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Parameter Identification Technology Used in Determining In-Flight Airload Parameters

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An investigation was conducted to determine the feasibility of utilizing a modified Newton-Raphson computer program, developed by Taylor and Iliff of NASA, to determine the airload and the aircraft parameters concurrently from in-flight empennage and aircraft response data. Only the lateral directional mode was considered in this study. The airload responses consisted of the horizontal stabilizer rolling moment and the vertical tail sideforce. Pilot rudder pedal force time history responses were also included in the investigation. Comparisons of the in-flight coefficient parameters are made with wind-tunnel results. The *a priori* feature of the program was not utilized. Although there are many other techniques available, this technique is becoming recognized throughout the industry as the preferred or standard approach. The results of this investigation substantiate the practicality of the technique for the purpose of evaluating airload derivatives.

Nomenclature

a_y	= lateral acceleration at the center of gravity, g units
C_l, C_n, C_Y	= rolling moment, yawing moment, and sideforce coefficient, respectively
FR	= pilot rudder pedal force, lb
g	= acceleration due to gravity, ft/sec^2
I_x, I_z	= moment of inertia about x- and z-body axes, respectively, slug-ft^2
L	= aircraft rolling moment/I_x, rad/sec^2
L_{HT}	= horizontal tail rolling moment, ft-lb
N	= aircraft yawing moment/I_z, rad/sec^2
p, r	= roll rate and yaw rate, respectively, rad/sec or deg/sec
V_0	= initial velocity, ft/sec
Y	= aircraft sideforce/[(aircraft mass)(V_0)], 1/sec
Y_{VT}	= vertical tail sideforce, lb
α	= angle of attack, deg
β	= angle of sideslip, rad or deg
δ_a, δ_r	= aileron and rudder deflections, respectively, rad or deg
δ_0	= constant control deflection, rad or deg
ϕ	= roll angle, rad or deg

Subscripts

HT, VT	= horizontal tail and vertical tail, respectively
$p, r, \beta, \delta_a, \delta_r$	= partial derivatives with respect to subscripted variables

Introduction

CERTIFYING business jet aircraft with the Federal Aviation Administration (FAA) requires many hours of flight testing to determine whether certain FAA structural load requirements are met. Airload data measurements are involved in this effort. In-flight airload data measurements are evaluated, and these reduced data are used analytically to simulate the airloads expected on the various aircraft components during dynamic flight. The purpose of these analyses is to verify the original loadings used in the aircraft design, or to calculate loadings on a new airplane of similar design.

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The utilization of the Taylor-Iliff computer program[1] provides a procedure whereby the airload parameters can be obtained routinely and accurately during the process of flight testing for certification purposes. In addition, the aircraft parameters can be obtained during the same conditions. This supplies the analyst with all of the time-invariant parameters required to produce accurate simulations, and eliminates the necessity of extended flight test programs.

The parameter identification technique developed by Taylor and Iliff[1] is a widely accepted procedure in the industry for determining in-flight parameters. This computer program computes parameter estimates from response data for a linear system that can be modeled in a state space format. A modified Newton-Raphson algorithm is utilized that computes parameters that minimize the error between the computed response and the actual recorded response. The technique has primarily been used to extract in-flight aerodynamic stability derivatives.[2,3] Many of the various approaches and applications of parameter identification were presented at two recent symposiums on the subject.[4,5] In a more recent conference, a subsequent technical paper was presented extending the analyses of this paper to the calculation of many of the component stability derivatives.[6]

The airload parameters were extracted from time histories of the horizontal stabilizer rolling moment and vertical tail sideforce. The aircraft responses recorded during the flight test program included roll rate, yaw rate, sideslip angle, roll angle, and lateral acceleration. Pilot rudder pedal forces were also recorded. To utilize these recorded variable responses in the Taylor-Iliff computer program, a mathematical model was formulated for the equation of state and the observations of the aircraft system.

