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Wing Rock Analysis of Slender Delta Wings, Review and Extension

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An analysis of existing experimental results, performed to pinpoint the flow physics of slender wing rock, especially in regard to the roles played by vortex liftoff and vortex breakdown, revealed that the influence of roll-rate-induced conical camber as well as of model support and wind-tunnel wall interference could be surprisingly large.

Nomenclature

b = wingspan
c_0 = wing root chord
f = oscillation frequency
k = reduced frequency, $\omega b/2U_\infty$
l = rolling moment: coefficient $C_l = l/(\rho_\infty U_\infty^2/2)Sb$
N = normal force: coefficient $C_N = N/(\rho_\infty U_\infty^2/2)S$
p = static pressure: coefficient $C_p = (p - p_\infty)/(\rho_\infty U_\infty^2/2)$
S = reference area (projected wing area)
s = wing semispan
t = time
U = horizontal velocity
w = width of test section
x = axial body-fixed coordinate
y = spanwise coordinate
z = out-of-plane deflection of apex, Fig. 17
α = angle of attack
Δ = increment or amplitude
Δt = time lag
ζ = dimensionless z coordinate, z/c_0
η = dimensionless y coordinate, y/s_0
θ_A = apex half angle, $\pi/2 - \Lambda$
Λ = leading-edge sweep
ξ = dimensionless x coordinate, x/c_0
ρ = air density
σ = inclination of the roll axis
ϕ = roll angle
ω = angular frequency, $2\pi f$

Subscripts
A = apex
c = critical
VB = vortex breakdown
0 = mean value
1, 2 = numbering subscripts
∞ = freestream conditions

Differential Symbols
$C_{l\dot{\phi}} = \partial C_l/\partial(b\dot{\phi}/2U_\infty)$
$\dot{\phi}(t) = \partial\phi/\partial t$

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Introduction

SINCE the first publication of the slender wing rock of a sharp-edged 80-deg delta wing[1] (Fig. 1), intensive experimental and theoretical research has provided a gradual improvement of our understanding of the flow physics. This article attempts to review this development and outline our current knowledge of the flow physics of slender wing rock.

Background

Early theoretical efforts attempted to predict the experimental results in Ref. 1 with varying success. A numerical analysis[2] was shown to be able to predict the general wing rock characteristics. In order to match the experimental results[1] a certain magnitude of the bearing friction in the model suspension had to be assumed. A semiempirical prediction method was also developed[3] based upon experimental results. In the numerical method[2] no effects of vortex breakdown were included, although the presence of breakdown during wing rock had been observed experimentally[4] (Fig. 2). In the beginning there was some speculation about the role played by the breakdown phenomenon. However, it could be shown[5] that vortex breakdown had a strongly damping influence and that a flow mechanism that could drive the wing rock was the vortex asymmetry expected to occur on slender delta wings according to Polhamus[6] (Fig. 3). It supplied the aerodynamic spring needed for the oscillatory wing rock motion, and this statically stabilizing effect became dynamically destabilizing because of convective time-lag effects.[5] Using the results in Fig. 3, together with the breakdown results[7] in Fig. 4, which show how the breakdown more or less jumps from the trailing edge to 75% chord on an 80-deg delta wing, an analytic method was developed that could predict the experimentally observed maximum limit-cycle amplitude of the wing rock.[8]

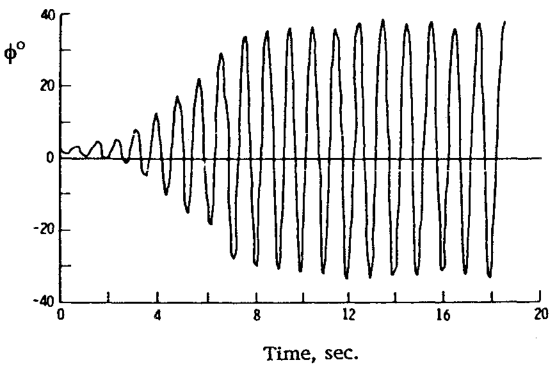

Fig. 1 Time history of wing rock of an 80-deg delta wing at α = 27 deg (Ref. 1).

