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Sources of High Alpha Vortex Asymmetry at Zero Sideslip

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A review of existing experimental results for slender bodies and delta wings, tested at high angles of attack, reveals that no physical evidence exists that vortex asymmetry on slender pointed bodies or delta wings has ever occurred through the so-called hydrodynamic instability process. It will be shown that in the numerous tests performed, asymmetric flow separation and/or asymmetric flow reattachment, were the flow mechanisms triggering the vortex asymmetry. Slender wing rock is found to result from a basic lack of roll damping, existing for attached leading-edge vortices, and the vortex-asymmetry is generated at nonzero roll angle, i.e., for asymmetric flow conditions.

Nomenclature

b = wingspan
c = reference length, d
c_0 = delta wing center chord
d = maximum diameter of body of revolution
ℓ = rolling moment, coefficient $C_\ell = \ell/(\rho_\infty U_\infty^2/2)$
Re = Reynolds number based on d and freestream conditions
S = reference area, $\pi d^2/4$ or projected wing area
U = horizontal velocity
Y = side force, coefficient $C_Y = Y/(\rho_\infty U_\infty^2/2)$
α = angle of attack
θ_A = apex half-angle
θ_c = cone half-angle
Λ = leading-edge sweep
ρ = air density
ϕ = body roll angle

Subscripts
A = apex
c = cone
∞ = freestream conditions

Introduction

THE flow over a slender body of revolution changes as sketched in Fig. 1 when the angle of attack is increased from 0–90 deg.[1] In early attempts to understand the physics leading to the change from symmetric to asymmetric vortices, it was assumed that hydrodynamic instability was the basic mechanism leading to Karman vortex shedding in the case of two-dimensional type flow at $\alpha = 90$ deg, and to a steady asymmetric vortex pattern for three-dimensional type flow at $\alpha < 60$ deg, where the axial space coordinate corresponded to the time variable in the two-dimensional case[2] (Fig. 2). This analogy would apply to bodies with nonslender noses, where vortex shedding starts on the aft body rather than on the nose. However, in most cases of practical interest the nose is slender and the analogy does not apply.

That nose microasymmetries dictated the asymmetric flow development on slender pointed noses was shown early[3] (Fig. 3), and it was recently demonstrated[4] that a manufactured elliptic micro-asymmetry (Fig. 4) could produce a side force variation with roll angle that was very similar to that with a nominally axisymmetric tip (cf. Figs. 5a and 5b). At $\alpha = 40$ deg, the similarity is stunning, whereas at $\alpha = 30$ deg the controlled asymmetry appears to be more effective than the natural, uncontrolled one.

Although in most cases of practical interest the boundary-layer transition process with associated laminar-turbulent separation bubble[5] (Fig. 6) would dominate the flow separation process and the resulting vortex asymmetry, great efforts were expended to produce a test of a perfectly smooth symmetric body in laminar flow to determine the role of hydrodynamic instability in the generation of asymmetric flow on a slender nose. Due to practical difficulties, no test results were ever obtained for slender noses in which no nose microasymmetry was found to play a dominant role.

Thus, tests could not show hydrodynamic instability to be an important factor in the generation of asymmetric flow over slender forebodies. However, there were apparent indirect proofs that it played an important role. Flow visualization results for a very slender delta wing[6] (Fig. 7) showed that