Flight Test Airplane and Instrumentation

The airplane used in the study was the Learjet Model 35 shown in Fig. 1. This is a small business jet aircraft with two fuselage mounted Garrett TFE731-2 turbofan engines, lightly swept low wing with wing-tip fuel tanks, and a T-tail. The control devices include trailing edge flaps, outboard ailerons, spoilers, rudder, elevator, and controllable incidence horizontal tail. In this study, only the aileron and rudder are of interest. These controls are reversible and are actuated by a system of pulleys and cables. The aileron breakout force is approximately 10 lb; and the rudder, 22 lb. There is an aileron-rudder interconnect; however, its effects were neglected in the analyses, since the interconnect spring is very weak. Angle of attack and sideslip vanes were mounted on the aircraft nose boom as shown in Fig. 1. Some other instrumentation in-

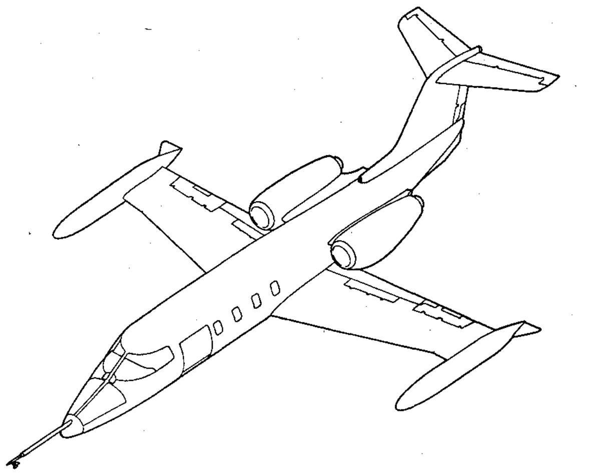

Fig. 1 The Learjet Model 35 airplane.

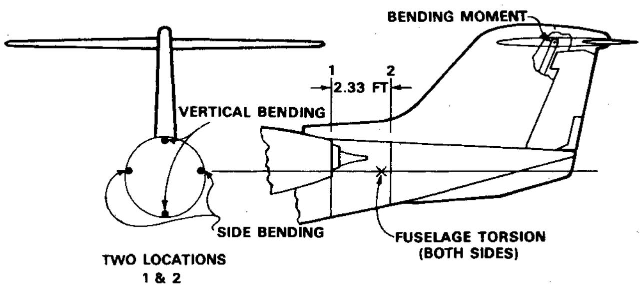

Fig. 2 Location of bending and torsion strain gages.

cluded empennage mounted strain gages, roll-rate gyroscope, yaw-rate gyroscope, lateral accelerometer, ceramic rheostats to measure the control deflections, and a strain gage mounted on the rudder pedal to measure the pilot force. The aircraft gross weight for the flight test program was approximately 14,000 lb.

Airload responses were obtained from calibrated strain gages mounted on the flight test aircraft as shown in Fig. 2. A bending moment bridge was mounted on the horizontal tail hinge pin fitting, which supports the horizontal tail. This strain-gage bridge measures the horizontal tail rolling moment about the longitudinal axis at this location. Sideforce responses were determined from two vertical bending bridges located at the top and bottom of the aft fuselage at two locations, from two side bending bridges at these same two locations on both sides of the fuselage, and from a torque gage mounted similar to the side bending bridges. From ground calibration tests, equations to determine the vertical tail sideforce responses were formulated.