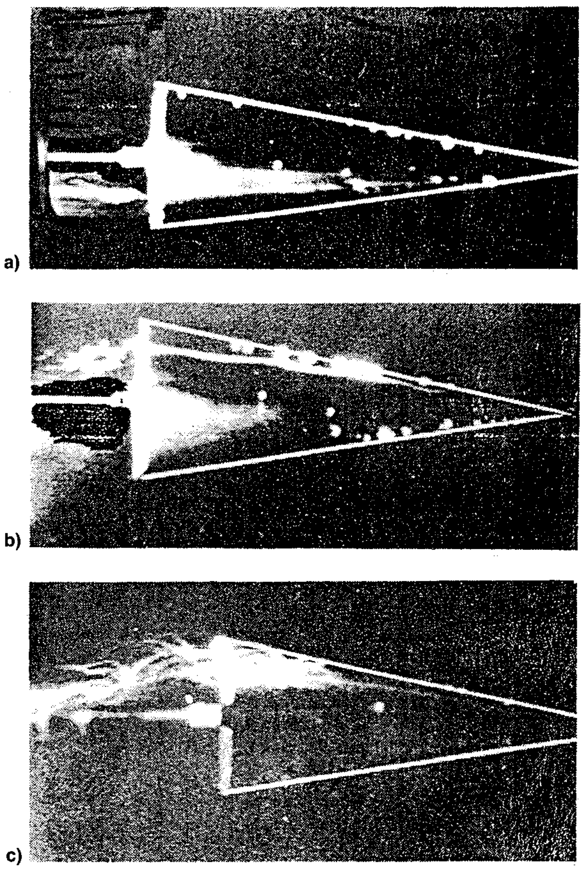

Fig. 2 Vortex bursting during wing rock on an 80-deg delta wing.[4] α = a) 22, b) 25, and c) 32 deg.

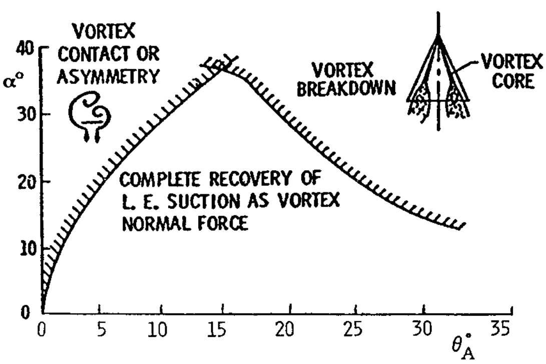

Fig. 3 Leading-edge suction recovery boundaries for delta wings.[6]

Based upon the results[6] in Fig. 3 it was postulated in Ref. 5 that the $\alpha - \theta_A$ dependence of vortex asymmetry constituted the boundary for slender wing rock. The only experimental data[1] available at the time of the analysis[5] showed wing rock of an 80-deg delta wing to start at α = 27 deg, in perfect agreement with the postulated wing rock boundary. Because it had been shown[5] that vortex asymmetry could drive the wing rock and that vortex breakdown would provide roll damping, it was concluded[5] that wing rock would only be possible for $\theta_A < 15$ deg, i.e., $\Lambda > 75$ deg (see Fig. 3). Later experimental results[9,10] have shown both conclusions to be premature (Fig. 5). The figure shows that Werle's boundary for the region of "connected vortices" (Ref. 11) gives an early warning of impending wing rock. It has been shown, both experimentally[1] and theoretically,[12], that an 80-deg delta wing is undamped in roll at $\alpha > 20$ deg for zero sideslip (Fig. 6). The experimental results obtained by using a low friction air-bearing[13] show wing rock of an 80-deg delta wing to start close

