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Flow Physics Generating Highly Nonlinear Lateral Stability Characteristics of 65-Degree Delta-Wing–Body

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A review of the highly nonlinear effect of roll angle on the measured rolling moment of a 65-deg delta-wing–body model at roll-axis inclinations from σ_0 = 15.5 to 48.4 deg reveals that at $\sigma_0 \leq 25$ deg moderately nonlinear rolling moment characteristics are generated by vortex breakdown starting to occur on the dipping, windward wing-half, whereas at σ_0 >25 deg, more complex, highly nonlinear $C_l(\phi)$ characteristics are produced through the added, rapid movement of vortex breakdown on the lifted, leeward wing-half.

Introduction

TESTS of a 65-deg delta-wing–body configuration[1] (Fig. 1) generated highly nonlinear $C_l(\phi)$ characteristics, which changed dramatically when the inclination of the roll axis was varied from $\sigma_0 = 15.5$ to 48.4 deg (Fig. 2). In the present paper an attempt is made to provide a rational description of the changes in flow physics that should have occurred when σ_0 was varied from $\sigma_0 = 30$ deg, the roll-axis inclination generally used in previous tests.[2,3]

Discussion

At the turbulent test conditions,[1] vortex breakdown did not occur on the delta-wing–body model at $\phi = 0$ until $\alpha \geq 25$ deg (Fig. 3). At $\sigma_0 = 15.5$ deg, where vortex breakdown does not occur on the delta wing, $\phi = 0$ is a stable trim point[4] (Fig. 2). At $\phi \neq 0$ and $19.3 \leq \sigma_0 \leq 25$ deg, the critical state with associated highly nonlinear moment characteristics is caused by vortex breakdown starting to occur on the dipping, windward wing-half, an event that can be expected to be associated with both ϕ and σ_0 hysteresis according to the experience with separated flow in general. According to the experimental results for an 80-deg delta wing,[5] one could also expect a certain degree of unsteadiness.

The $C_l(\phi)$ characteristics in Fig. 2 show that at $\sigma_0 = 19.3$ deg the critical state occurred at $|\phi| \approx 32$ deg, when vortex breakdown started to occur on the dipping, windward wing-half, generating a statically destabilizing, stepwise change of the rolling moment. As the inclination σ_0 of the roll axis was increased to 20.7 and 25 deg, this critical state occurred at lower and lower roll angles. The reason for the absence at $\sigma_0 \leq 16.5$ deg of a critical state, with the associated highly nonlinear, almost discontinuous changes of the rolling moment, is that at $\sigma_0 = 16.5$ deg the roll-induced changes of leading-edge sweep $\Lambda(\phi)$ and angle of attack $\alpha(\phi)$ [Eqs. (1) and (2)] are incompatible with the occurrence of vortex breakdown on the wing:

$$\Lambda(\phi) = \Lambda \pm \Delta\Lambda \tag{1a}$$

$$\Delta\Lambda = \tan^{-1}(\tan\sigma_0 \sin\phi) \tag{1b}$$

$$\alpha(\phi) = \tan^{-1}(\tan\sigma_0 \cos\phi) \tag{2}$$

The minus sign applies to the dipping, windward wing-half.

At $\sigma_0 = 16.5$ deg, Eq. (2) gives for $\phi = 45$ and 60 deg the alpha values $\alpha(\phi) = 11.7$ and 14.4 deg, and for the windward and leeward wing halves, the corresponding lambda values $\Lambda(\phi) = 53.3$ and 50.8 deg, respectively, $\Lambda(\phi) = 76.7$ and 79.2 deg. Even without accounting for the body-induced breakdown delay,[6] one finds that according to the experimental results[7] in Fig. 4, vortex breakdown with associated nonlinear effect on $C_l(\phi)$ could never occur on the delta-wing–body configuration at $\sigma_0 \leq 16.5$ deg. The observed effect of the elastic deflection under load of the thin-plate delta-wing models[7] affected only the data for $\Lambda \geq 70$ deg in Fig. 4.