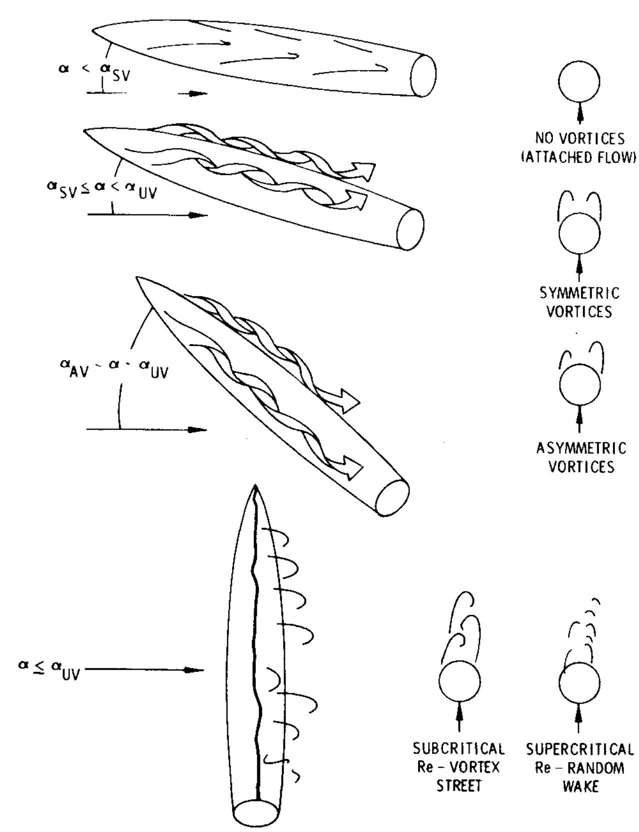

Fig. 1 Effect of angle of attack on leeside flowfield.[1]

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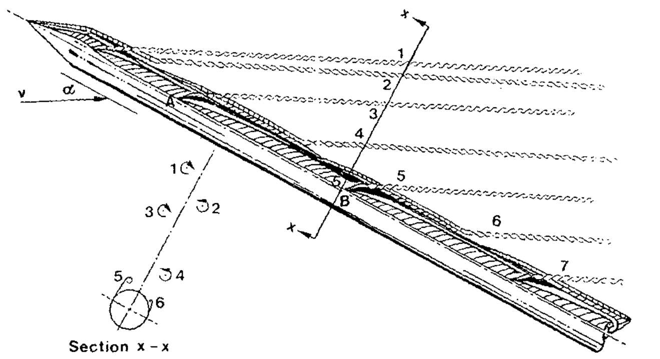


Fig. 2 Asymmetric steady vortex array on inclined body of revolution.[2]

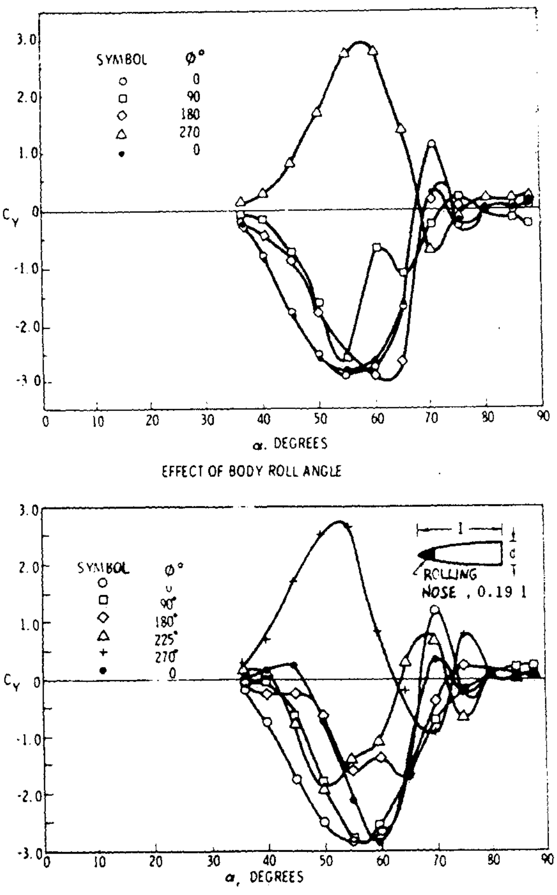


Fig. 3 Effect of roll angle on the side force on an l/d = 3.5 pointed ogive.[3]