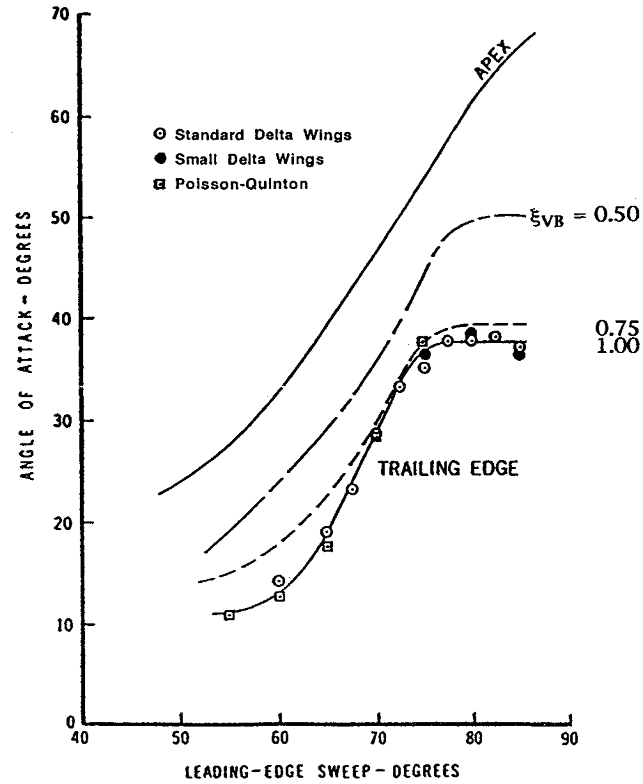

Fig. 4 Effect of leading-edge sweep on vortex breakdown.[7]

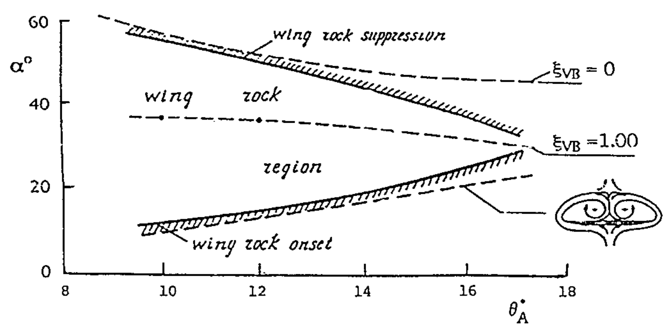

Fig. 5 Wing rock boundaries.[10]

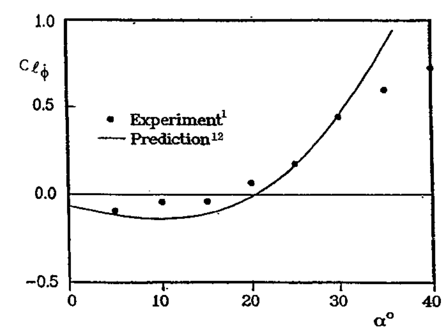

Fig. 6 Roll damping of 80-deg delta wing.

to the angle of attack predicted for zero friction[12,14] (Fig. 7). Water-tunnel tests with a regular bearing[9] gave, as expected, a wing rock boundary somewhat farther away from that for zero friction, but still below the value obtained in wind-tunnel tests with a similar bearing.[1] The fact that the slender delta wing is undamped already for small, finite amplitudes[12,14] (Fig. 6) means that vortex asymmetry is not required in order to start the wing rock, in agreement with the experimental results in Fig. 5. The so-called vortex liftoff, which experiments by

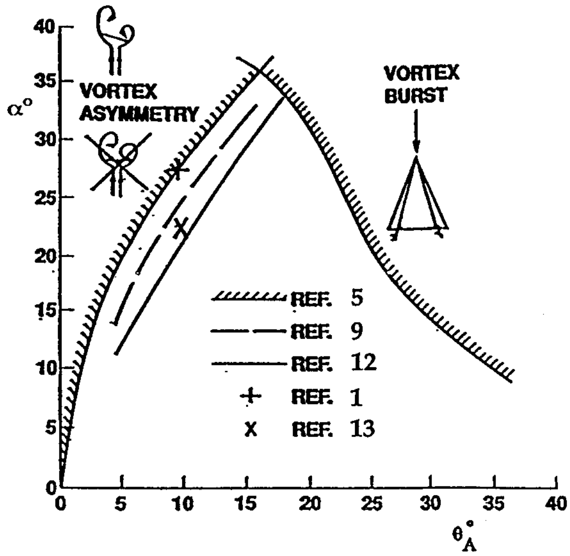

Fig. 7 Revised boundary for wing rock of slender delta wings.[14]

