

# Generation of Comprehensive Longitudinal Aerodynamic Data Using Dynamic Wind-Tunnel Simulation

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A novel method of generating comprehensive longitudinal aerodynamic data of aircraft using dynamic wind-tunnel simulation is presented. The method utilizes the motion and force responses of an aircraft model to control surface inputs to determine trim lift characteristics, longitudinal stability derivatives, and neutral point. In addition, large-amplitude lift and pitching moment responses characterizing the unsteady aerodynamic behavior are also generated using the same experimental setup. The new test method is demonstrated using a generic delta wing aircraft model with one degree of freedom in pitch. The model pitch attitude and lift force responses to elevon dynamic inputs are measured and used to deduce longitudinal aerodynamic data. Comparison of these results with static test data and Datacom estimates shows good agreement.

## Nomenclature

$C_L$	= lift coefficient, $L/\bar{q}S$
$C_{L_a}$	= lift curve slope, $\text{rad}^{-1}$
$C_m$	= pitching moment coefficient, $M/\bar{q}S\bar{c}$
$C_{m_q} + C_{m_a}$	= pitch damping derivative, $\text{rad}^{-1}$
$C_{m_a}$	= static stability derivative, $\text{rad}^{-1}$
$C_{m_e}$	= pitch control derivative, $\text{rad}^{-1}$
$\bar{c}$	= mean aerodynamic chord, m
$h_c$	= location of c.g., fraction of $\bar{c}$
$h_n$	= location of neutral point, fraction of $\bar{c}$
$I_y$	= moment of inertia about pitch axis, $\text{kg}\cdot\text{m}^2$
$L$	= lift force, N
$M$	= pitching moment, N-m
$q$	= body axis pitch rate, deg/s or rad/s
$\bar{q}$	= freestream dynamic pressure, $\text{N/m}^2$
$S$	= wing reference area, $\text{m}^2$
$SM$	= static margin, $h_n - h_c$
$V$	= freestream velocity, m/s
$\alpha$	= angle of attack, deg or rad
$\delta_e$	= elevon deflection, trailing edge down from datum is positive, deg or rad
$\theta$	= pitch attitude, deg or rad

## I. Introduction

STUDY of stability and control characteristics of an aircraft configuration is part of the design process and includes static trim, static stability, dynamic stability, and responses. Static aerodynamic force and moment data are required to determine trim and static stability. Dynamic stability derivative data are required to determine the dynamic stability and response characteristics.

During preliminary design, both static aerodynamic data and dynamic stability derivative data are estimated using analytical expressions and empirical methods based on experimental database.<sup>1</sup> Once the configuration is frozen, aerodynamic force and moment data are generated from static wind-tunnel tests. Dynamic stability derivatives are obtained from force and mo-

ment data on models subjected to free or forced oscillations in a wind tunnel using derivative rigs.<sup>2</sup>

Dynamic wind-tunnel simulation is an alternative technique for determining stability derivatives.<sup>3–8</sup> This technique relies on conducting flight-test-like experiments in a wind tunnel using dynamically scaled models. The models have rotary and translational degree of freedom (DOF) or only rotary DOF and are equipped with servocontrolled surfaces to excite the model just as in real flight. Miniature incidence, angular rate, and acceleration sensors pick up the dynamic response of the model. The model motion responses to specific control inputs are generated. From these measured responses stability derivatives are estimated using parameter estimation techniques.

The measurement of aerodynamic forces on a model in the dynamic wind-tunnel simulation for estimating stability derivatives has not been reported in the literature. The combined measurement of aerodynamic force and motion responses significantly enhances the capability of dynamic wind-tunnel simulation and comprehensive aerodynamic data can be generated. This article presents such a dynamic wind-tunnel simulation experiment and demonstrates its utility by determining the longitudinal stability and response characteristics of a generic delta wing aircraft model with pitch DOF.

## II. Novel Dynamic Wind-Tunnel Simulation

At the Flight Mechanics and Control Division of the National Aerospace Laboratories, India, dynamic wind-tunnel simulation with only rotary DOF has been used to estimate dynamic stability derivatives.<sup>7,8</sup> The advantage of having only rotary DOF is the simplicity of the model mount in the form of a gimbal and the absence of any cable or heave travel mechanisms.

