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Slender Wing Rock Revisited

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Analysis of experimental results for slender delta wings reveals that asymmetric liftoff of the leading-edge vortices on slender delta wings does not start the wing rock, although it is responsible for the large limit cycle amplitude observed in experiments. As a consequence, the interaction of slender wing rock does not depend upon the interaction between the two leading-edge vortices, but can be generated by one wing half by itself, making slender wing rock more likely to occur on high agility aircraft than previously thought.

Nomenclature

b = wing span
$C_{l\dot{\phi}}$ = $\partial C_l/\partial(b\dot{\phi}/2U_\infty)$
$C_{\bar{l}\dot{\phi}}$ = integrated mean value
l = rolling moment; coefficient $C_l = l/(\rho_\infty U_\infty^2/2)Sb$
S = reference area, wing area
t = time
U = velocity
α = angle of attack
β = angle of sideslip
Δ = increment or amplitude
θ_A = apex half-angle
$\hat{\theta}_A$ = effective apex half-angle, Eq. (1)
θ_{LE} = complimentary angle to the leading-edge sweep, $\pi/2 - \Lambda$
Λ = leading-edge sweep angle
ρ = air density
ϕ = roll angle
$\dot{\phi}$ = $\partial\phi/\partial t$

Subscripts
A = apex
LV = left LE vortex
LE = leading edge
LIM = limit cycle
RV = right LE vortex
v = vortex
WR = wing rock
0 = initial or time-average value
∞ = freestream condition

Superscript
$-$ = barred quantities denote integrated mean values, e.g., $C_{\bar{l}\dot{\phi}}$

Introduction

WHEN slender wing rock was first observed in experiments with an 80-deg delta wing,[1] its occurrence coincided with the appearance of asymmetric leading-edge vortices. It was shown[2] that vortex asymmetry could indeed generate wing rock, whereas vortex breakdown was the flow mechanism limiting the growth of the wing rock amplitude,[2,3] Implicit in the analyses in Refs. 2 and 3 is the assumed existence of vortex asymmetry through hydrodynamic instability,[4] implying that vortex asymmetry can be generated for the symmetric flow conditions existing at zero sideslip and roll.

It can now be shown[5] that no experimental evidence exists which supports the claim that vortex asymmetry can be caused by hydrodynamic instability. Recent tests and analyses show that on slender sharp-edged delta wings symmetric vortices exist for symmetric flow conditions until symmetric or asymmetric vortex breakdown occurs at very high angles of attack.[6,7] Consequently, the slender wing rock problem needs to be revisited to update the author's earlier analysis.[2,3]

Discussion

In a recent experimental investigation,[8] the effect of leading-edge sweep on wing rock was found to be of a rather complicated nature. The results for an 80-deg delta wing were in general agreement with an earlier experiment[1] (Fig. 1), and showed the downstream progression of vortex liftoff from apex described in Ref. 2. However, it was found that wing rock occurred even in the absence of asymmetric vortex liftoff, e.g., at $\alpha = 31$ deg on a 75-deg delta wing. A recently developed analytic method[9] predicts that the roll damping of an 80-deg delta wing is lost, even without vortex liftoff, when the angle of attack exceeds $\alpha = 20$ deg. This is in good agreement with experimental forced-oscillation results[1] (Fig. 2). The fact that the free-oscillation results[1] showed no wing rock to occur on the 80-deg delta wing until vortex liftoff took place at a higher angle of attack, is the likely result of the presence of bearing friction in the test. The nonlinear, more or less discontinuous increase of the undamping due to vortex liftoff[2] had no difficulty in overpowering the mechanical (frictional) damping, and wing rock resulted (Fig. 1). The situation is different in free flight at 20 deg $< \alpha <$ 27 deg, in the absence of mechanical damping.

