more hazardous maneuver than was predicted. At this flight condition, the excursions must be kept small. The flight maneuver resulted in twice the sideslip peaks predicted and in a somewhat higher roll rate than predicted. In addition, there was more yaw-jet firing than was predicted, and the motion was more poorly damped than predicted. It is obvious from comparing the predictions with the results of the actual maneuver that the stability and control derivatives are significantly different. 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 much worse.

Actual Bank Maneuver for STS-1



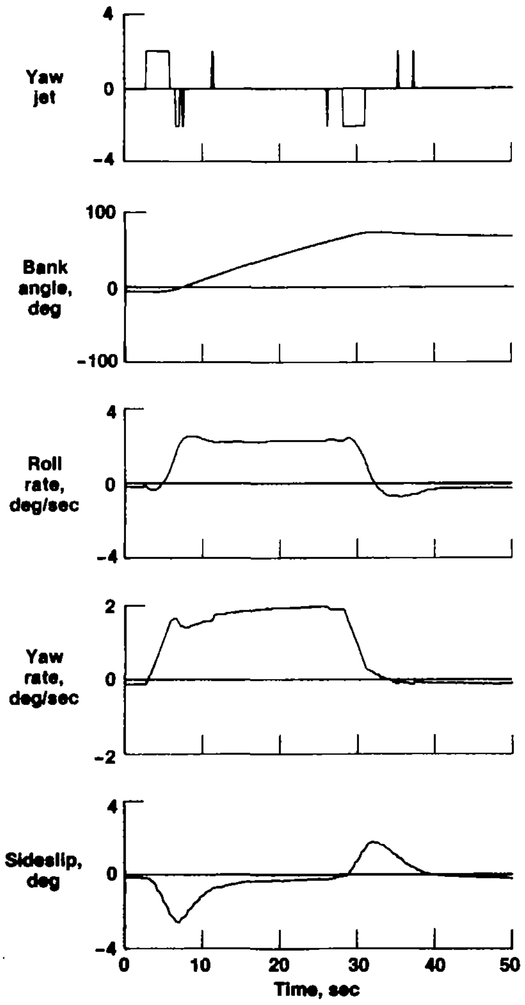
The obvious way to assess the problem with the first bank maneuver is to compare the flight-determined stability and control derivatives with the predictions. Of all the derivatives obtained from STS-1, the most important one that differed most from predictions at the flight condition being discussed was L_{YJ}, which is the rolling moment due to the firing of a single yaw jet. Since the entry tends to monotonically decrease in Mach number, the derivative can best be portrayed as a function of the guidance system "Mach number," which is V/1000. This figure shows L_{YJ} as a function of guidance "Mach number." Only the estimates from STS-1 are shown in these figures. The prediction is shown by the solid line. The symbols designate the estimates, and the vertical bars, the uncertainties. The dashed line is the fairing of the flight data.

Roll Due to Yaw Jet Estimates



The control system software is very complex; it cannot be changed and verified between STS missions, so an interim approach was taken to eliminate large excursions on future flights. The flight-determined derivatives were put into the simulation data base, and the Shuttle pilots practiced performing the maneuver manually to attain a smaller response within more desirable limits. The maneuver was performed manually on STS-2 and STS-3. This figure shows the manually flown maneuver from STS-2. The maneuver appears to be much better behaved, for roll rate (p), yaw rate (r), and angle of sideslip (β) are 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. For STS-5 through STS-8, the control system automatically inputs the commands. The resulting maneuvers look nearly identical to the maneuver shown in this figure.

Bank Maneuver After Problem Solved



Maximum likelihood parameter estimation techniques were used in the F-14 program to effect control system changes that improved the handling qualities of the aircraft 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 on for future control system design, placard modification or removal, and flight procedures for the Space Shuttle.

CONCLUSIONS

PARAMETER ESTIMATION IMPORTANT IN FLIGHT TEST

PARAMETER ESTIMATES USED TO

- IMPROVE HANDLING QUALITIES
- REFINE CONTROL SYSTEMS
- UPDATE SIMULATIONS
- MODIFY PLACARDS

CAREFUL SCRUTINY OF ESTIMATE NECESSARY