Using single DOF experiments important dynamic stability and damping derivatives are estimated.<sup>8</sup> With pitch DOF the model response to pitch control surface input is generated and static stability and pitch damping derivatives estimated. By repeating the experiment at three c.g. locations, the neutral point is deduced as the static stability varies linearly with c.g. Similarly, from roll and yaw DOF experiments, roll and yaw damping derivatives are estimated, respectively.<sup>8</sup> However, with rotary DOF only moment derivatives can be estimated.

The scope of dynamic wind-tunnel simulation with rotary DOF can be enhanced by measuring aerodynamic forces in addition to motion variables. In case of a model with pitch DOF, measurement of lift enables the estimation of lift derivatives. In dynamic wind-tunnel simulation, trim lift can be

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measured directly as the model is trimmed at a reference angle of attack using servodriven pitch control surface. As  $C_{L_a}$  and  $C_{m_a}$  can be estimated at each trim angle of attack, the neutral point can be deduced from tests at a single c.g. location instead of tests at a minimum of three c.g. locations when the lift data are not available.

As the lift is measured directly, large-amplitude responses covering the nonlinear high-angles-of-attack regime beyond stall can be easily generated. While lift time histories are measured directly, pitching moment can be computed from pitch attitude responses. Conventionally, these responses are generated in large-amplitude rigs where the complete model is forced by a drive mechanism to undergo large-amplitude excursions in the wind tunnel, and the aerodynamic forces and moments acting on the model are measured.<sup>9–11</sup>

The large-amplitude longitudinal responses generated using dynamic wind-tunnel simulation are more realistic for the following reasons:

- 1) The model is initially trimmed at a reference angle of attack.
- 2) For a tailless configuration like a delta wing, the pitch control surface forms an appreciable part of the wing and its deflection influences the wing load distribution.
- 3) The response is generated by moving the control surface.
- 4) As the model is excited aerodynamically using the control surface, aerodynamic lag associated with it is taken care of in the dynamic simulation.

Thus, in a single experimental setup, comprehensive longitudinal aerodynamic data in the form of trim lift characteristics, dynamic stability derivatives, neutral point, and large-amplitude lift and pitching moment responses can be generated. Conventionally, three different facilities are required to generate the same data.

### III. Model and Instrumentation

The model chosen for demonstrating the method is a generic delta wing aircraft configuration adopted from a delta wing–body configuration for which extensive static test data are available.<sup>12</sup> The wing is a delta planform of aspect ratio 2.31 and has a leading-edge sweep of 60 deg. Both leading and trailing edges are beveled. Fuselage is a cylindrical body with an ogive nose. The model has elevons for pitch control. Figure 1 shows the geometrical details of the model. The elevons have a travel of  $\pm 30$  deg and are driven by a high-torque miniature radio-controlled (R/C) servo. The model is fabricated using plywood and balsa sheet to make it lightweight and its pitch inertia representative of the dynamic scaling of a combat aircraft. The reference dimensions and pitch inertia of the model are given in Table 1.

A single-axis gimbal fixed to the model allows a pitch travel of 0–60 deg or  $\pm 30$  deg. Precision ball bearings are used to

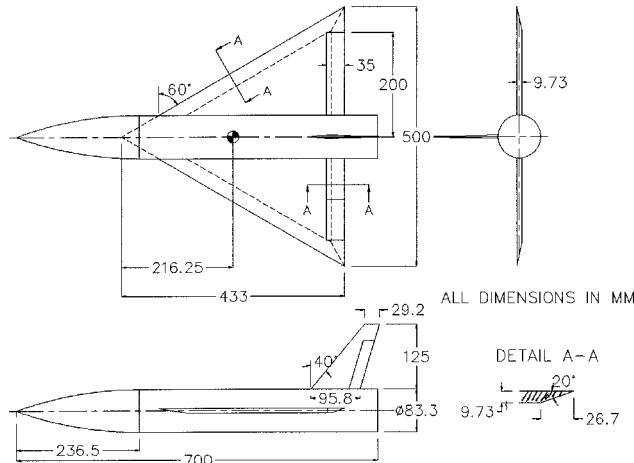


Fig. 1 Geometric details of the generic aircraft model.