In free flight at $\alpha \geq 20$ deg, an 80-deg delta wing is undamped in roll[9] (Fig. 2). It will oscillate in roll until a critical roll angle is exceeded, where the asymmetric flow condition causes the leeside wing to experience vortex liftoff. The resulting large undamping will cause a buildup of the wing-rock amplitude until the damping action of the vortex breakdown

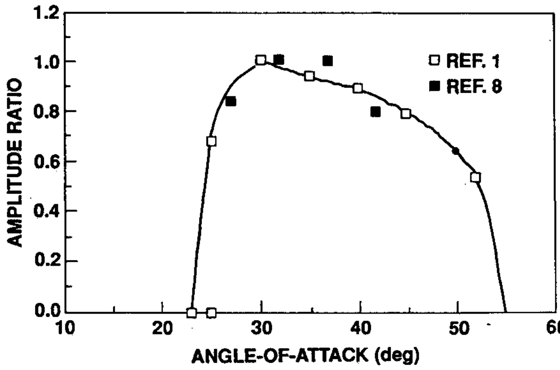

Fig. 1 Wing rock amplitude ratio for an 80-deg delta wing.[8]

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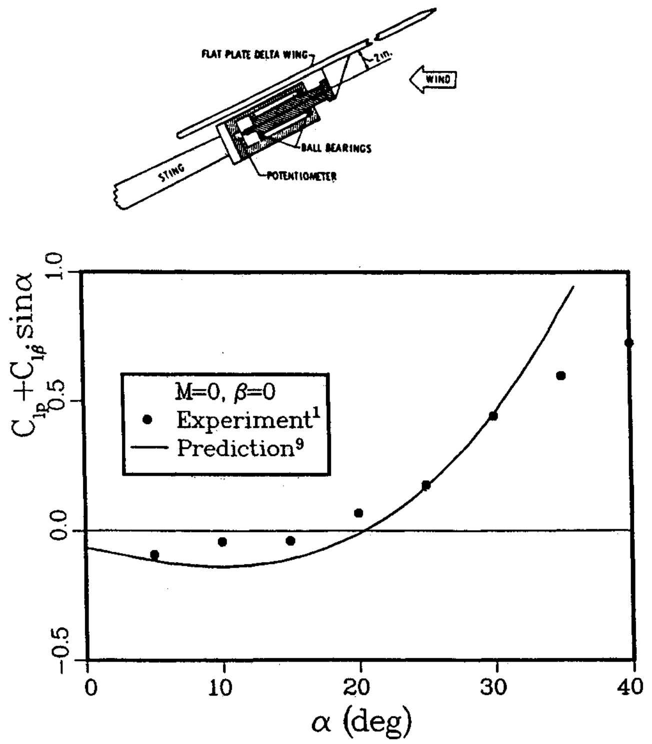

Fig. 2 Roll damping of 80-deg delta wing.[9]

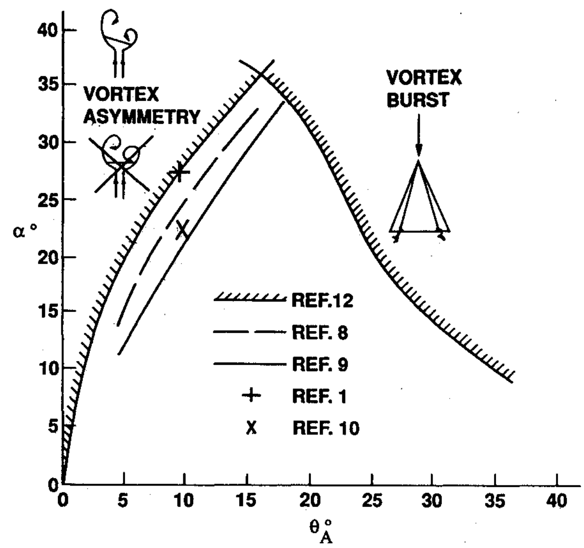

Fig. 3 Revised boundary for asymmetric vortex shedding from delta wings.[5]