Mathematical Model

Sufficient documentation of the Taylor-Iliff modified Newton-Raphson minimization technique has been presented in the literature previouslyl.[1,2] The parameter identification technique is illustrated in the block diagram of Fig. 3. The equations depicted are

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{1}$$

$$y(t) = Fx(t) + Gu(t) + b \tag{2}$$

$$z(t) = y(t) + n(t) \tag{3}$$

where $x(t)$ is the state vector of the position and velocity state variables, $u(t)$ is the control input vector, $y(t)$ is the resulting computed response vector, $n(t)$ is the Gaussian white noise contaminant vector, b is the constant bias vector, and $z(t)$ is the measured response (the observation) vector. The matrices, identified as A, B, F, and G, contain the time-invariant airload and aircraft (stability and control) parameters. These parameters are estimated to minimize a weighted least squares function. For an explanation of this parameter identification technique, refer to Refs. 1 and 2.

In this study, only the lateral-directional mode was considered. The lateral-directional equations of motion for these analyses were for the equation of state.

$$\begin{bmatrix} \dot{p} \\ \dot{r} \\ \dot{\beta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} L_p & L_r & L_\beta & 0 \\ N_p & N_r & N_\beta & 0 \\ 0 & -1 & Y_\beta & g/V_0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} p \\ r \\ \beta \\ \phi \end{bmatrix} + \begin{bmatrix} L_{\delta_a} & L_{\delta_r} & L_{\delta_0} \\ N_{\delta_a} & N_{\delta_r} & N_{\delta_0} \\ Y_{\delta_a} & Y_{\delta_r} & Y_{\delta_0} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \\ 1 \end{bmatrix} \tag{4}$$

and for the observation equation (2)

$$\begin{bmatrix} p \\ r \\ \beta \\ \phi \\ \hline a_y \\ L_{HT} \\ Y_{VT} \\ FR \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \hline 0 & 0 & Y_\beta \dfrac{V_0}{g} & 0 \\ L_{p_{HT}} & L_{r_{HT}} & L_{\beta_{HT}} & 0 \\ 0 & 0 & Y_{\beta_{VT}} & 0 \\ 0 & 0 & FR_\beta & 0 \end{bmatrix} \begin{bmatrix} p \\ r \\ \beta \\ \phi \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \hline Y_{\delta_a} \dfrac{V_0}{g} & Y_{\delta_r} \dfrac{V_0}{g} & 0 \\ L_{\delta_{a_{HT}}} & L_{\delta_{r_{HT}}} & 0 \\ Y_{\delta_{a_{VT}}} & Y_{\delta_{r_{VT}}} & 0 \\ 0 & FR_{\delta_r} & 0 \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \\ 1 \end{bmatrix} + b \tag{5}$$

Maneuvers

Two types of maneuvers were analyzed in this study. These are described as maneuvers with separate control inputs and flat yaw maneuvers. The separate control input maneuvers were designed specifically for parameter identification and were performed by inputing the rudder and the aileron separately and independently. These were mild inputs made at

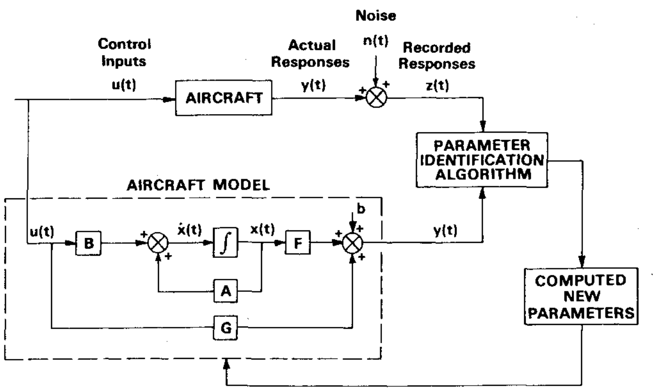

Fig. 3 The parameter identification technique.