Table 1 Reference parameters of the model

Mean aerodynamic chord, 0.289 m
Wing reference area, 0.1084 m <sup>2</sup>
Pitch inertia of the model, 0.03754 kg·m <sup>2</sup>

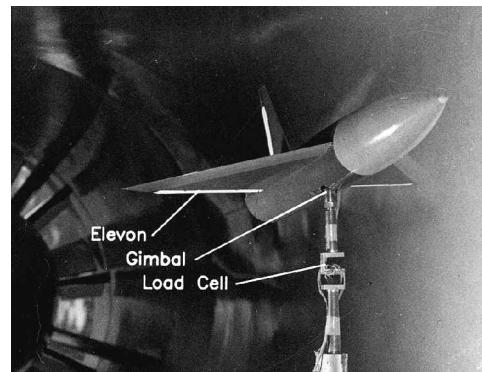


Fig. 2 Generic aircraft model in the wind tunnel.

minimize gimbal friction. The model is balanced to locate its c.g. at the center of the gimbal axes, which is chosen at 0.25c. The model with gimbal is fixed to the vertical strut located at the center of the tunnel test section. A precision continuous-type conductive plastic potentiometer mounted to the gimbal measures pitch attitude. Lift is measured using a load cell fixed to the vertical support strut. The load cell measures the total force acting along the strut and is designed to minimize the effect of side loads on the measurement.

The load cell output is amplified using a bridge amplifier. During wind OFF and wind ON, the load cell measures the model weight and the difference between lift and model weight, respectively. The elevon deflection is measured by the feedback potentiometer in the R/C servo. The model input/outputs are acquired on a personal computer using a 12-bit A/D conversion card at a sampling rate of 80/s. The sensors are precisely calibrated prior to wind-tunnel tests.

To minimize the aerodynamic interference of the load cell and the support strut, they are covered by an aerofoil-shaped glove. Figure 2 shows the model in the wind tunnel with the glove removed. Elevon inputs are generated on the personal computer and fed to the R/C servo. The two inputs used are the doublet and the step. The doublet is a pulse followed immediately by another pulse of the same amplitude, but of opposite polarity. It is easy to generate and has energy spread over a larger bandwidth as compared to the step. Further, as the control surface returns to the datum, steady-state trim is not altered. The doublet is ideally suitable for generating responses for parameter identification.<sup>13</sup> In the present experiments the elevon doublet is used to generate responses for estimating stability derivatives. The step elevon input is used for generating large-amplitude pitch responses.

In a preliminary experiment, pitch rate and pitch acceleration were measured using a rate gyro and an accelerometer mounted inside the model. The measured pitch rate and pitch acceleration were compared with that derived by numerical differentiation and filtering of the pitch attitude response. As the comparison was good, establishing the adequacy of pitch attitude measurement, pitch rate, and pitch acceleration sensors was dispensed with. This makes the model lighter and the instrumentation simpler. The three measurements made in the present experiments are the elevon input, pitch attitude, and the lift.

### IV. Dynamic Wind-Tunnel Simulation Tests

Dynamic wind-tunnel simulation is conducted in the low-speed dynamic wind tunnel of the Flight Mechanics and Con-

trol Division, National Aerospace Laboratories. This is an open-circuit-induced draught-type tunnel with  $1.2 \times 1.2$  m test section and a variable speed capability of 20–45 m/s. The present tests are conducted at a tunnel speed of 21.5 m/s corresponding to a dynamic pressure of  $245 \text{ N/m}^2$ . The test Reynolds number is  $0.42 \times 10^6$  based on  $\bar{c}$ .

For generating the basic lift characteristics of the configuration, the elevons are fixed at 0 deg and the model pitch attitude is set to different values in the range 0–45 deg, and in each case the lift on the model is measured.

With pitch DOF, the model is trimmed at several angles of attack up to 40 deg by operating the elevon. In the range 0–20 deg, at each trim angle of attack, the model is excited by an elevon doublet input and its response is acquired. The typical data length is of a 12.5-s duration corresponding to 1000 samples.

To generate large-amplitude responses, the model is trimmed at a reference angle of attack and excited by a step elevon input. To study the effect of input amplitude, the model is excited by elevon steps of varying amplitude and its responses obtained.