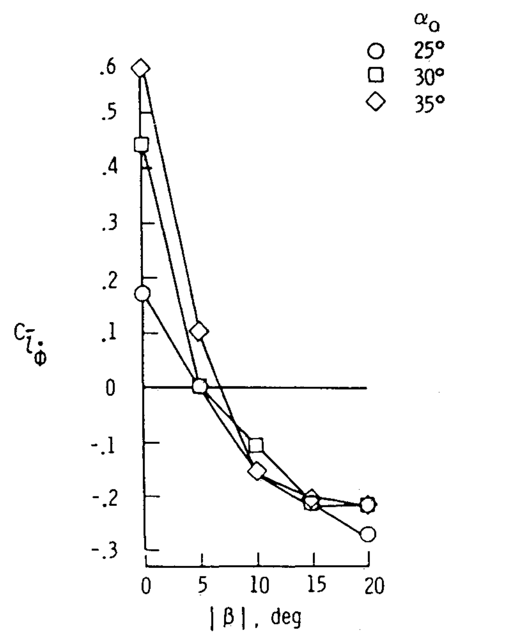

Fig. 4 Effect of sideslip on the roll damping of 80-deg delta wing measured in forced roll oscillations of 10-deg amplitude at $\phi = 0$.[1]

on the windward wing brings the net damping to zero, resulting in the observed[1] and predicted[2,3] large limit cycle amplitude. Although bearing friction delayed the start of wing rock in the test,[1] it didn't have a significant influence on the magnitude of the final limit-cycle amplitude, because it is largely determined by the magnitude of the huge, discontinuous change of the rolling moment generated by the vortex liftoff.[2] The main effect of the bearing friction was to move the wing-rock boundary (for $\beta = 0$, $\phi = 0$) to a higher angle of attack (Fig. 3). The predicted free-flight boundary[5] is shown by the solid line and the boundary determined in water-tunnel tests[8] is shown by the dashed line. The bearing friction had less of a chance to affect the results in the denser fluid (water) than in the test in air of an 80 deg ($\theta_A = 10$ deg) delta wing[1] (+ data point at $\alpha = 27$ deg in Fig. 3). An even lower effect of friction was apparently realized in a wind-tunnel test using an air bearing,[10] producing wing rock closer to the free-flight boundary[5] (× data point at $\theta_A = 10$ deg and $\alpha = 22$ deg in Fig. 3). The main effect of friction on the amplitude characteristics (as exemplified by Fig. 1) is to delay the occurrence of wing rock and make the resulting rise steeper to the limit cycle amplitude when vortex lifoff occurs.

The forced oscillation results[1] shown in Fig. 4 for the 80 deg ($\theta_A = 10$ deg) delta wing are for a moderate roll amplitude ($\Delta\phi = 10$ deg). Thus, at $\alpha = 25$ deg the flow asymmetry apparently never became large enough to cause vortex liftoff at $\beta = 0$. However, at the higher angles of attack, $\alpha = 30$ and 35 deg, vortex asymmetry did occur, resulting in substantially increased undamping.

It is shown in Ref. 2 how the effective leading-edge sweep $(\Lambda - \bar{\theta}_A)$ is affected by roll and sideslip angles. The effective apex half-angle $\bar{\theta}_A$ can be expressed as follows:

$$\bar{\theta}_A = \theta_A + \Delta\theta_A \tag{1a}$$

$$(\Delta\theta_A)_{R,L} = \pm\tan^{-1}(\tan\alpha\sin\phi) \tag{1b}$$

$$(\Delta\theta_A)_{R,L} = \tan^{-1}(\tan\beta/\cos\alpha) \tag{1c}$$

The plus sign refers to the right (starboard) wing half, and the minus sign to the opposite wing half. Equating $\Delta\theta_A$ due to roll and sideslip gives the following roll-induced effective sideslip:

