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Ground Facility Interference Effects on Slender Vehicle Unsteady Aerodynamics

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A critical examination of recent dynamic test results obtained at high angles of attack reveals that various kinds of ground facility interference effects can distort the measurements. Particular problems are posed by both asymmetric and symmetric support structures. It is also found that the fuselage-like structures commonly used to attach a sting or strut to the model can cause unacceptable distortion of the high-alpha steady and unsteady aerodynamic characteristics.

Nomenclature

b = wingspan
c = wing root chord
D = maximum body diameter
f = oscillation frequency
k = reduced frequency, $\omega b/2U_\infty$
L = body length
l = rolling moment coefficient, $C_l = (\rho_\infty U_\infty^2/2)Sb$
m = pitching moment coefficient, $C_m = (\rho_\infty U_\infty^2/2)Sc$
N = normal force coefficient, $C_N = (\rho_\infty U_\infty^2/2)S$
n = yawing moment coefficient, $C_n = (\rho_\infty U_\infty^2/2)Sb$
p = static pressure coefficient, $C_p = (p - p_\infty)/(\rho_\infty U_\infty^2/2)$
S = reference area, projected wing area
s = local half-span
t = time
U = horizontal velocity
w = width of test section
x = axial body-fixed coordinate
y = spanwise body-fixed coordinate
α = angle of attack
β = angle of sideslip
Δ = increment or amplitude
η = dimensionless y coordinate, y/s
Λ = leading-edge sweep angle
ξ = dimensionless x coordinate, x/c
ρ = air density
ϕ = roll angle
ψ = coning angle
Ω = dimensionless coning rate, $\dot{\psi}b/2U_\infty$; $\dot{\psi}l/2U_\infty$ for body alone
ω = angular frequency, $2\pi f$
$\bar{\omega}$ = reduced frequency, $\omega c/U_\infty$

Subscripts
A = apex
B = vortex breakdown
V = vortex
∞ = freestream conditions

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

Introduction

IT is generally recognized that the presence of support struts can introduce appreciable support interference. Numerous publications have detailed the effects of both windward[1,2] and leeward[3,4] side support struts on the static aerodynamic characteristics of flight vehicles. Unlike the case with static aerodynamic measurements, the effects of support interference in dynamic tests cannot simply be calibrated out. The experimental determination of wind-tunnel dynamic data can be seriously compromised by support interference, motion coupling, and Reynolds number deficiencies.[5–11] In spite of the progress made in the understanding of the underlying flow physics, facility interference effects continue to plague high-alpha measurements in dynamic wind-tunnel tests. The problem becomes especially difficult when coupling between support and wall interference is present.[9–11]

That the problem of support interference becomes much more difficult in the case of a symmetric support, with the sting offset in the plane of the total angle of attack, than in the case of an asymmetric support[10,11] is not well recognized. The complication arises because the effects of a symmetric support are not readily apparent, contrary to the case for asymmetric support interference, where the effect is easily revealed by asymmetry in aerodynamic characteristics that are expected to be symmetric.[9–13]

In addition to the type of symmetric support interference prevalent in rotary balance tests[7–9] and in oscillatory experiments,[11,13] the interference associated with the fuselage-like structures commonly used to attach a sting or strut to the underside of flat-plate wings can under certain conditions severely distort the high-alpha steady and unsteady aerodynamic characteristics. When distortion caused by the proximity of tunnel walls[14] is present, the support and wall interference effects are inevitably coupled,[9–11] resulting in what is herein referred to as facility interference. Various examples will be presented to illustrate the influence of ground facility interference on dynamic experimental results.

Asymmetric vs Symmetric Supports

As already mentioned, an advantage of sorts with an asymmetric support is that a deviation from the expected symmetric

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aerodynamic characteristics immediately alerts the test engineer of the presence of support interference. In contrast, symmetric support effects, although equally important, may not be readily detectable. Significant differences are found in the pitching moment at medium and high angles of attack; between the aerodynamic characteristics obtained for the AGARD WG16A model on a windward strut support[15] and those measured on sting supports.[16] The strut-induced increase of the adversity of the pressure gradient at the trailing edge resulted in a nose-up pitching moment increment at $20 < \alpha < 32$ deg (Fig. 1).

The support system shown in Fig. 2 was used in a recent water-tunnel investigation of dynamic vortex breakdown on sharp-edged delta wings.[17] The model was connected to a support that extended horizontally from a vertical turntable. That is, the support was asymmetric, causing interference similar to that observed in rolling tests[18] of a 65-deg delta wing[10] (Fig. 3). In the absence of asymmetric support interference the left- and right-hand loops would be of the same shape and size. That the support in Fig. 2 did indeed produce significant flow asymmetry is confirmed by the conclusions in Ref. 17 that "As expected, wing, body, and wing-body vortex bursting were invariably asymmetric." Whereas, it is true that body vortices, with or without the occurrence of vortex burst, are invariably asymmetric at high angles of attack,[19] asymmetric vortex burst has not been observed on 60- and 70-deg delta wings for symmetric flow conditions.