Lift is deduced from the load cell output by subtracting wind off tare and  $C_L$  is computed by nondimensionalizing it. The pitching moment coefficient is computed using the relation

$$C_m = \frac{I_y}{\bar{q} \cdot S \cdot \bar{c}} \cdot \ddot{\theta} \quad (1)$$

## V. Analysis and Discussion of Results

Figure 3 shows the lift characteristics of the model. For comparison, lift data of the 60-deg delta wing–body from Ref. 12 are shown. The match is good up to an angle of attack of 24 deg. At larger angles of attack the present data show a similar trend, but the values are lower. Note that the model test Reynolds number, the model mount, and blockage are different for the two cases. In addition, the high-angle-of-attack lift data for the delta wing–body have been corrected for support interference.<sup>12</sup> Interference corrections have not been applied to the present data.

Figure 4 shows the plot of trim lift coefficient obtained as a function of angle of attack. The basic lift characteristic of the model is also plotted. Because of elevon deflection for trim, trim lift is different. At low angles of attack it is higher than the untrimmed lift, mainly because of the positive deflection of the elevon for trim, which is necessitated by the positive pitching moment of this configuration at zero angle of attack.<sup>12</sup>

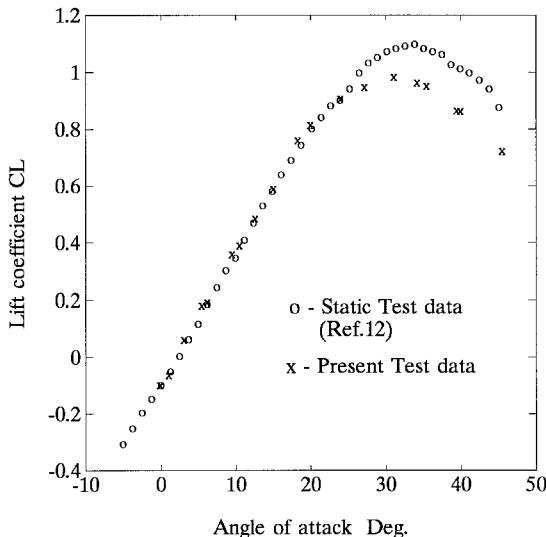


Fig. 3 Lift characteristics of the generic aircraft model.

The wind-tunnel model with pitch DOF is modeled as a linear time-invariant system. This state-space model is valid for linear lift range and is based on quasisteady flow assumption. The model input is  $\delta_e$  and its state variables are  $\theta$  and  $q$ . The measurements are  $q$ ,  $q$ ,  $\theta$ , and  $C_L$ . In the present experiments  $\theta$  is the same as  $\alpha$ .

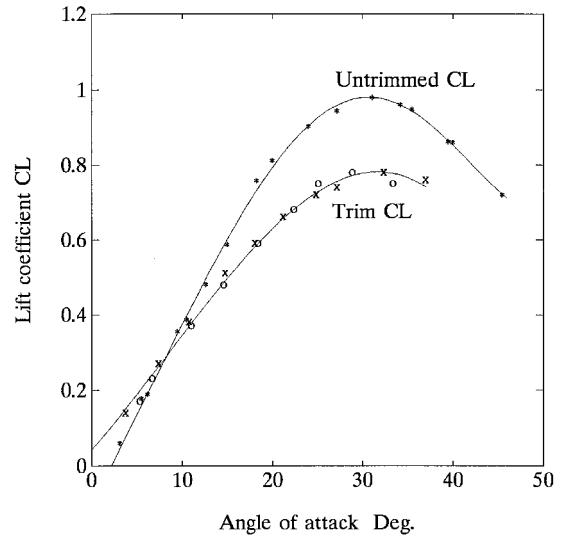


Fig. 4 Trim lift characteristics of the generic aircraft model.