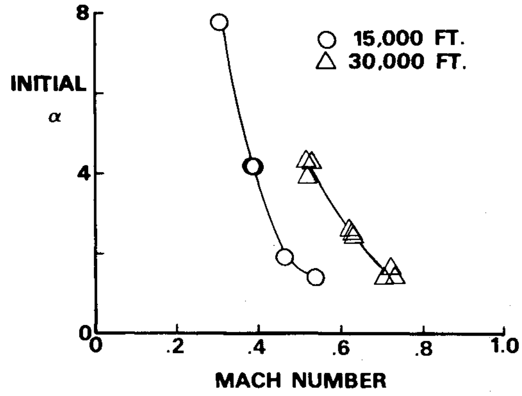

Fig. 5 Angle-of-attack ranges for the maneuvers.

both high and low frequency (e.g., step and doublet inputs) as shown in Fig. 4. The purpose was to excite the various lateral-directional modes and to separate the effects of the two control inputs to achieve a unique set of derivatives. The predominant source of data was from the flat yaw maneuvers. For these maneuvers, the pilot inputed a predetermined rudder pedal force while maintaining wings level with the ailerons. After the aircraft oscillations subsided, the pilot returned the aircraft to straight and level flight.

Method of Analysis

The parameter identification technique utilized in this investigation was the Taylor-Iliff modified Newton-Raphson minimization technique.[1] The *a priori* option of the computer program was not used; consequently, the results were not forced to give preferential weightings to particular parameter estimates previously determined. The equations of motion are presented in Eqs. (4) and (5).

The analyses were conducted differently for the two types of maneuvers considered. For the flight data where the inputs were made separately and independently as typified by Fig. 4, the aircraft parameters were identified first by initially deleting the last three equations in Eq. (5). The resulting aircraft parameters and bias terms were input as constants in the equations before identifying the airload parameters. This resulted in no significant change in the accuracy of the parameters; however, a significant reduction in computer time was realized.

In the analyses of the flat yaw maneuvers, roll rate, roll angle, and lateral acceleration were deleted from Eqs. (4) and (5). The primary consideration was to identify the airload parameters for these maneuvers since there was doubt that some of the aircraft parameters could be determined uniquely due to the concurrent rudder and aileron inputs. Consequently, for the expedience and savings in computer time, no attempt was made to analyze the aircraft parameters for these maneuvers.