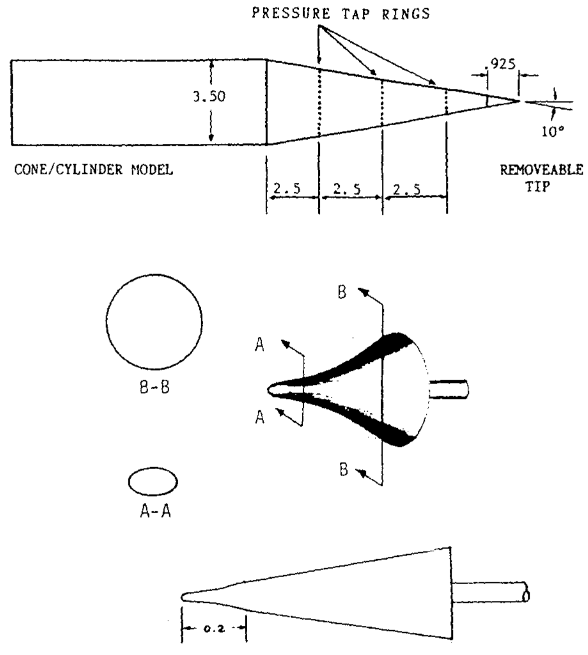
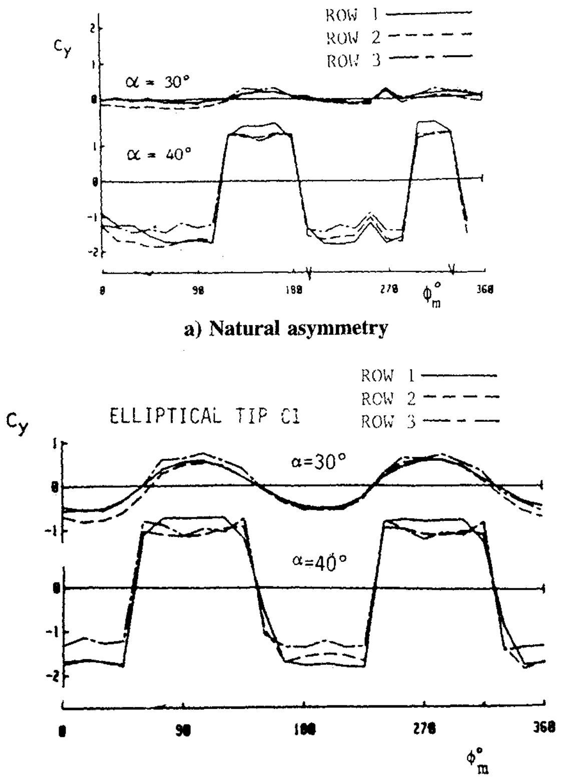


Fig. 4 Sketches of model used in test.[4]



a) Natural asymmetry

b) Controlled asymmetry

Fig. 5 Variation of sectional side force with roll angle.[4]

asymmetric vortices existed for presumably symmetric flow separation, indicating that the vortex asymmetry must have been generated by the hydrodynamic instability process. Combining this with the correlation of the dependence of flow asymmetry on slenderness ratio for slender noses and slender delta wings[7] (Fig. 8), appeared to provide positive proof that hydrodynamic instability was the cause of the observed vortex asymmetry; in which case, asymmetric flow separation on slender forebodies was not a precondition for vortex asymmetry, but rather a consequence of it.

Recent attempts to repeat Bird's results[6] have been unsuccessful (Fig. 9). Tests with sharp-edged delta wings with leading-edge sweeps of 82 and 86 deg did not show any vortex asymmetry over the tested alpha range, $0 < \alpha < 45$ deg. When investigating this further, the authors[8] found that the likely reason for the difference in test results was the difference in leading-edge geometry in the two cases (Fig. 10).