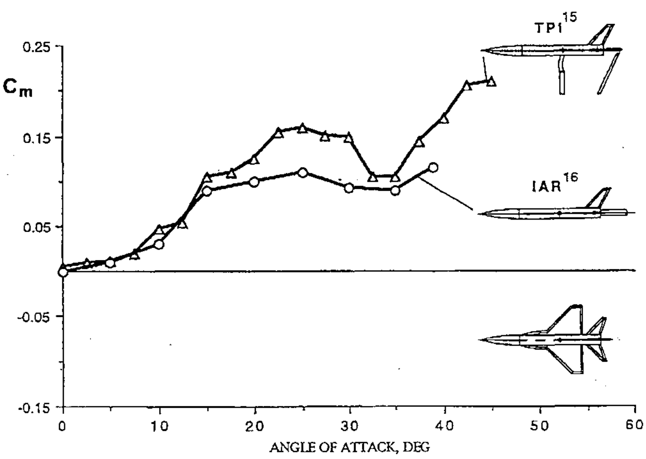

Fig. 1 Strut-induced support interference.

Rotary Balance Data

The problem of rotary rig support interference was first brought to the attention of the technical community by Malcolm[20] and O'Leary[21] through their careful experiments with alternative support structures. Although the rotary balance support is geometrically symmetric, the rotational flowfield causes the interference effects to be asymmetric. That it is difficult to become aware of the presence of the interference caused by a symmetric support is illustrated by the rotary balance results[21] in Fig. 4. In the case of $\alpha = 50$ deg, e.g., the effect of the dummy strut was insignificant. This should not be misinterpreted to signify that the interference from the main support is also insignificant. A more plausible explanation is that at $\alpha = 50$ deg the interference of the basic support was so large that the presence of the dummy strut caused no measurable change.[8] The results for $\alpha = 40$ and 60 deg not only show an effect of the dummy strut, but through the different effects on roll and yaw characteristics also give an indication of the complexity of the interference.[6-10] A true evaluation of the support interference is possible through the

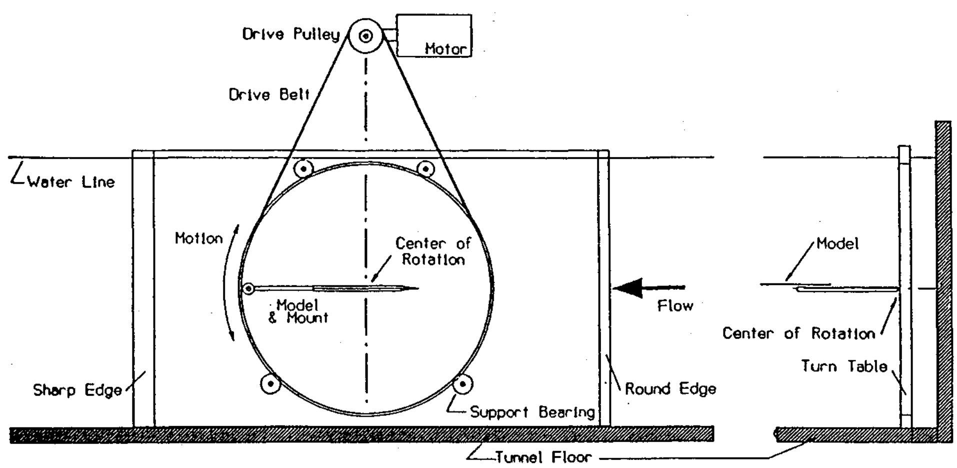

Fig. 2 Asymmetric support structure.[17]

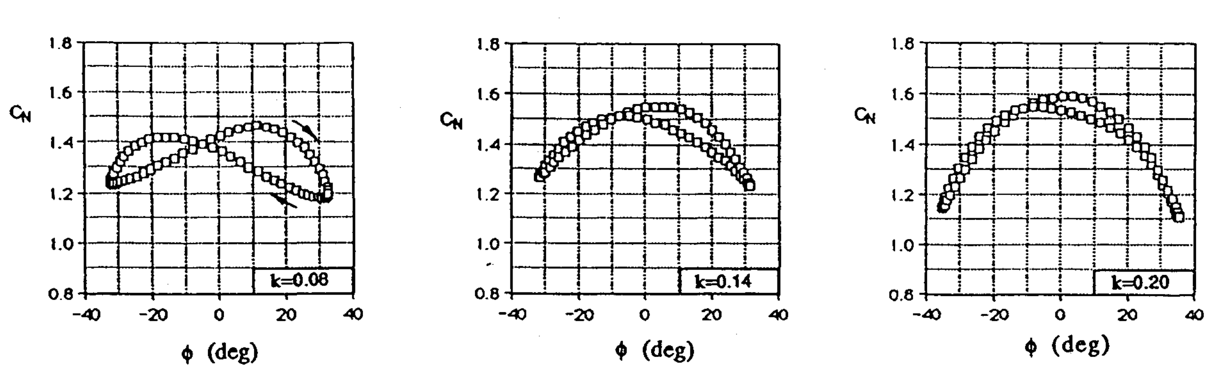

Fig. 3 Asymmetric support interference on a 65-deg delta wing.[18]