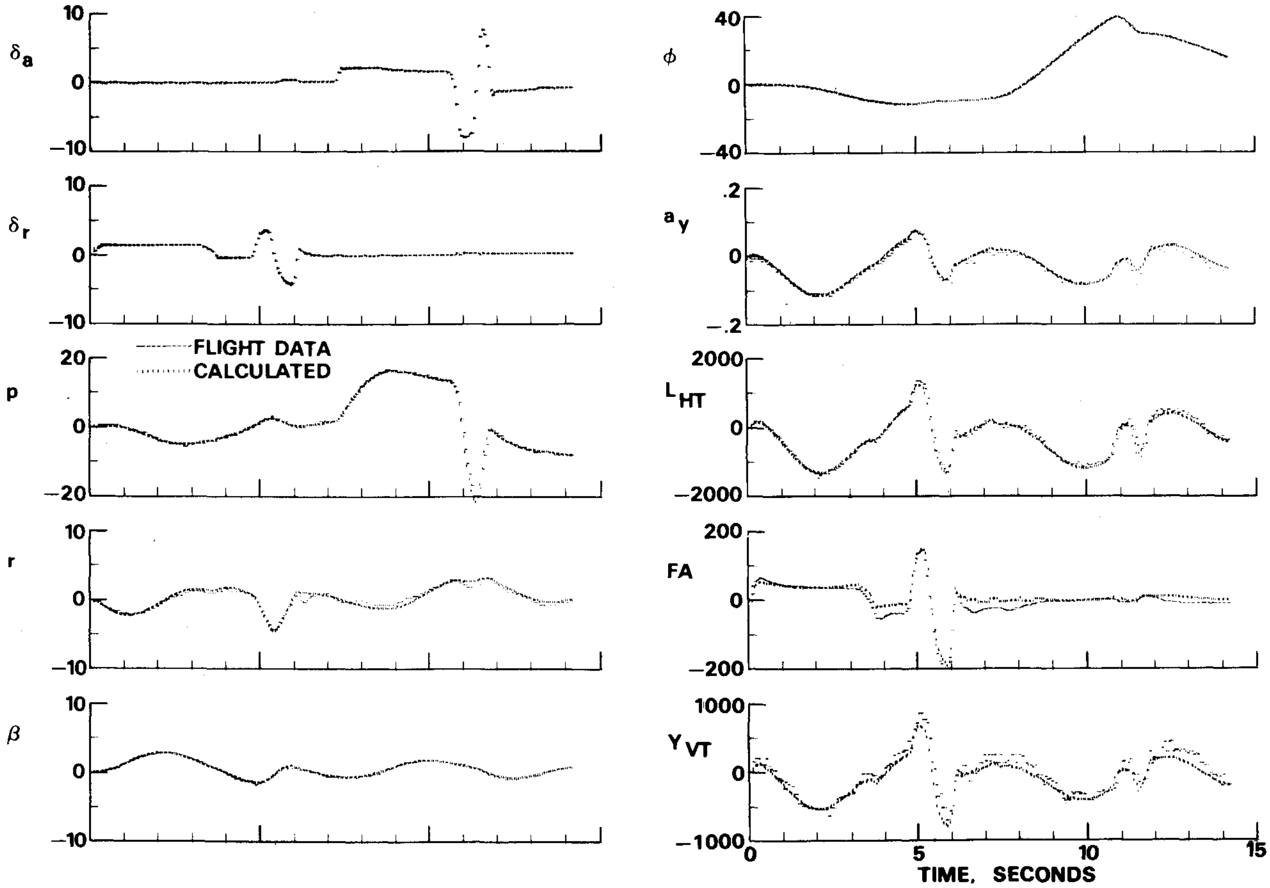

Fig. 4 Typical matches of a maneuver with separate control inputs; Mach no. =0.723, altitude=30,000 ft.