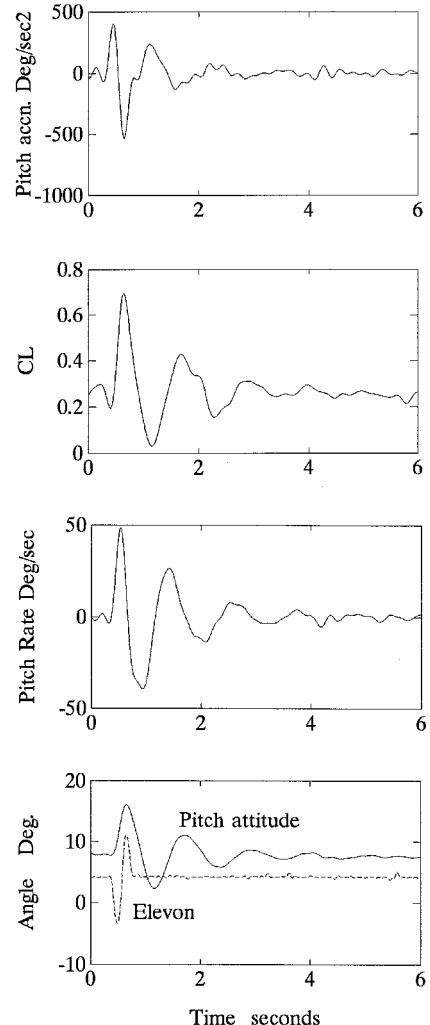
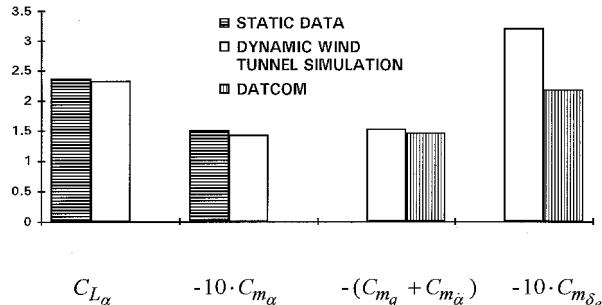
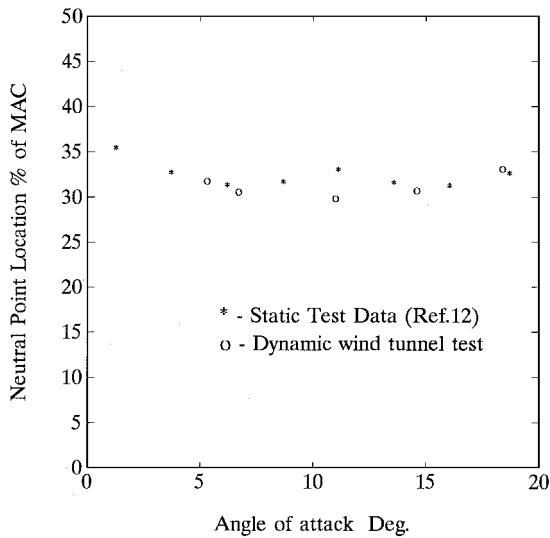


Fig. 5 Response of generic aircraft model to an elevon doublet.

**Table 2** Estimated longitudinal derivatives

Trim angle of attack, deg	Trim elevon, deg	$C_{L_\alpha}$ , rad $^{-1}$	$C_{m_\alpha}$ , rad $^{-1}$	$C_{m_q} + C_{m_\alpha}$ , rad $^{-1}$	$C_{m_{\delta_e}}$ , rad $^{-1}$
5.3	6.14	2.42	-0.181	-1.27	-0.284
6.7	5.54	2.31	-0.142	-1.52	-0.317
11.0	4.00	2.18	-0.116	-1.72	-0.413
14.6	3.10	2.25	-0.141	-1.89	-0.410
18.4	1.96	1.91	-0.171	-1.82	-0.351

**Fig. 6** Comparison of estimated derivatives with static test data and Datcom estimates. (Angle of attack = 6.7 deg.)**Fig. 7** Variation of neutral point with angle of attack.