The $C_l(\phi)$ characteristics in Fig. 2 for $\sigma_0 = 25.9$ and 27.8 deg not only are free of the discontinuous type of nonlinearities usually associated with vortex breakdown but also exhibit a roughly linear variation through $\phi = 0$, with opposite slopes. What can be the explanation? The apparent absence of a critical state at $\sigma_0 = 25.9$ deg (Fig. 2) may be the result of unsteadiness in the movement of vortex breakdown on to the wing, as observed for an 80-deg delta wing.[5] This could result in the measured negligible time-averaged effect on $C_l(\phi)$, explaining the similarity with the experimental results for $\sigma_0 \leq 16.5$ deg. This implies that the time-averaged vortex breakdown at $\xi_{VB} = 0.77$, shown for $\alpha = 26$ deg in Fig. 3, was not measured for the same flow conditions as in Fig. 2. Because the two tests were made in the Subsonic Aerodynamic Research Laboratory wind-tunnel facility, using similar support systems, there was probably no significant difference in ground facility interference. Instead, the reason must be differences in the flow conditions at which the measurements were made, caused by different approaches to the test conditions. In Fig. 3, the measurements were made at $\phi = 0$ for changing angles of attack, whereas in Fig. 2, the test condition was obtained by changing the roll angle at constant σ_0, resulting in a change of the leading-edge sweep for the two wing-halves at a constant inclination of the roll axis, Eq. (1). Thus, the probable reason for the breakdown locations to be different at $\phi = 0$ in Figs. 2 and 3 is the difference in hysteresis effects associated with the different approaches to the test condition $\phi = 0$ at $\sigma_0 = 25.9$ deg.

At $\sigma_0 = 27.8$ deg, vortex breakdown already occurs on the delta wing at $\phi = 0$. If the angle of attack is decreased, vortex breakdown moves rapidly off the delta wing (Figs. 3 and 4). This breakdown movement is very sensitive to a change of roll angle from $\phi = 0$. As Eq. (1) shows, the leading-edge sweep is decreased on the dipping, windward wing-half and increased on the opposite, leeward side. The experimental results[7] in Fig. 4 show that a change of leading-edge sweep would have a very strong effect on the occurrence of vortex breakdown, especially for a 65-deg delta wing. Based on the data[7] in Fig. 4, one expects breakdown to move rapidly off the rising, leeward wing-half and advance somewhat less rapidly on the dipping, windward-half, both events contributing to the measured statically destabilizing data trend at $\sigma_0 = 27.8$ deg in Fig. 2.

What are the flow physics generating the $C_l(\phi)$ characteristics at $28 \leq \sigma_0 \leq 30.7$ deg? The experimental results for a 60-deg delta-wing–body configuration[8] (Fig. 5) provide the answer. The data show clearly that the swirling, helical flowfield downstream of a usually spiral vortex breakdown generates suction on the wing, which, although being of lesser magnitude than the suction generated by

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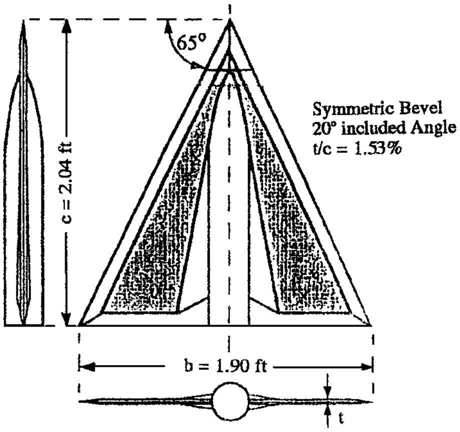


Fig. 1 Model of 65-deg delta-wing–body.

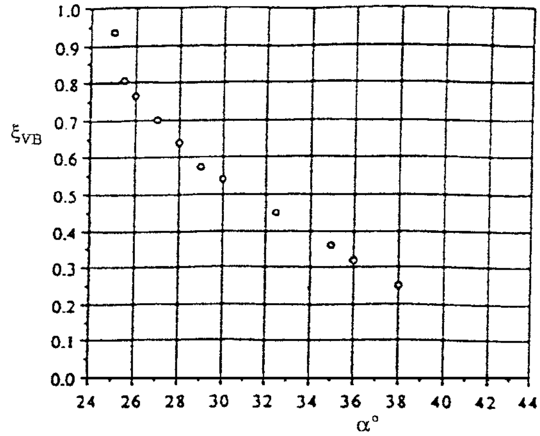


Fig. 3 Measured vortex breakdown location at $\phi = 0$ (Ref. 1).