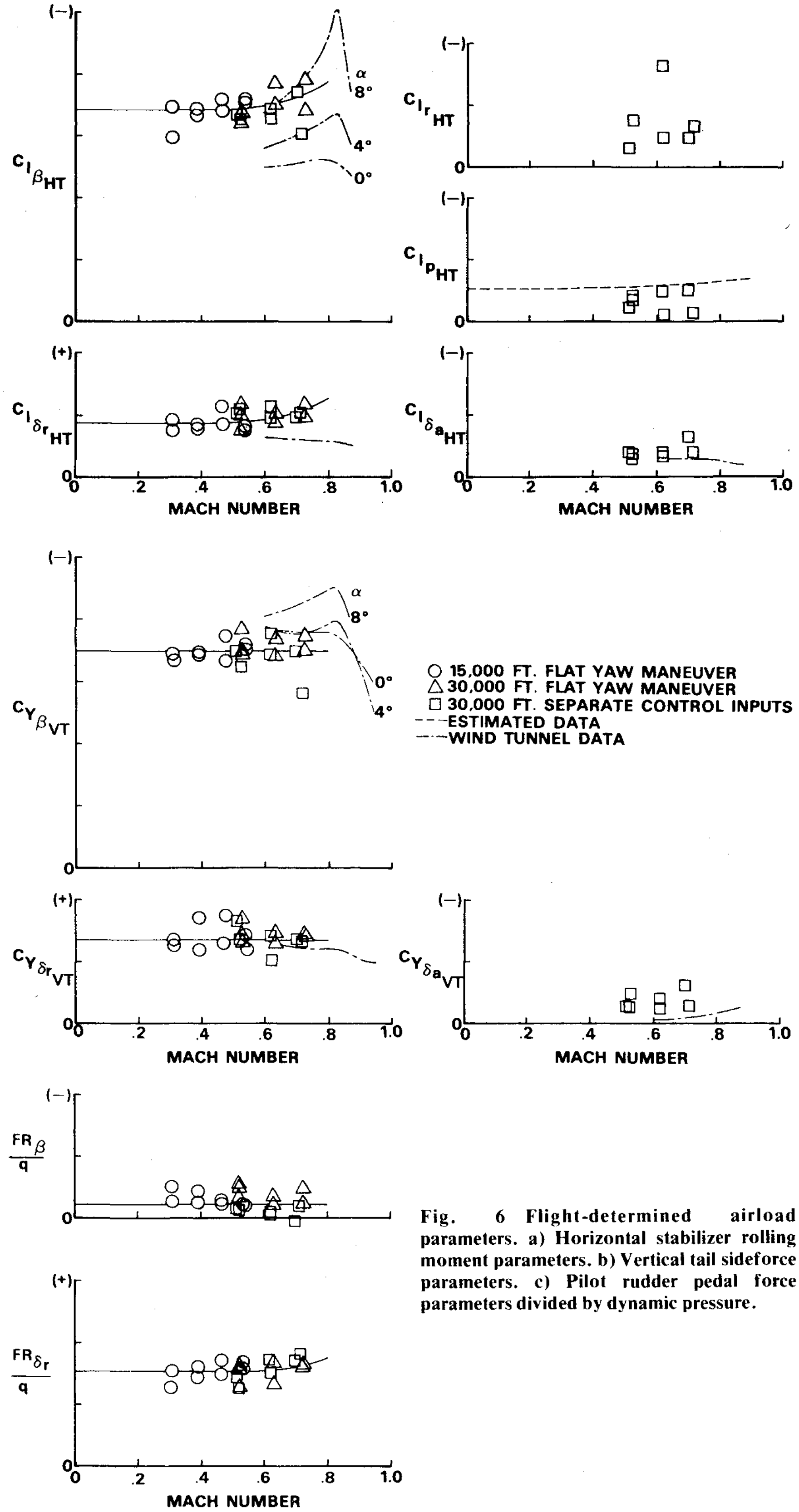

Fig. 6 Flight-determined airload parameters. a) Horizontal stabilizer rolling moment parameters. b) Vertical tail sideforce parameters. c) Pilot rudder pedal force parameters divided by dynamic pressure.

Results

Although the amount of desirable flight data available was limited, and improvements in the accuracy of the instrumentation system were indicated; the results achieved were sufficient to provide credence to the approach. The time history matches in Fig. 4 are excellent by any method. Even with the angle of attack variance with Mach number as shown in Fig. 5, the airload and aircraft parameters compare well with wind tunnel results and analytic estimates.

The worst match in Fig. 4 was for the rudder pedal force and was due primarily to cable stretch, friction, and breakout force characteristics of this control system. These characteristics were not modeled in Eq. (5). The airload parameters obtained from the horizontal stabilizer rolling moment time