The state-space equations are given by

$$\begin{bmatrix} q \\ \theta \end{bmatrix} = \begin{bmatrix} (M_q + M_\alpha) & M_\alpha \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} q \\ \theta \end{bmatrix} + \begin{bmatrix} M_{\delta_e} \\ 0 \end{bmatrix} \cdot \delta_e \quad (2)$$

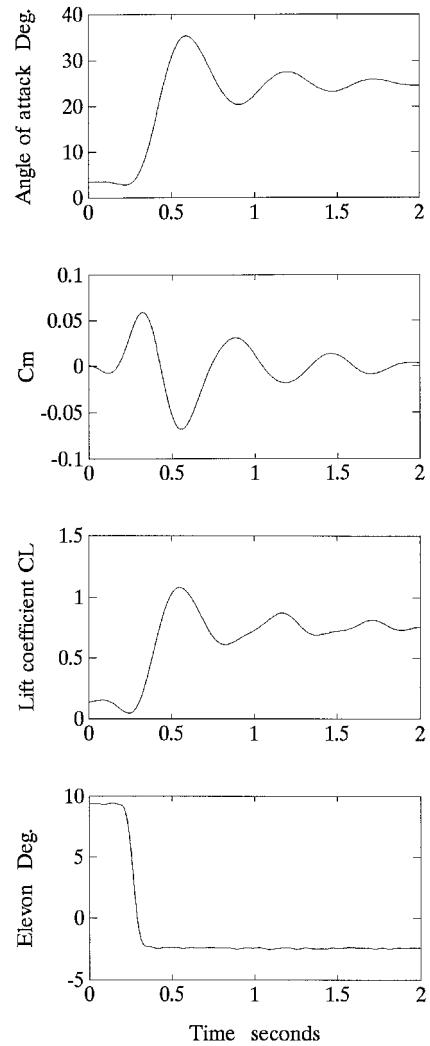
$$\begin{bmatrix} q \\ q \\ \theta \\ C_L \end{bmatrix} = \begin{bmatrix} (M_q + M_\alpha) & M_\alpha \\ 1 & 0 \\ 0 & 1 \\ C_{L_\alpha} \cdot \bar{c}/2V & C_{L_\alpha} \end{bmatrix} \cdot \begin{bmatrix} q \\ \theta \end{bmatrix} + \begin{bmatrix} M_{\delta_e} \\ 0 \\ 0 \\ C_{L_{\delta_e}} \end{bmatrix} \cdot \delta_e \quad (3)$$

where

$$M_\alpha = \frac{C_{m_\alpha} \cdot \bar{q} \cdot S \cdot \bar{c}}{I_y}, \quad (M_q + M_\alpha) = \frac{(C_{m_q} + C_{m_\alpha}) \cdot \bar{q} \cdot S \cdot \bar{c}^2}{I_y \cdot 2 \cdot V} \quad (4)$$

$$M_{\delta_e} = \frac{C_{m_{\delta_e}} \cdot \bar{q} \cdot S \cdot \bar{c}}{I_y}$$

Figure 5 shows a typical response of the model to an elevon doublet input. The elevon doublet is shown along with the

**Fig. 8** Large-amplitude response of the generic aircraft model to an elevon step.

model pitch response. Pitch rate and pitch acceleration shown are derived from pitch attitude measurement by numerical differentiation and filtering.

The parameters of this state-space model are estimated using the maximum-likelihood estimation (MLE) procedure.<sup>14</sup> The nondimensional derivatives are obtained from the model parameters using Eq. (4). The estimated derivatives are given in Table 2. The static derivatives  $C_{L_\alpha}$  and  $C_{m_\alpha}$  are compared with static data.<sup>12</sup> As  $C_{m_q} + C_{m_\alpha}$  and  $C_{m_{\delta_e}}$  data were not available for comparison, the same were estimated using Datcom.<sup>1</sup> These comparisons are shown in Fig. 6. Dynamic wind-tunnel simulation results are in close agreement with static data and Datcom estimates except for pitch-control effectiveness. The discrepancy in  $C_{m_{\delta_e}}$  is attributed to the inaccuracy in the elevon deflection measurement.

From  $C_{L_\alpha}$  and  $C_{m_\alpha}$  the static margin and neutral point are computed using the relation

$$SM = (h_n - h_c) = -C_{m_\alpha}/C_{L_\alpha}, \quad \therefore h_n = h_c - C_{m_\alpha}/C_{L_\alpha} \quad (5)$$

The neutral point location obtained using the previous equation is shown in Fig. 7 as a function of angle of attack. The neutral point data from Ref. 12 are also plotted for comparison. It is seen that the comparison is good.