$$\Delta\beta = \tan^{-1}(\sin\alpha\sin\phi) \tag{2}$$

For $\phi = \Delta\phi = 10$ deg, Eq. (2) gives $\Delta\beta = 4.26$, 5.0, and 5.7 deg for $\alpha = 25$, 30, and 35 deg, respectively. The results for $|\beta| = 0$ in Fig. 4 indicate that $|\beta| + \Delta\beta > 4.26$ deg is needed for vortex liftoff on the leeside wing. Thus, at $|\beta| \geq 4.26$ deg leeside vortex liftoff will occur during the roll-oscillation at $\alpha = 25$ deg. In Fig. 5 the predictions[8] at $\alpha = 25$ deg are shown for two intact leading-edge vortices at $|\beta| \leq 4.26$ deg and for only one active vortex at $|\beta| \geq 4.26$ deg. The predictions are in rather good agreement with the experimental results, especially when one considers that the predictions are the locally linearized values $C_{l\dot{\phi}}$ for infinitesimal roll amplitude, whereas the experimental results are the measured integrated values $C_{\bar{l}\dot{\phi}}$ for $\Delta\phi = 10$ deg. The effect of leeside vortex liftoff some time during the oscillation at $|\beta| > 4.26$ deg may account for the deviation between prediction and experiment at $|\beta| = 5$ deg in Fig. 5. A nonlinear analysis is needed to include this effect.

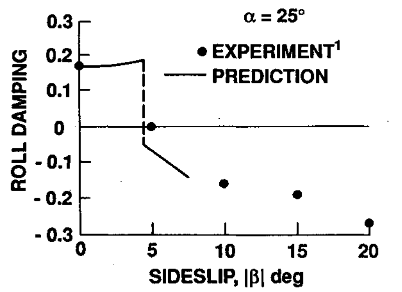

Fig. 5 Comparison of predicted and measured effect of sideslip on the roll damping of 80-deg delta wing at α = 25 deg.

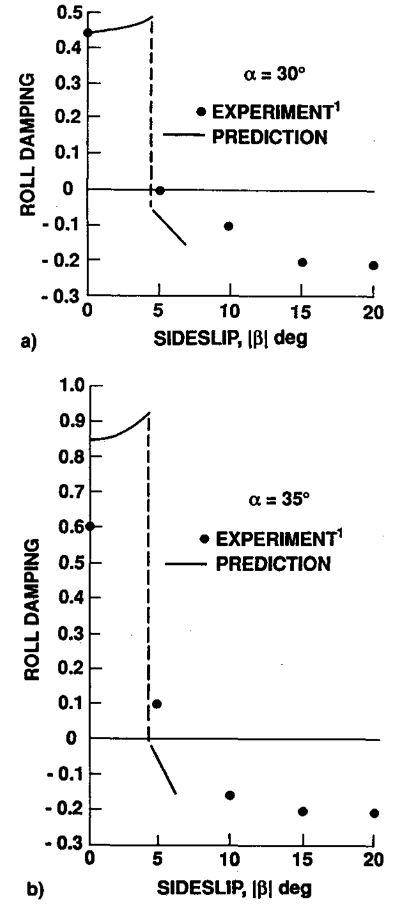

Fig. 6 Comparison of predicted and measured roll damping of 80-deg delta wing: a) α = 30 deg, b) α = 35 deg.

As the angle of attack is increased, the leeside vortex liftoff will occur earlier, at a lower effective apex half-angle $\bar{\theta}_A$ in Fig. 3. That is, on the oscillating delta wing it will occur at a lower $\Delta\theta_A$, Eq. (1b), closer to ϕ = 0, where $|\dot{\phi}|$ is maximum. Thus, the nonlinear undamping effect will increase (which is also the data trend displayed in Fig. 6) at least for α = 35 deg, (Fig. 6b). The deviation at $|\beta|$ = 0 for α = 35 deg is probably caused by vortex breakdown on the windward side.[2,3] The experimental results[11] in Fig. 7 show that for Λ = 80 deg − 5.7 deg = 74.3 deg, vortex breakdown will occur when $\alpha \geq 35$ deg.