Considering the observed dominant effect of nose tip microasymmetries[1] (Fig. 3), one can see how the apex for Bird's delta wing,[6] having a conical geometry, would produce the same type of vortex asymmetry observed on slender forebodies. The conclusion to be drawn in this case is that asymmetric flow separation on the nose tip caused the observed vortex asymmetry on Bird's delta wing, in the same manner that it is generated on a slender nose. This was also the conclusion drawn in a very recent publication,[9] where the comparison shown in Fig. 11 was made between the cross-sectional geometries (10% of c_0 downstream of the apex) of

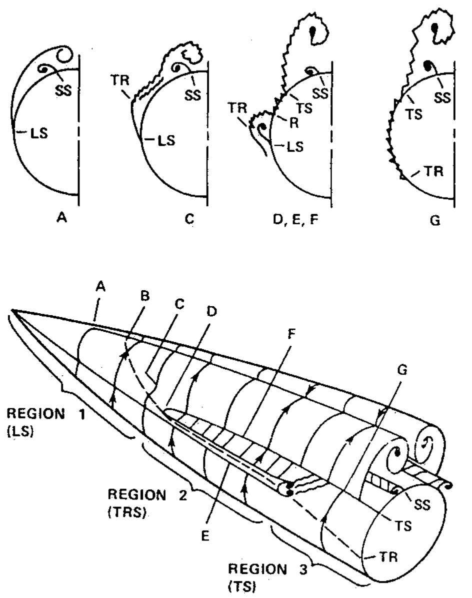


Fig. 6 Sketch of flow over a 3.5 caliber pointed ogive at transitional Reynolds number.[5]

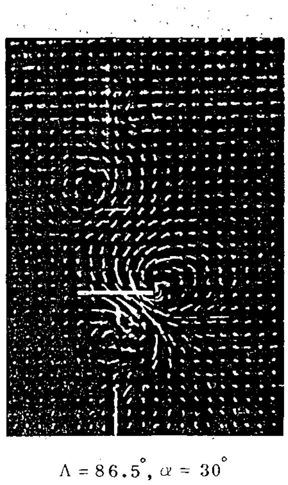


Fig. 7 Tuft flow picture of asymmetric vortex shedding from an 86.5 deg delta wing at α = 25 deg.[6]

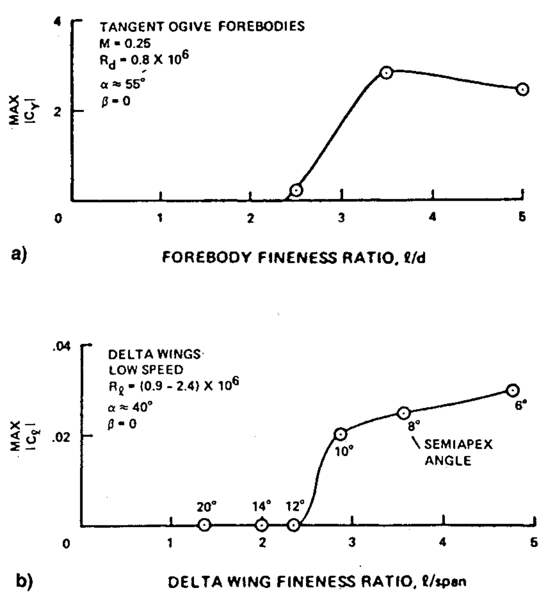


Fig. 8 Effect of fineness ratio on maximum side force and rolling moment.[7]