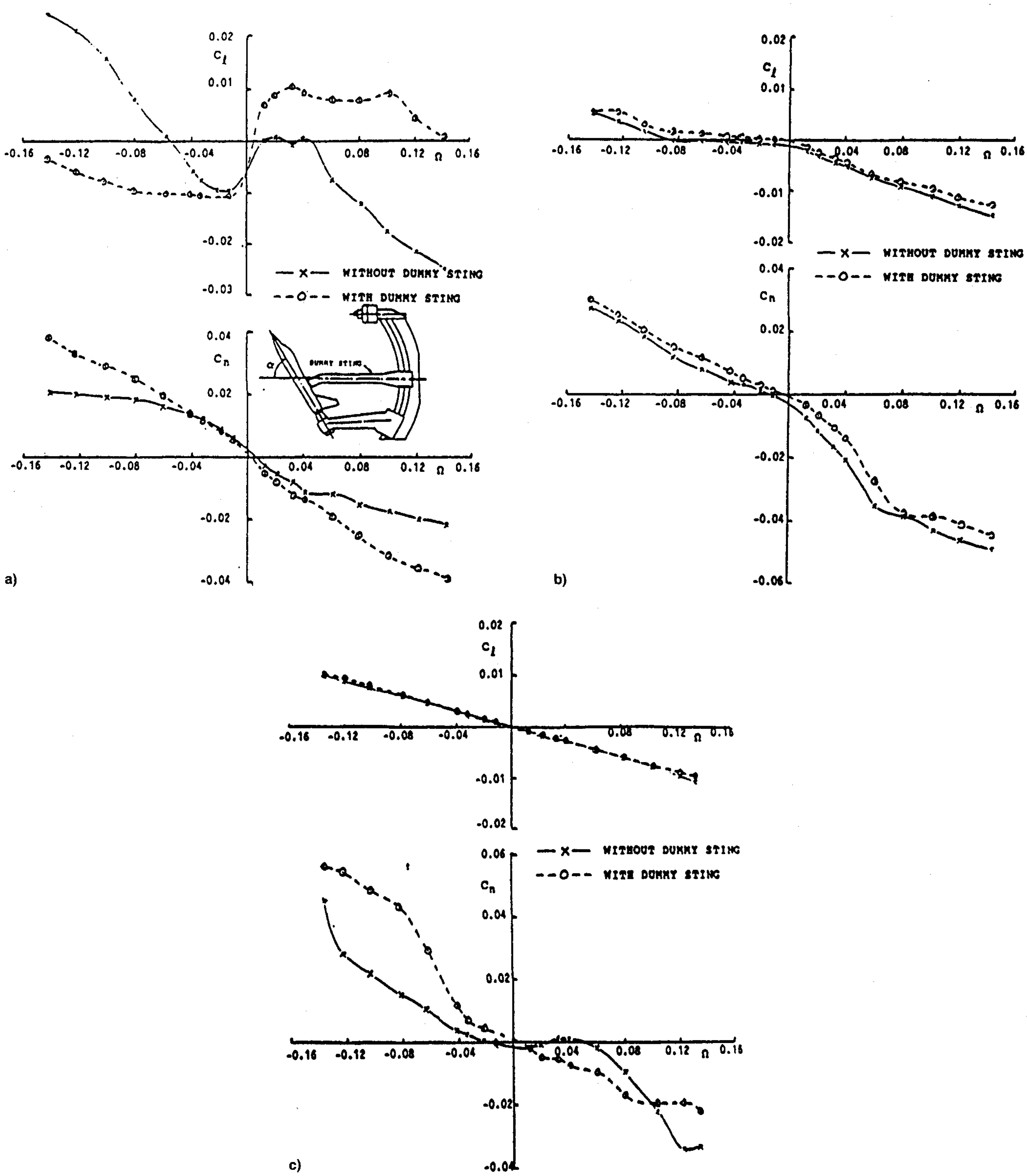

Fig. 4 Effect of dummy sting on experimental lateral characteristics of the HIRM 2 model.[21] α = a) 40, b) 50, and c) 60 deg.

use of the orbital-platform testing concept (OPLEC)[9,22–24] (Fig. 5). At high angles of attack, the most damaging source of interference is a top-mounted sting, as will be discussed later in connection with Fig. 7. By eliminating the need to use a top-mounted support and the associated C-strut structure, OPLEC eliminates the prime source of high-alpha support interference. OPLEC allows the use of a regular sting support up to 90-deg angles of attack. Tests on an ogive–cylinder body[25] have shown that at high angles of attack even a sting diameter equal to the body diameter causes no measurable interference effects.[6] Thus, the sting support in Fig. 5 causes no high-alpha support interference. OPLEC tests of the cone–cylinder used in coning tests by Yoshinaga et al.[26] gave the results[24] shown in Fig. 6. The figure exhibits the incremental effect of the C-strut support structure on the location of vortex breakdown in the form of a contour plot that shows $\Delta x_B/L = [(x_B)\text{no support} - (x_B)\text{support}]/L$. It can be seen how for some combinations of coning rates and angles of attack the support has minimal interference, consistent with earlier observations for slender aircraft models.[8]