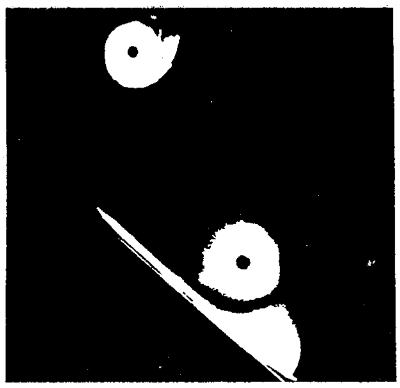

Fig. 8 Static vortex core position above 80-deg delta wing at σ = 35 deg and ϕ = 45 deg (Ref. 16).

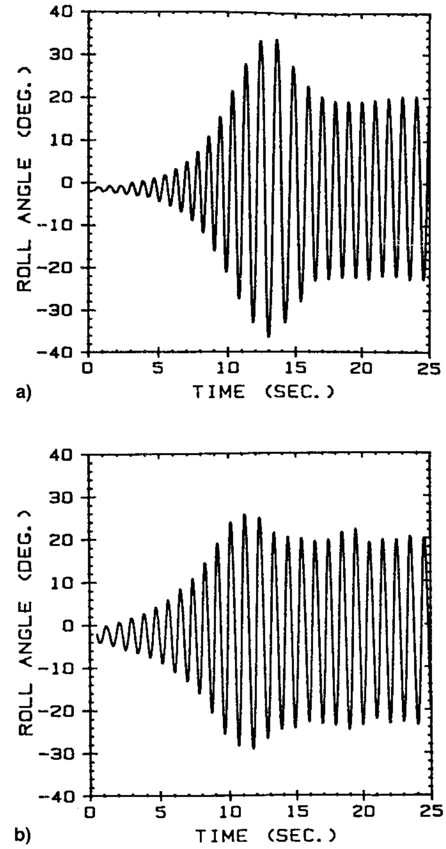

Fig. 9 Wing rock time histories of 80-deg delta wing at σ = 40 deg (Ref. 17): a) without and b) with initial vortex breakdown.

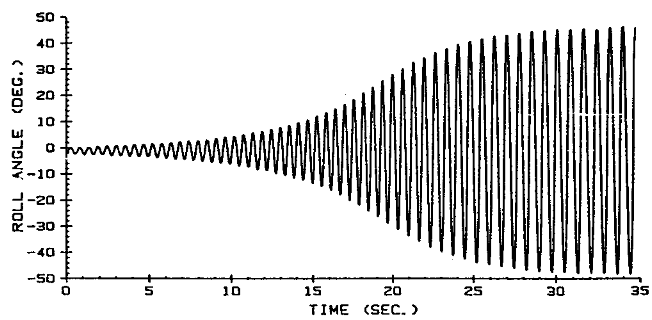

Fig. 10 Wing rock time history of 80-deg delta wing at σ = 30 deg (Ref. 16).

Stahl et al.[15] have shown would not occur at zero roll angle for sharp-edged delta wings, occurs on the leeward wing half at some finite roll angle, as sketched in Fig. 7 and illustrated experimentally[16] in Fig. 8. The predicted wing rock boundary for zero friction[12,14] in Fig. 7 intersects the boundary for starting vortex breakdown on the wing[6] at $\theta_A \approx 18$ deg. That is, one would not expect wing rock to occur on delta wings with less than 72-deg leading-edge sweep. This is in good agreement with the results[10] in Fig. 5.

Analysis

Experimental results for a sharp-edged 80-deg delta wing at α = 40 deg gave two different types of wing rock time histories[17] (Fig. 9). In one case (Fig. 9a), where vortex breakdown did not occur on the wing until some time after the start of the wing rock, the amplitude shot up to $\Delta\phi \approx 35$ deg before settling down to $\Delta\phi \approx 20$ deg. In the other case (Fig. 9b), where breakdown occurred on the wing from the start, only a modest overshoot to $\Delta\phi \approx 25$ deg was recorded before the amplitude reached its final value, $\Delta\phi \approx 20$ deg. These wing rock characteristics are very different from those observed at σ = 30 deg (Ref. 16 and Fig. 10), which were of the same asymptotic type as those observed in earlier tests[1,4] (Fig. 1). The wing rock boundaries in Fig. 7 suggest that the reason for this difference is that at σ = 30 deg the wing rock starts without the presence of vortex breakdown, whereas at σ = 40 deg the breakdown is expected to be present from the start. In order to understand how vortex breakdown in one case could be absent during the buildup to the maximum amplitude (Fig. 9a), it is instructive to consider the results obtained for a 65-deg delta wing describing high-rate/large-amplitude roll oscillations.[18-21]