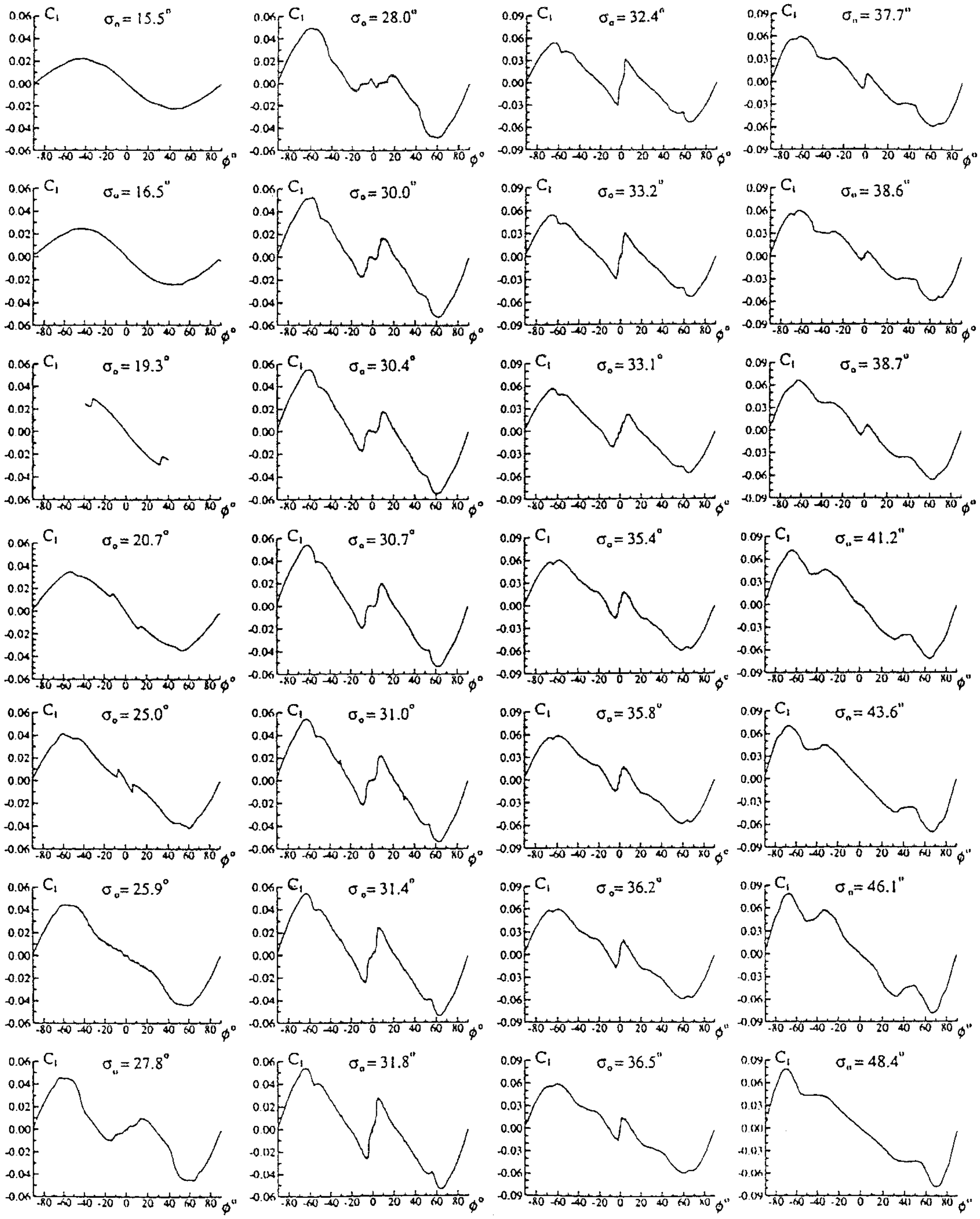


Fig. 2 Measured static rolling moment $C_l(\phi)$ at roll-axis inclinations from $\sigma_0 = 15.5$ to 48.4 deg (Ref. 1).