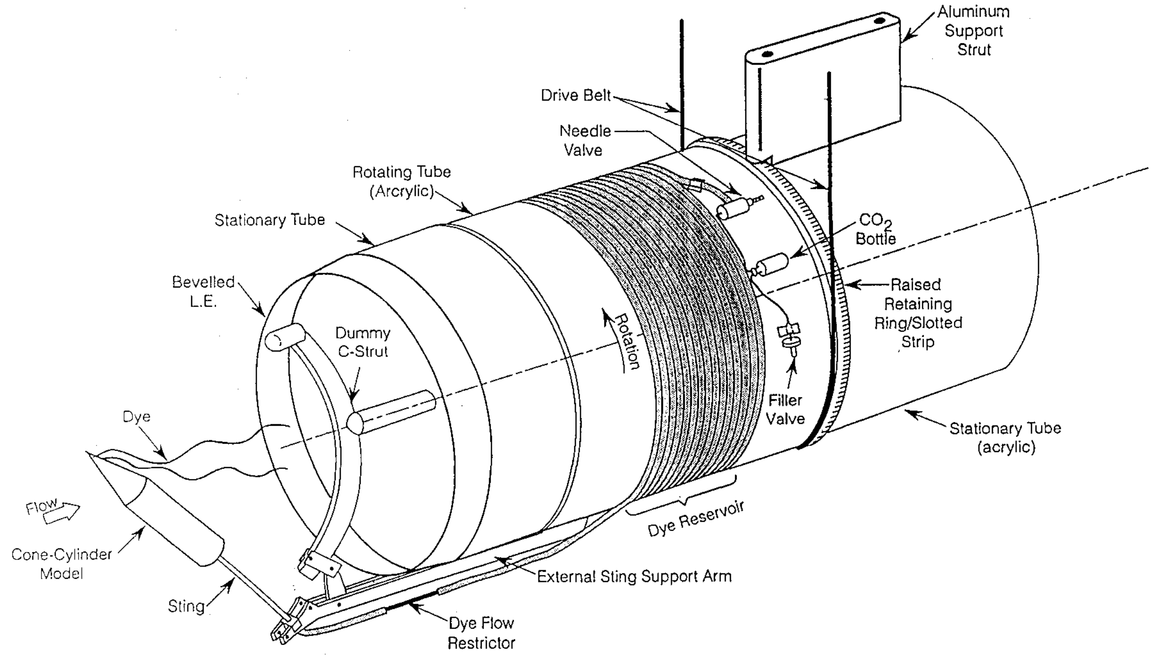

Fig. 5 Orbital-platform testing concept.[22]

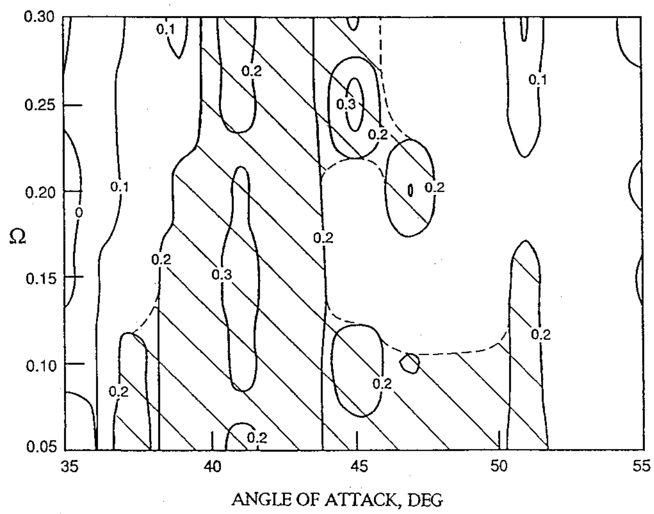

Fig. 6 Incremental effect of C-strut support on vortex breakdown on a coning cone–cylinder.[24]

Figure 6 gives a quantitative measure of the type of support interference experienced in wind-tunnel tests of an advanced aircraft model[20] (Fig. 7). There is in all likelihood a (positive and negative) range of coning rates for which the forebody vortices do not pass close to the support, resulting in negligible support interference. However, as is discussed in Ref. 7, there is clearly a range of (positive and negative) coning rates in which the support strongly affects the path of the vortices, as is manifested through the large rate-hysteresis effects in Fig. 7. The effect of the support inclination α_s can be compared with the change in the effect of the dummy strut when increasing the angle of attack from α = 40 to 60 deg in Fig. 4. The reason for the hysteresis in Fig. 7 is that the top support prevents the free lateral movement of the forebody vortices, causing them to be locked to one side of the support for a certain interval of sideslip β or coning rate Ω. This is discussed in detail in Ref. 7. If the tests[20] had been performed using the orbital platform concept[22–24] (Fig. 5), the effect of the support in Fig. 7 could have been quantified, producing a graph similar to that in Fig. 6.

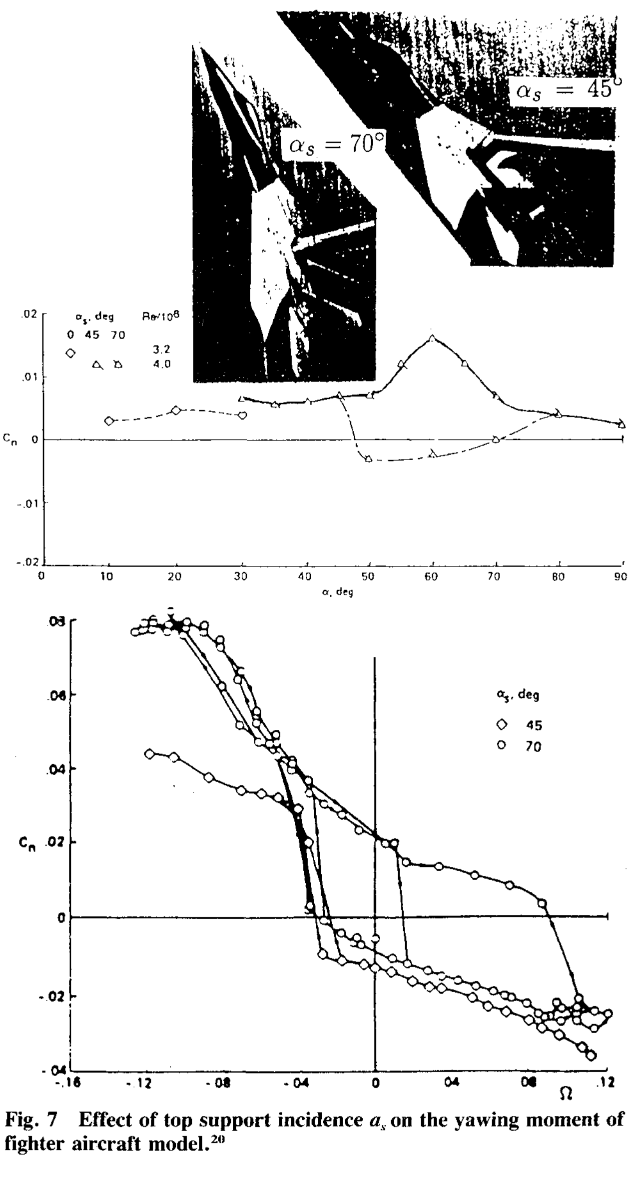

Fig. 7 Effect of top support incidence α_s on the yawing moment of a fighter aircraft model.[20]