The static rolling moment of a 65-deg delta wing at 30-deg inclination of the roll axis exhibits highly nonlinear characteristics in the range -10 deg $< \phi <$ 10 deg (Fig. 11). The almost discontinuous Cl change in Fig. 11 is caused by the breakdown of the leading-edge vortices, as illustrated by the insets in Fig. 11. It was found that the presence of critical states[22,23] makes the effect of the roll-rate-induced conical camber[20,21] (Fig. 12) very powerful for certain combinations of angle of attack, roll angle, and roll rate. The camber effect postulated for zero roll angle[21] (Fig. 12) was verified in static tests with a deformed sheet metal model.[24,25] If the suggested static tests[24] at nonzero roll angles had been performed also, they should have verified that the camber effect increases greatly near critical states, such as $\pm\phi_c$ in Fig. 11. Only such a very large roll-rate-induced camber effect can explain the experimental characteristics[18,21] in Fig. 13. For the positive

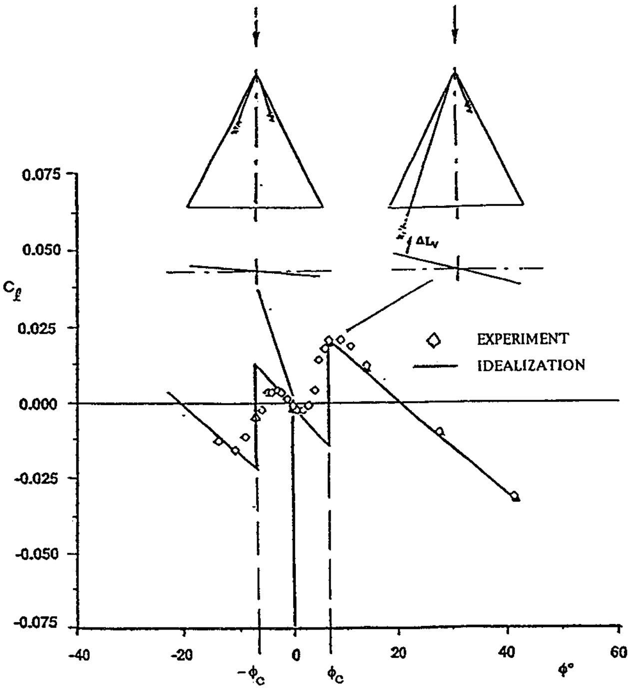

Fig. 11 $C_\ell(\phi)$ characteristics of 65-deg delta wing at α = 30 deg (Ref. 21).

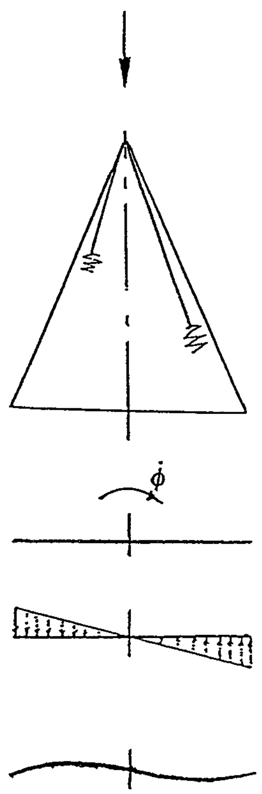

Fig. 12 Roll-rate-induced camber.[20]

roll rate in Fig. 13, the roll-rate-induced camber delays vortex breakdown on the downstroking and promotes it on the upstroking wing half. For $\bar{\dot{\phi}}b/2U_\infty$ = 0.05, the effect was apparently large enough to prevent the breakdown from moving downstream of the trailing edge on the port wing and upstream of it on the starboard wing (see sketches in Fig. 13). This explains why the statically destabilizing $Cl(\phi)$ discontinuities never materialized under the dynamic conditions ($\bar{\dot{\phi}}$ = 0.05).