That vortex liftoff can occur on one wing half, without interaction from the leading-edge vortex from the opposite side, is demonstrated by the experimental results at α = 25 deg for an 85-deg delta wing, described in Ref. 7 as follows:

> As α increases to 25°, however, one of the vortices stays attached to the surface without bursting throughout the wing rock cycle, while the other vortex goes through the lift-off and reattachment-breakdown process. The observed wing rock motion is nevertheless rather steady. At α = 35°, regular wing rock is replaced by erratic rolling motions.

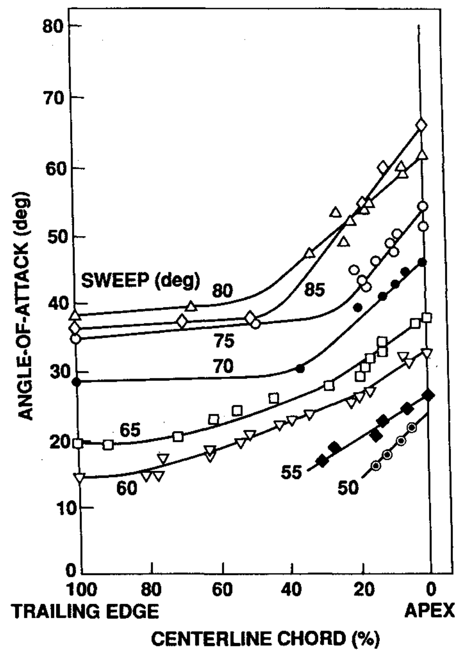

Fig. 7 Vortex breakdown position on sharp-edged delta wings.[11]

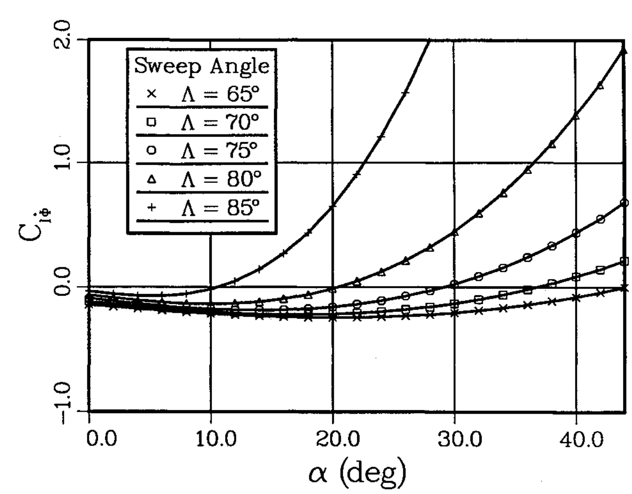

Fig. 8 Effect of leading-edge sweep on delta wing roll damping at β = ϕ = 0.[9]

Based upon Polhamus' leading-edge suction analogy,[12] the ratio between vortex-induced and attached-flow lift contributions is

$$\tfrac{1}{2}(\tan\alpha/\tan\theta_{LE})\cos^2\theta_{LE} \tag{3}$$

For θ_{LE} = 5 deg, i.e., Λ = 85 deg, Eq. (3) shows that the lift, and therefore, the rolling moment, is almost exclusively generated by the leading-edge vortices at $\alpha \geq 25$ deg. This explains how the vortex-induced loads on one wing half can generate wing rock around a nonzero roll angle.

Based upon the agreement between prediction[9] and experiment[1] for the 80-deg delta wing shown in Fig. 2, the predicted large effect of leading-edge sweep shown in Fig. 8 is credible. Thus, the 85-deg delta wing should lose its roll damping when α = 11 deg is exceeded. In the test,[8] wing rock was observed at $\alpha \geq 17$ deg and was associated with asymmetric vortex liftoff. This supplied the extra undamping needed to overcome the bearing friction, just as in the case of the 80-deg delta wing.