Delta Wing with Fuselage-Like Mounting Structure

In a recent test of a sharp-edged 65-deg delta wing, a fuselage-like semicircular section was attached to the bottom side to cover force transducers and devices for pressure measurements[27] (Fig. 8a). Figure 8b shows how the presence of the fuselage-like cover on the bottom side promoted vortex breakdown to move upstream as much as $\Delta\xi_B/\xi_B \approx 0.20$. Forward of the fuselage, at $\xi < 0.23$, the effect more or less disappeared, and the breakdown location approached that measured by others without a fuselage[28,29] (Fig. 8). The difference between the vortex breakdown location for fuselage off in Ref. 27 and that measured by others[28,29] is probably the result of differences in sting support geometry, tunnel turbulence, and Reynolds number. However, the incremental effect of the presence of a fuselage is likely to be very similar in the other tests. Similar promotion of breakdown is caused by a regular fuselage[30] (Fig. 9). It is shown in Ref. 31 that the large effect on vortex breakdown in Fig. 9 is the likely result of the fuselage-induced upwash at the leading edges, with the upwash generated by the windward portion of the fuselage. As it is largest near the apex, it will generate a negative wing-camber effect, which in experiments has been shown to promote vortex breakdown[32] (Fig. 10). It should be noted that the 3.5D tangent-ogive nose of the fuselage in Fig. 9 will not generate asymmetric forebody vortices until $\alpha >$ 32.6 deg,[19] where the lower forebody vortex could interact with the adjacent leading-edge vortex.[33]

If the model to be tested is a pure delta wing, the fuselage-like body on the wing underside (Fig. 8a) presents a special type of support interference, the effect of which becomes pronounced in the presence of sideslip[27] (cf. Figs. 8b and 11). The centerbody acts in this case as a barrier, similar to a splitter plate, preventing the crossflow stagnation region from adjusting to the sideslip-induced flow conditions. Judging by

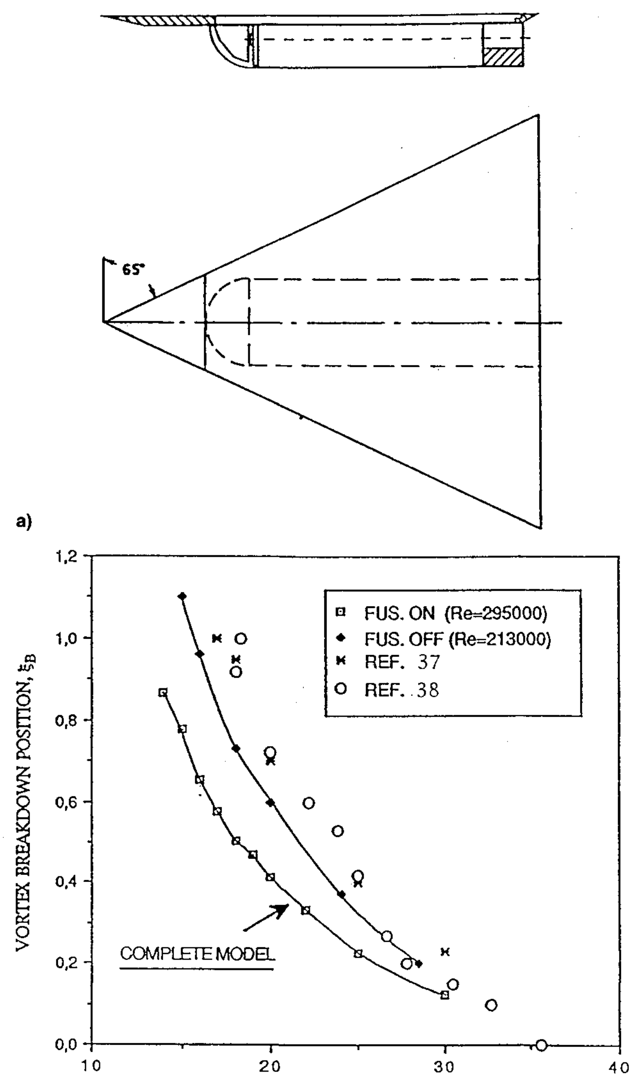

Fig. 8 Effect of windward support structure on vortex breakdown on a 65-deg delta wing[27]: a) fuselage-like centerbody and b) effect of centerbody on vortex breakdown.