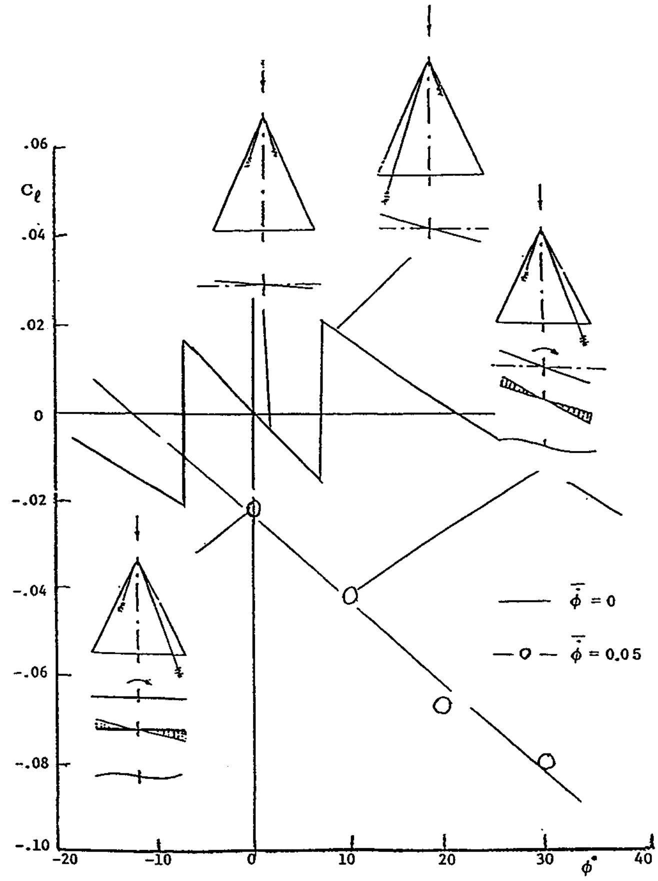

Fig. 13 Effect of positive roll rate on $C_\ell(\phi)$ characteristics of 65-deg delta wing.[21]

In the same manner the roll-rate-induced camber could have delayed the occurrence of vortex breakdown on the rolling 80-deg delta wing in Fig. 9. Other experimental results for an 80-deg delta wing[26] (Fig. 14) provide the explanation for the difference between Figs. 9a and 9b. In accordance with the exhibited α hysteresis in Fig. 14 one expects the rate-induced camber to be able to delay the occurrence of vortex breakdown at a certain location on the wing more if the breakdown initially is located downstream of the trailing edge than if it initially already is located on the wing. However, in both cases, Fig. 9a as well as Fig. 9b, the final result at $t > 15$ s is the same, i.e., wing rock at a limit-cycle amplitude of $\Delta\phi \approx$ 20 deg.

The results[12] in Fig. 15 show that for the downstroking wing half with its steadily decreasing effective sweep angle, the aerodynamics become more and more damped, an effect amplified by the increase of the associated reference area.[27] Thus, a limit cycle amplitude will be reached by the wing-rocking delta wing also in the absence of vortex breakdown, as was observed experimentally[17] ($\Delta\phi \approx$ 35 deg in Fig. 9a).

Judging by the experimental investigation by Weinberg,[28] wind-tunnel wall interference could have contributed to the initial delay of the occurrence of static vortex breakdown in Fig. 9a, before any roll-rate-induced effects could be generated. The wall-induced upwash along the leading edge was shown by Weinberg[28] to generate a positive camber effect that increases with increasing ratio of wingspan b to tunnel width w. His tests showed a very definite delay of vortex breakdown with increasing b/w. In contrast to the delay of vortex breakdown generated by wall interference,[28] breakdown is promoted by the presence of a fuselage.[29,30] Such a delay can be expected to result through the interference effects from the fuselage-like structure often used to support the model in