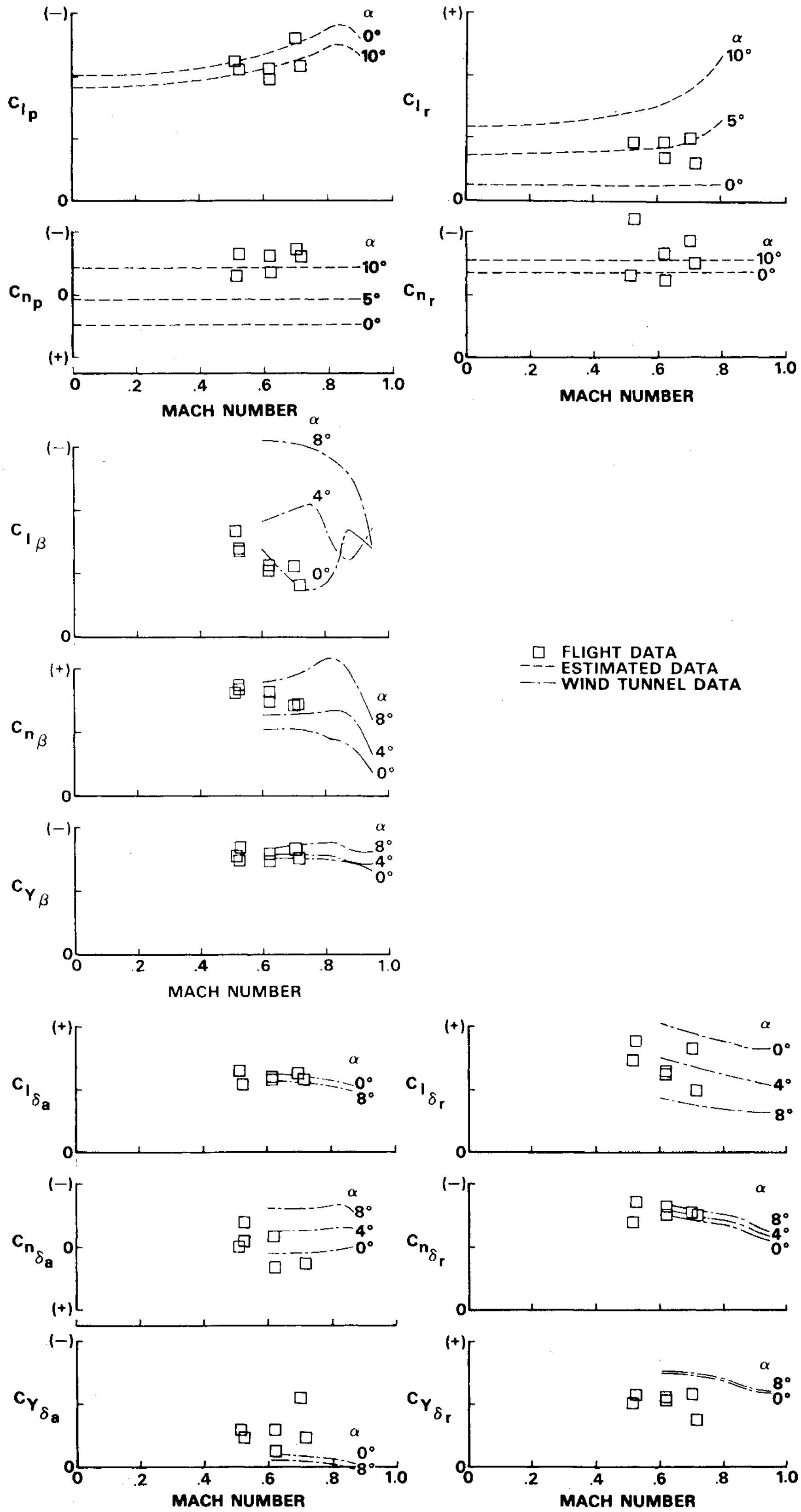

Fig. 7 Flight-determined aircraft parameters.

histories are presented in Fig. 6a as a function of Mach number. The sideslip parameter from wind-tunnel analyses exhibits an angle-of-attack influence not apparent in the flight data (see Fig. 5). Wind-tunnel or analytic data are not available to confirm the flight-extracted yaw rate parameter results. The resulting parameters from the vertical tail sideforce time histories correlate well with wind-tunnel results as shown in Fig. 6b. The associated rotary parameters were negligible. Figure 6c shows the rudder pedal force parameters divided by dynamic pressure. The aircraft parameter comparisons are presented in Fig. 7.

Concluding Remarks

The feasibility of using the Taylor-Iliff computer program to identify airload parameters in conjunction with the identification of the aerodynamic parameters has been demonstrated. The applicability was shown for a T-tail aircraft; adaptation to conventional and twin tailed aircraft would have to be investigated. The technique provides a method that can be used routinely to obtain adequate results without excessive flight hours and computer time.

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