Figure 8 shows the model response to a large-amplitude elevon step input. The effect of deflecting the elevon can be clearly seen in the beginning of the response where the lift

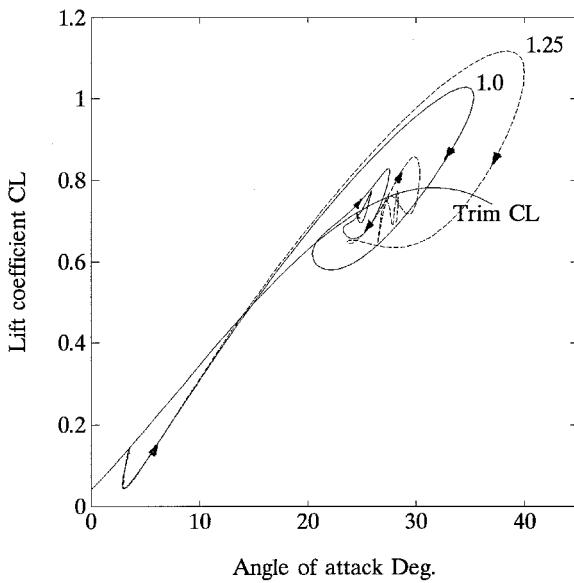


Fig. 9 Large-amplitude lift responses.

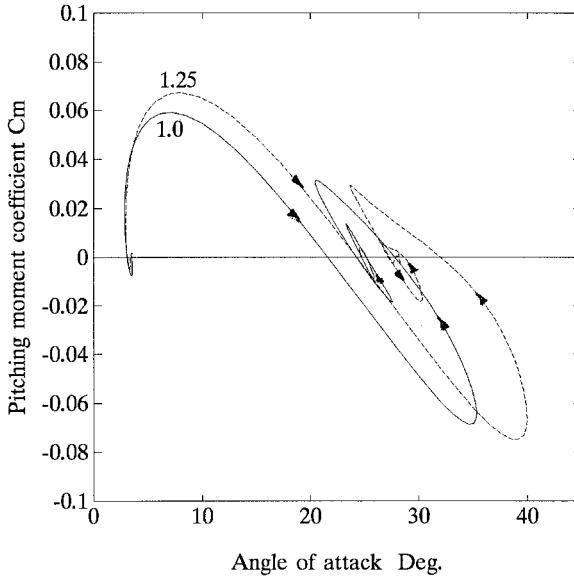


Fig. 10 Large-amplitude pitching moment responses.

first decreases because of the decrease in elevon deflection before building up with an increase in angle of attack.

Figures 9 and 10 show the cross plots of  $C_L$  and  $C_m$ , respectively, with angle of attack during a step elevon response. The two response curves shown correspond to two elevon steps of different amplitude. The labels 1.0 and 1.25 in both Figs. 9 and 10 indicate the elevon input amplitude with respect to the first elevon input, which is taken as one. It can be seen that the dynamic lift attainable is more than the static lift. In Fig. 10 it can be seen that the pitching moment is zero at the beginning and at the end as the model moves from one trim condition to the other, while the angle of attack changes from one trim to the other.

From the cross plots it is seen that the two responses are essentially the same at low angles of attack, but differ appreciably at high angles of attack. This is attributed to flow separation, leading-edge vortex breakdown, aerodynamic lags, and hysteresis. Large-amplitude lift responses show the dynamic lift effects and the lift attainable during high-angle-of-

attack maneuvers beyond stall. These large-amplitude lift and pitching moment responses are useful in aerodynamic modeling at high angles of attack.

## VI. Conclusions

A novel method of generating comprehensive longitudinal aerodynamic data of aircraft configuration using dynamic wind-tunnel simulation has been presented and demonstrated.

The aerodynamic data generated include 1) trim lift characteristics, 2) location of neutral point and its variation with angle of attack, 3) static and dynamic stability derivatives, and 4) dynamic lift and pitching moment response at high angle of attack.

The advantage of this method is that using simple model instrumentation and wind-tunnel tests, all of the previous data are generated in a single experimental setup. It promises to be a cost-effective experimental technique of generating comprehensive aerodynamic data for stability and control studies of aircraft configurations.

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