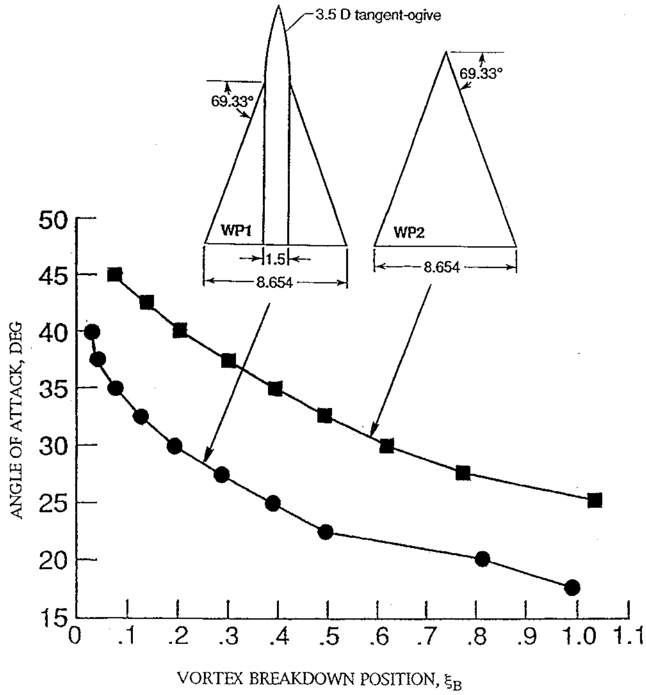

Fig. 9 Effect of fuselage on delta wing vortex breakdown.[30]

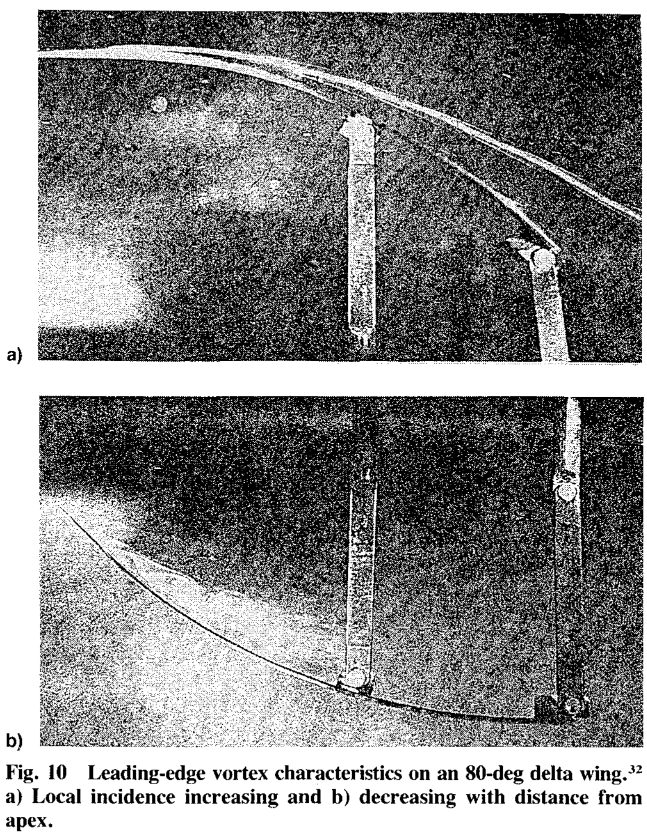

Fig. 10 Leading-edge vortex characteristics on an 80-deg delta wing.[32] a) Local incidence increasing and b) decreasing with distance from apex.

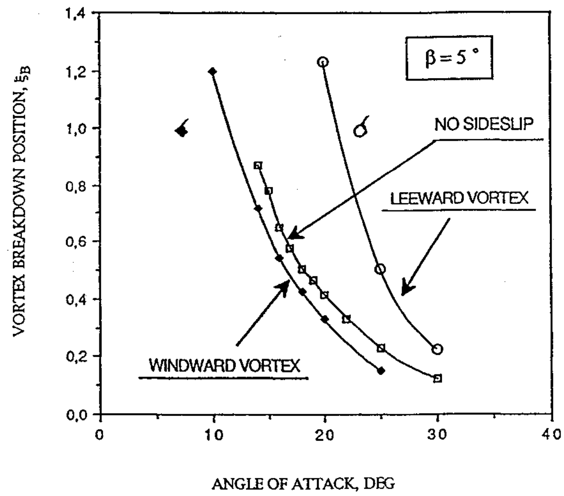

Fig. 11 Effect of windward centerbody on the vortex breakdown of a 65-deg delta wing at 5-deg sideslip.[27]

the effect of leading-edge sweep Λ on delta wing vortex burst[29] (Fig. 12a), one expects that the effect of 5-deg sideslip on the breakdown location on the upwind and downwind wing halves should not differ as much as was observed in the test.[27] The upwind breakdown movement was only 20% of the movement on the downwind wing half. The analysis in Ref. 34 showed that using the $\beta - \Lambda$ equivalence concept shown in Fig. 12b gave a very satisfactory prediction of the measured lateral stability of slender delta-wings. Using this equivalence concept, together with the experimental results[29] in Fig. 12b, one predicts that the upwind side would experience vortex breakdown at the trailing edge at 5-deg lower angle of attack than at zero sideslip, and the downwind side at 10.5-deg higher angle of attack. The predicted data points are marked with flags in Fig. 11. It can be seen that, as expected, the effect of the crossflow obstruction presented by the centerbody is largest on the upwind wing half, almost completely canceling the expected effect of sideslip. That the use of a bottom-side centerbody is far from unusual is exemplified by recent tests of sharp-edged delta wings[35,36] (Figs. 13a and 13b).