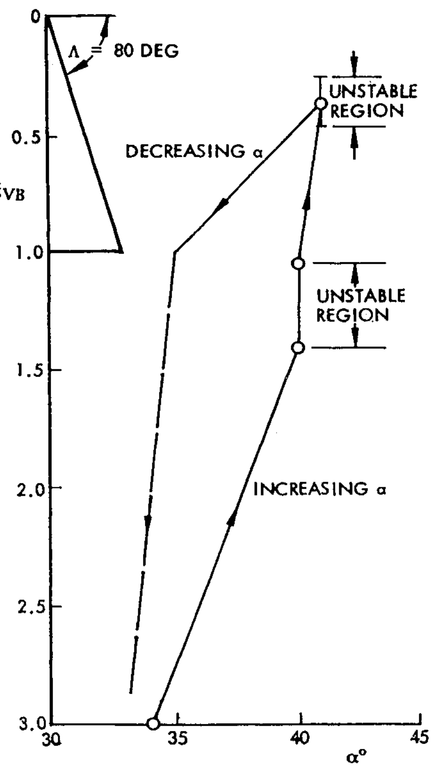

Fig. 14 Hysteresis effects on vortex breakdown for an 80-deg delta wing.[26]

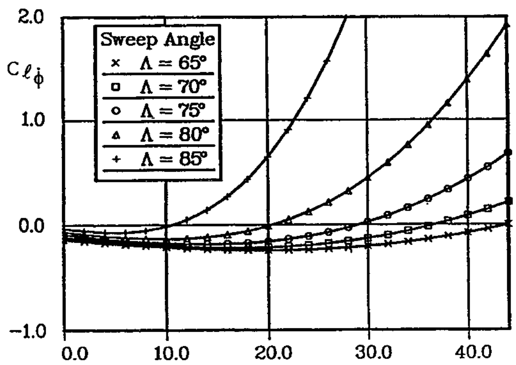

Fig. 15 Effect of leading-edge sweep on delta wing roll damping.[12]

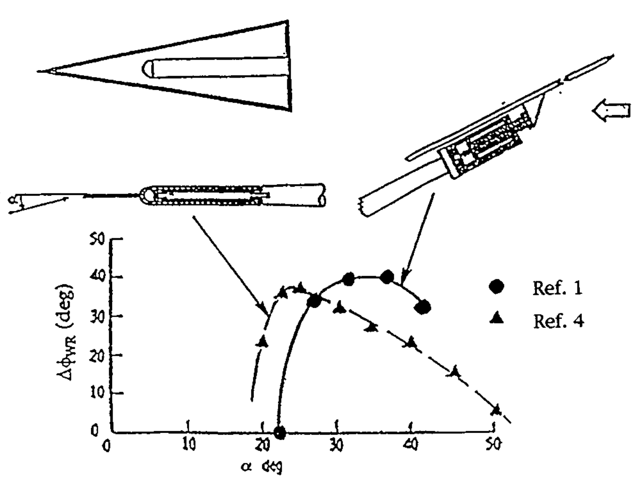

Fig. 16 Effect of centerbody extent on the wing rock of an 80-deg delta wing.