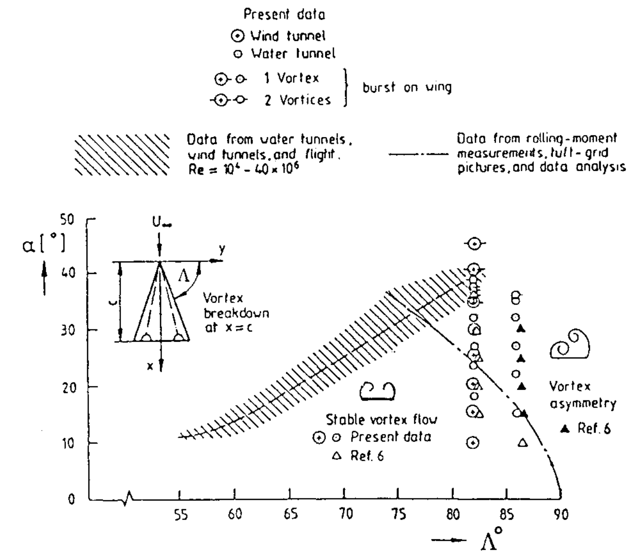


Fig. 9 Dependence on leading-edge sweep of onset angles-of-attack of vortex breakdown and asymmetry for delta wings at low-speed flow.[8]

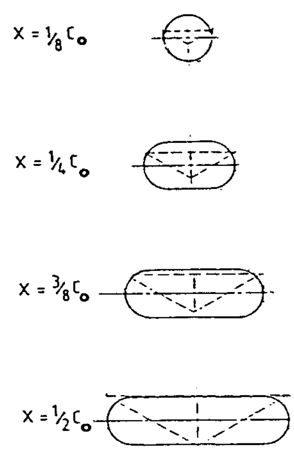


Fig. 10 Cross-sectional shapes for present 86 deg and Bird's 86.5 deg delta wings.[8]

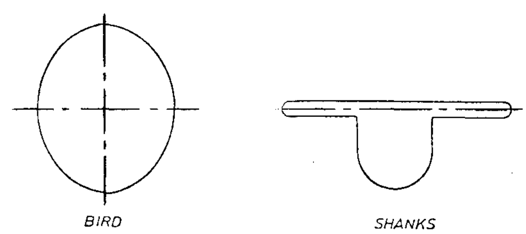


Fig. 11 Comparison of apex shapes.[9]

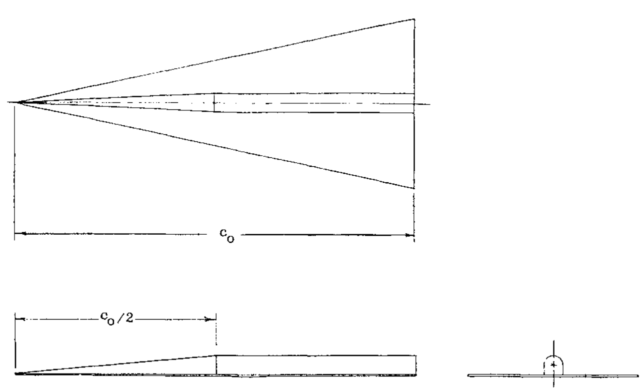


Fig. 12 Shank's delta wing model.[10]

Bird's[6] and Shank's[10] delta wings (the latter supplying the results used in Fig. 8b).

Therefore, one would expect the correlation shown in Fig. 8 to hold for Bird's test results. However, the delta wing results[10] shown in Fig. 8 are for the geometry shown in Fig. 12. That is, the "fuselage bump" in Fig. 11 is on the top side, at least according to the definition in Ref. 10 (see Fig. 13). It is shown in Ref. 11 that when the outlets of two flow visualization tubes were placed on the bottom side—near the apex on an 85-deg delta wing—asymmetric leading-edge vortices resulted at $\alpha = 35$ deg, even for symmetric flow conditions; whereas the vortices were symmetric when the tubes were placed on the leeward (top) side. Likewise, one would expect the "fuselage" in Figs. 11 and 12 to affect the flow separation when placed on the windward (bottom) side, as shown in Fig. 11, but to have little effect when placed on the leeward (top) side, as was the case for the results shown in Fig. 8b. In that case, the initial separation is already set by the delta-wing leading-edge geometry.[12] Thus, the fuselage can only affect the flow separation through some type of feedback mechanism.