The bottom-side centerbody will have a large interference effect in tests where the delta wing describes yawing or rolling motions. It can, therefore, be expected to have a significant effect on slender wing rock.[37–41] In Ref. 37 the centerbody did not extend far forward of the trailing edge, in contrast to the case in Ref. 38 (Fig. 14). As a consequence, one expects the interference effect to be much larger in the latter case,[38] causing early vortex breakdown.[30,31] Thus, the measured wing rock amplitude for the sharp-edged 80-deg delta wing should be smaller, because of the earlier occurrence of the breakdown-induced damping effect.[39] Figure 14 shows that the measured limit-cycle amplitude was indeed significantly smaller at $\alpha > 26$ deg in the test using the extended centerbody.[38] At $\alpha > 26$ deg, where vortex burst was observed to occur on the rocking delta wing,[37,38] the experimental results show that the longer centerbody[38] through its promotion of vortex breakdown causes a decrease of the wing-rock amplitude. In the test with the roll axis underneath the wing plane,[37] the added degree of freedom produces a lateral motion of the leading edge. This induces a velocity component in the wing plane that produces a constant angle of sideslip along the leading edge of the downstroking wing half. The associated increase of the effective leading-edge sweep promotes vortex breakdown[29] (Fig. 12a). Thus, with the roll axis in the wing plane the experiment with the shorter centerbody[37] would have produced an even larger limit-cycle amplitude.

At $\alpha < 26$ deg, the experimental results show a reversal of the effect, the short centerbody[37] producing a smaller limit-

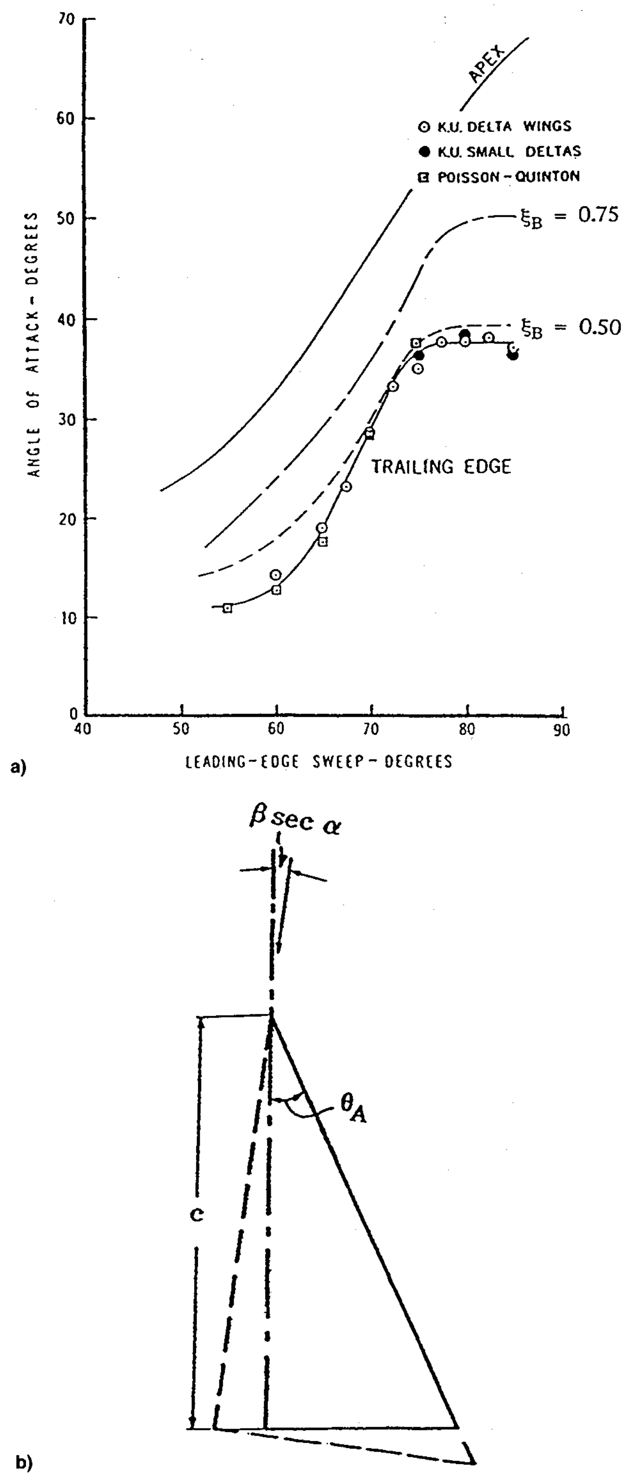

Fig. 12 Effect of leading-edge sweep on vortex breakdown: a) effect of Λ on x_B as a function of angle of attack[29] **and b) sideslip-induced change of effective leading-edge sweep.**[34]

cycle amplitude. This effect of the centerbody can be attributed to reduced vortex-induced undamping at $\alpha < 26$ deg, in the absence of vortex burst. By limiting the outboard travel of the crossflow stagnation point on the downwind wing half, the centerbody on the bottom side decreases the effective sweep of that leading edge. It has been shown that the intact leading-edge vortex generates undamping in roll that increases with increasing sweep[41,42] (Fig. 15). For example, at $\alpha = 26$ deg in Fig. 15, increasing the sweep from 80 to 85 deg increases the undamping from $Cl\dot{\phi} \approx 0.2$ to 1.4. In contrast, decreasing the sweep from 80 to 75 deg increases the

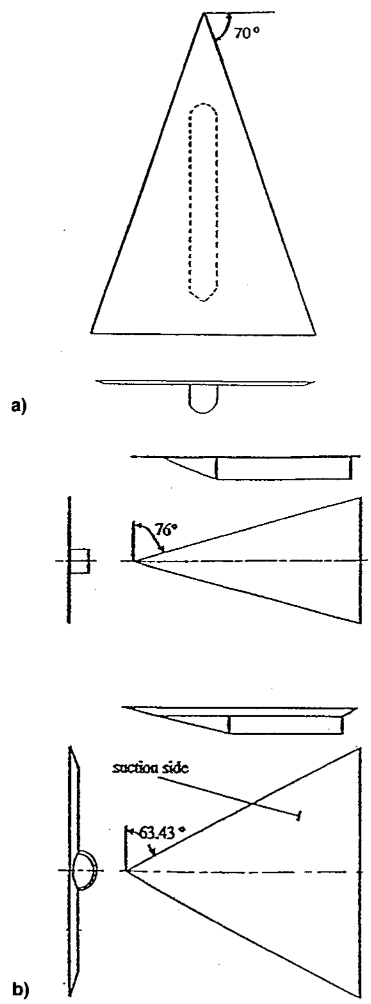

Fig. 13 Examples of windward side centerbodies used in tests of delta wings: References a) 35 and b) 36.