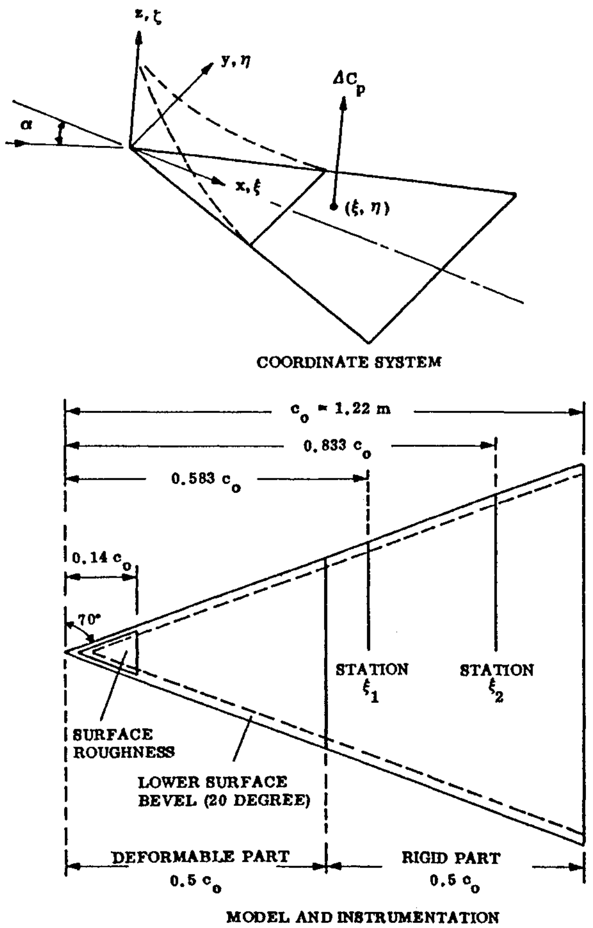

Fig. 17 Bending deformation of 70-deg delta wing.[32]

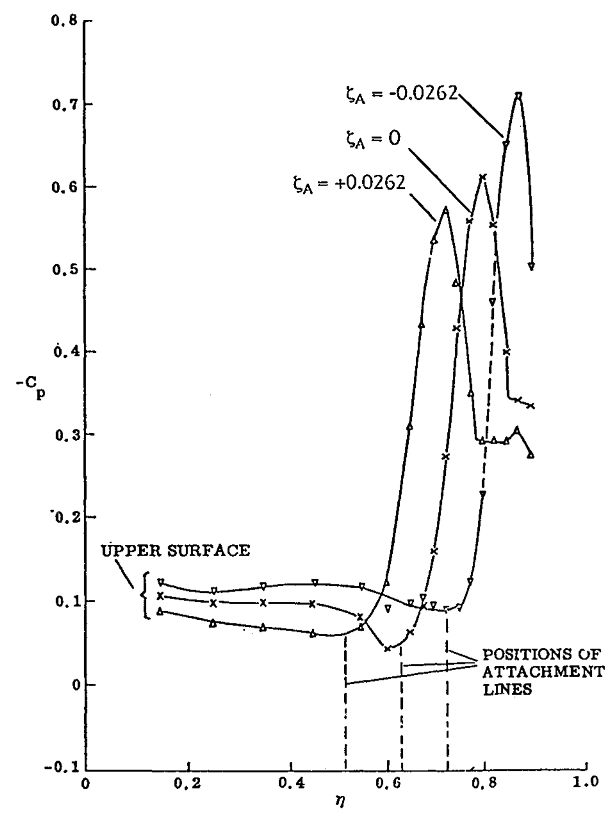

Fig. 18 Spanwise pressure distribution at $\xi_1 = 0.583$ for static deformation of a 70-deg delta wing.[32]

wind-tunnel tests. It can be shown[31] that such interference is the likely reason for the early appearance of breakdown in the test performed by Levin and Katz[4] with a center body extending from $\xi \approx 0.40$ to $\xi = 1.00$, resulting in a smaller limit-cycle amplitude than in the test performed by Nguyen et al.[1] with a model on which the fuselage-like structure had very limited extent upstream of the trailing edge (Fig. 16).

Even in the absence of vortex breakdown the roll-rate-induced camber effect[21,24] has to be included in the prediction, as is indicated by experimental results[32] (Figs. 17 and 18). The static results in Fig. 18, which could represent the dynamically equivalent steady results for a pitching delta wing, have to be modified to account for time-history effects, although these effects will be much less dramatic than in the case of the unsteady effects of vortex breakdown.[33,34]

Conclusions

A critical review of existing experimental results has led to the following conclusions in regard to the flow physics of slender wing rock.

1) Although vortex liftoff does not initiate slender wing rock, it plays an important role in producing the maximum wing rock amplitude.

2) Although the limit-cycle motion can be established in the absence of vortex breakdown, vortex breakdown plays an essential role in limiting the magnitude of the maximum limit-cycle amplitude.

3) Experimental results for slender wing rock are very sensitive to the effects of support and wind-tunnel wall interference, especially in the high-alpha region where the wing rock amplitude reaches maximum.

4) Roll-rate-induced camber effects can play an important role in the high-alpha region, especially when vortex breakdown is the flow mechanism limiting the amplitude buildup.

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