It appears that the minute body near the apex could have acted similarly to the small center splines tested on slender bodies with triangular cross section.[13] When the height of the spline was high enough, it acted as a splitter plate, decoupling the two vortex-flow fields. However, when the height of the splitter plate was decreased sufficiently, the "mischievous" centerline spline effect[14] shown in Fig. 14 apparently resulted, causing the leading-edge vortices to become asymmetric. The reattaching flow cannot find a stable stagnation point on top of the centerline spline. As a result, the stagnation point moves to one side of the centerline spline, forcing an asymmetry into the crossflow separation geometry, resulting in asymmetric leading-edge vortices.

Thus, in the case of the geometry shown in Fig. 12, asymmetric reattachment, rather than asymmetric (primary) flow separation, is the likely cause of the vortex asymmetry leading to the measured rolling moment shown in Fig. 8b. Such an effect, generated by the center body, is the probable cause of the vortex asymmetry observed on a 87.5-deg delta wing.[15] Of course, if the center spline or spline-like body is tall enough, it will have the opposite effect, acting as a splitter plate, decoupling the two crossflow sides and forcing vortex symmetry, as has been demonstrated.[16,17]

Fig. 15 shows the α-θ_A boundary for asymmetric leading-edge vortices at symmetrical flow conditions, as presented in Ref. 18. As this publication dealt with "*Sharp-Edged Delta Wings*," according to the title of the paper, the present author assumed that the boundaries in Fig. 15 were also for sharp-edged delta wings. However, this is true only for the boundary for vortex breakdown. The boundary for vortex asymmetry was based on Bird's data,[6] which Stahl[8] has shown to be for a rather thick delta wing with rounded leading edges. Repeating the test with sharp-edged delta wings, Stahl could not obtain the vortex asymmetry observed by Bird (Fig. 9).

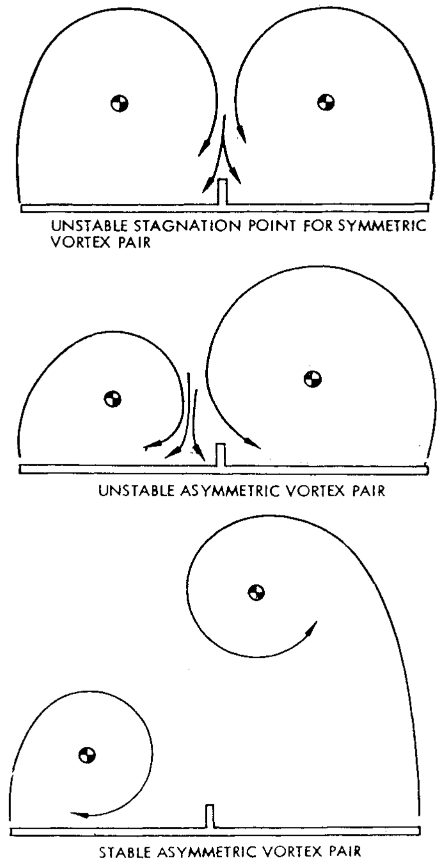


Fig. 14 Mischievous centerline spline effects on vortex geometry.[14]

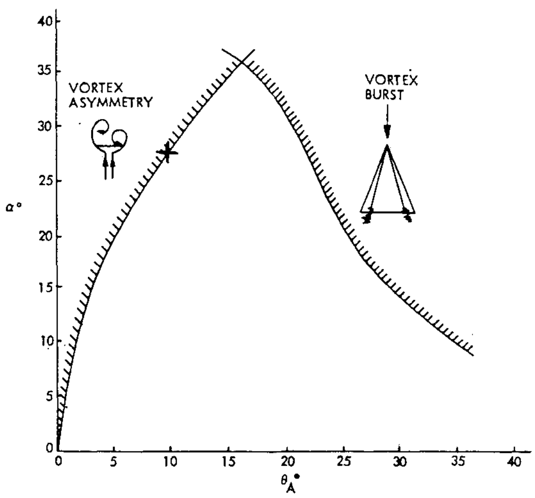


Fig. 15 Boundaries for vortex asymmetry and vortex breakdown.[18]