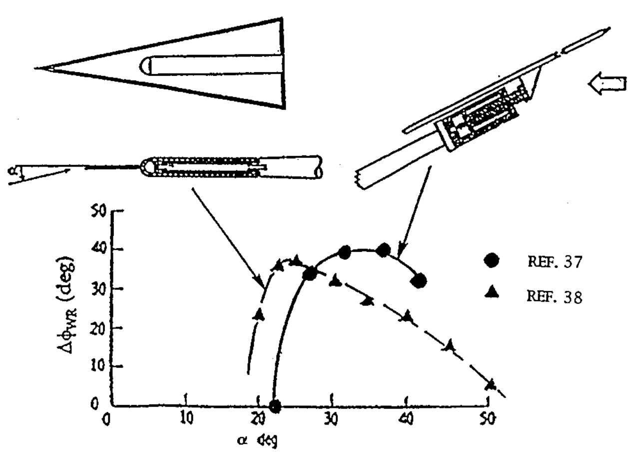

Fig. 14 Effect of centerbody on wing rock of an 80-deg delta wing.[37,38]

damping by only $\Delta Cl\dot{\phi} \approx -0.3$, from $Cl\dot{\phi} \approx 0.2$ to $Cl\dot{\phi} \approx -0.1$. That is, the centerbody-induced change of sweep will result in an increase of the magnitude of the undamping, explaining the data trend for $\alpha < 26$ deg in Fig. 14.

Wall Interference

The centerbody generates an upwash at the leading edge that decreases with increasing downstream distance from the apex[31]; the resulting negative camber effect would promote

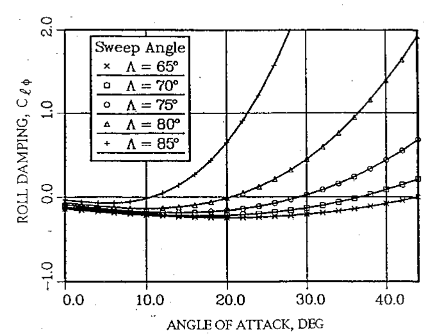

Fig. 15 Effect of leading-edge sweep on delta wing roll damping.[42]

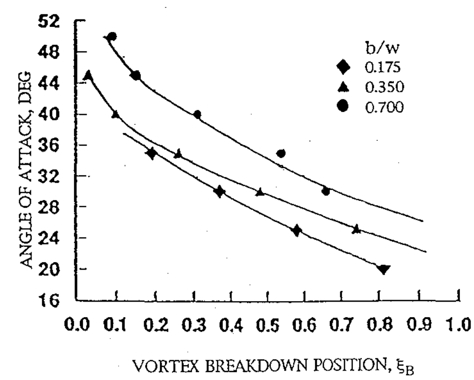

Fig. 16 Wind-tunnel wall interference effects on the vortex breakdown of a 70-deg delta wing.[14]

vortex breakdown, as demonstrated by the experimental results[30] in Fig. 9. Weinberg[14] has shown that tunnel-wall interference generates an upwash distribution along the leading edge that is of the opposite type, creating a positive camber effect. For $b/w = 0.44$, the induced upwash along the leading edge on a 70-deg delta wing is computed[14] to increase from 1.5 deg at the apex to 4.7 deg at the trailing edge. The induced camber effect delays vortex breakdown the larger the ratio b/w is (Fig. 16). When performing tests of delta wings with a constant chord (giving a constant test Reynolds number) to investigate the effect of sweep angle, the ratio b/w will vary with the sweep angle according to the relationship

$$b/w = (2c/w)\cot \Lambda \qquad (1)$$

Equation (1) shows how b/w varies with Λ when the wing root chord is kept constant. For instance, if $b/w = 0.1$ for an 80-deg delta wing, decreasing the sweep angle to 70 and 60 deg would result in $b/w = 0.25$ and 0.40, respectively. These values are within the tested range in Fig. 16, showing that the corresponding effect of wall interference would severely distort the measured effect of leading-edge sweep on vortex breakdown.

Even small protuberances on the windward side of delta wings can be expected to produce significant interference. For instance, Lambourne et al.[43] observed a profound effect on the vortex pattern of a 70-deg delta wing. A small protrusion on the bottom surface caused the leading-edge vortex to degenerate into a partial-span leading-edge vortex, while a new leading-edge vortex started to develop downstream of the protrusion.

Conclusions

A critical review of recent high-alpha experimental results reveals that the problem of ground facility interference is very complex and is likely to be of concern for some time to come. The use of symmetric supports can introduce significant distortions of the unsteady aerodynamics that are difficult to detect, contrary to the case for the effects of asymmetric support interference. Fuselage-like structures commonly used to attach the support to the underside of the wing can severely affect the vortex breakdown dynamics of slender wings. Conventional rotary rig balances exhibit some of the characteristics of asymmetric support interference introduced by flow curvature effects.

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