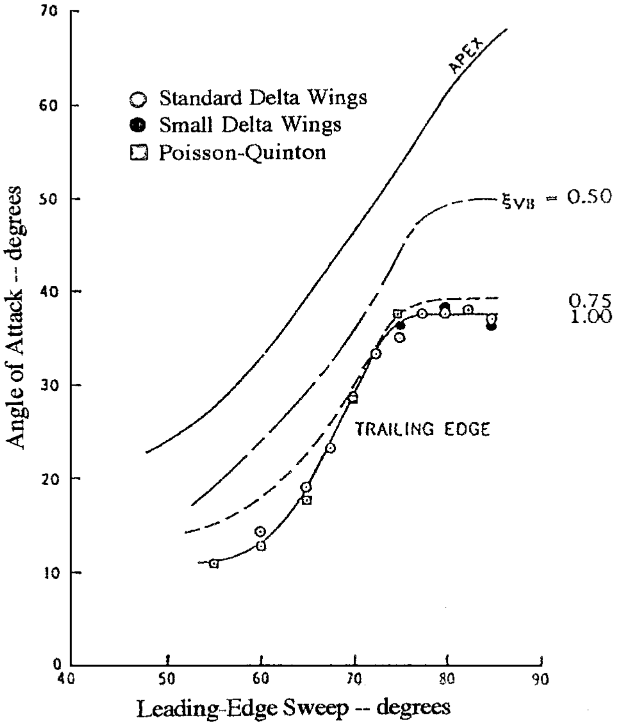
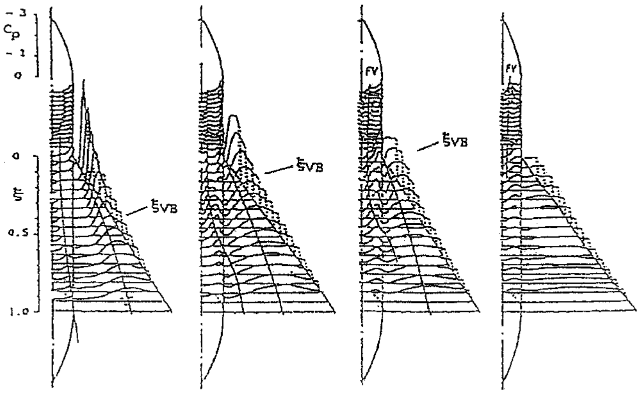


Fig. 4 Effect of leading-edge sweep on starting vortex breakdown.[7]



α = 19.3° α = 29.1° α = 34.1° α = 39.1°

Fig. 5 Suction-side pressure distribution on 60-deg delta-wing–body model at $Re = 1.4 \times 10^6$ (Ref. 8).

the intact vortex upstream of the breakdown, still is significant. Not until the breakdown reaches the apex of the delta wing is the vortex-induced lift lost completely and the classic dead-air region established. The results in Fig. 5 provide the flow-physics information about the complete loading generated by the vortex breakdown that is needed to fully understand the $C_l(\phi)$ characteristics in Fig. 2 for $28 \le \sigma_0 \le 30.7$ deg. Apparently, in that σ_0 range there exists a small angular range around $\phi = 0$ where the positive lift forces generated by the vortex upstream of breakdown and by the downstream swirling flow together compensate for the lift loss generated by the breakdown movement, resulting in the measured, statically stabilizing $C_l(\phi)$ characteristics around $\phi = 0$. Outside of this rather narrow ϕ range, around $\phi = 0$, the effect of the breakdown movement starts to dominate, generating the observed steep, statically destabilizing data trend up to $|\phi| \approx 10$ deg. As σ_0 is increased further, causing the vortex breakdown to advance, the combined lift of the vortex forward of breakdown and the swirling flow downstream of it decreases until at $\sigma_0 > 30.7$ deg the breakdown-induced lift loss dominates, generating a statically destabilizing data trend at $\phi = 0$ that persists until $\sigma_0 \ge 41.2$ deg, where statically stabilizing $C_l(\phi)$ characteristics around $\phi = 0$ are established. Figure 3 shows that at $\alpha > 41.2$ deg the breakdown location approaches $\xi_{VB} \approx 0.16$, where the fuselage no longer separates the two breakdown regions (Fig. 1). It appears from the $C_l(\phi)$ characteristics (Fig. 2) that the mean slope for $|\phi| < 20$ deg remains above a certain level until σ_0 is increased to 48.4 deg, where the slope is decreased significantly as a result of the dead-air region established on the top side.[8] The $C_l(\phi)$ trend at $\phi = 0$ is generated solely by the windward-side attached flow region, producing a statically stabilizing $C_l(\phi)$ trend at $\phi = 0$, that is less steep than before the dead-air region was established, causing the difference in slopes for $\sigma_0 = 46.1$ and 48.4 deg.

Conclusions

An analysis of the highly nonlinear roll-stability characteristics measured on a 65-deg delta-wing–body model at roll-axis inclinations from $\sigma_0 = 15.5$ to 48.4 deg reveals that the generating flow physics can be defined when considering the role played by the swirling flow downstream of the leading-edge vortex breakdown.

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