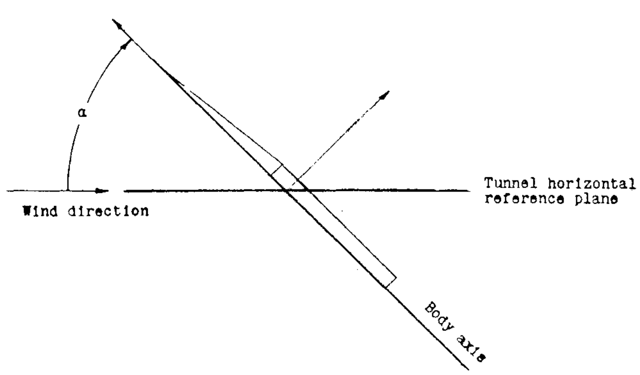


Fig. 13 Definition of windward and leeward sides.[10]

In any case, the present author misinterpreted the results in Fig. 15 to be valid for sharp-edged delta wings. Consequently, when wing rock on an 80-deg delta wing was observed[19] to start when the angle of attack was increased to fall on the boundary (+ data point in Fig. 15), he proceeded to show [20] that the vortex-asymmetry could generate the observed large-amplitude wing rock, and that vortex breakdown was providing the damping mechanism that limits the amplitude of slender wing rock.[21] This analysis has been referenced in support of analyses that predict vortex asymmetry on slender cones to be generated from a symmetric flow separation.

Later tests of slender delta wings[11] showed that wing rock could occur without vortex liftoff, i.e., at angles of attack below the boundary for vortex asymmetry in Fig. 15. The dashed line in Fig. 16 shows the α-θ_A boundary defined by those tests.[11] Also shown in Fig. 16, by the solid line,[22] is the

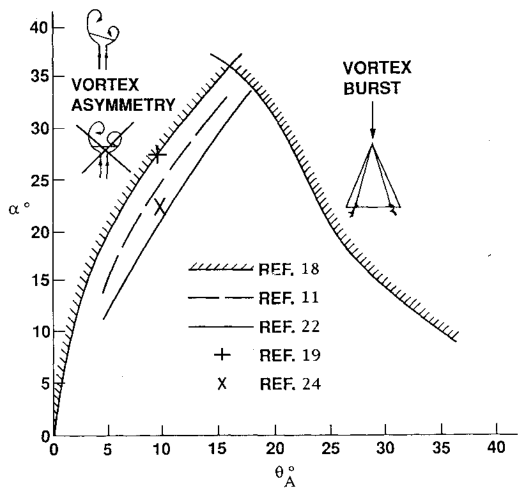


Fig. 16 Revised boundary for incipient wing rock of slender delta wings.[22]

boundary predicted for free flight.[23] It falls below the results obtained in free-to-roll tests.[11] The difference is due to the bearing friction present in the tests. It had less of an effect in the water tunnel[11] than in the wind tunnel[19] because of the different fluid densities. Using an air bearing in a later wind-tunnel test[24] decreased the effect of friction further (see the × data point in Fig. 16).

It is clear from the results in Fig. 16 that wing rock is initiated while the leading-edges vortices are still symmetric. Vortex asymmetry, with associated increase of the wing rock amplitude, occurs at a certain roll angle. That is, vortex asymmetry is the result of asymmetric crossflow conditions in the case of wing rock of slender delta wings.

Conclusions

A review of existing experimental results leads to the following conclusions:

1) Hydrodynamic instability cannot be shown to be the cause of vortex asymmetry in any of the tests analyzed here.

2) Symmetric flow separation cannot result in vortex asymmetry unless the crossflow reattachment is forced to be asymmetric.

3) The above facts have an important impact on the theoretical approach to be used.

Acknowledgments

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