At α = 25 deg, however, one vortex stayed attached and the other vortex went through the vortex liftoff/vortex breakdown process, apparently single-handedly supplying the wing rock mechanism described in Refs. 2 and 3 for the case that both vortices are working together. Remembering that the attached flow damping decreases with increasing angle of attack,[9] the results in Fig. 8 indicate that one leading-edge vortex by itself would be able to provide the undamping needed to cancel the attached flow damping when $\alpha > 12.5$ deg. And bearing friction could of course have delayed the occurrence of wing rock to $\alpha = 17$ deg. However, the wing rock that did occur at $\alpha = 17$ deg was of the regular, "double-sided" type. The "single-sided" type did not occur until $\alpha \geq 25$ deg. Why?

"Most of the tests were conducted with two 0.040″ diameter dye tubes taped along the mid-span of the model on the windward side, with the tube outlets located near the apex of the model." (The center chord was 10 in. long.) One is inclined to conclude that at $\alpha = 17$ deg the windward side disturbance was not close enough to apex to severely interfere with the leeward flow near apex, but that this became possible at higher angles of attack, e.g., at $\alpha = 25$ deg. This is in agreement with the fact that when the tubes were placed on the leeward side, regular wing rock, similar to that of the 80-deg delta wing, occurred through the range of angle of attacks tested, up to $\alpha = 38$ deg. Apparently, the windward side placement of the tube outlets generated the leeward side flow asymmetry, resulting in the observed asymmetric wing rock around a nonzero time-average roll angle. The extreme sensitivity of leeside vortex flow to minute windward side protuberances is well-documented.[13]

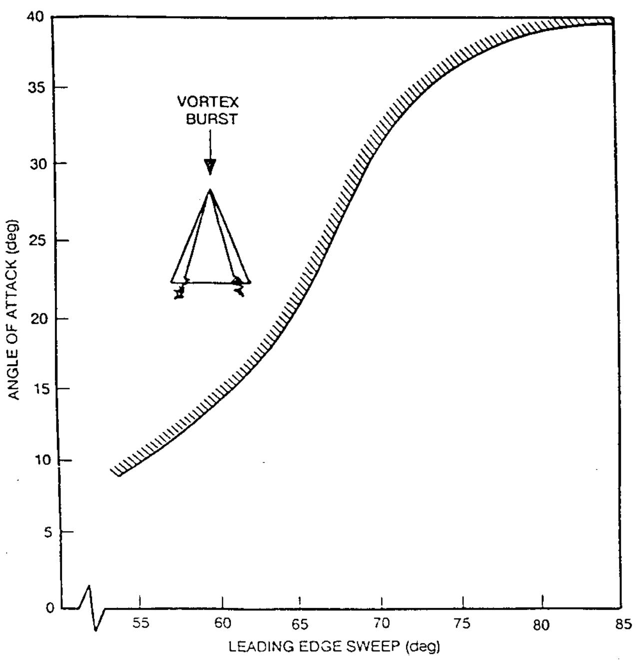

Fig. 9 Effect of leading-edge sweep on α boundary for vortex breakdown on delta wings.[12]

Figure 8 shows that the roll damping is lost for a 75-deg delta wing when the angle of attack exceeds $\alpha = 29$ deg. In the test,[8] wing rock was observed at $\alpha = 31$ deg without the occurrence of vortex liftoff (or vortex breakdown). The fact that the bearing friction could be overcome without resorting to the undamping contribution from vortex liftoff is probably due to the 50% increase of the wing area compared to the 80-deg delta wing, providing a fluid dynamic rolling moment that is 125% larger.

At $\alpha = 35$ deg, the boundary for vortex breakdown will be penetrated during roll oscillations of a 75-deg delta wing[12] (see Fig. 9). What was observed in the test[8] (Fig. 10) was that vortex breakdown occurred on one side of the wing and stayed there during the wing rock motion. It could occur on either wing half, but would not switch sides during the rocking motion.

No vortex liftoff, of the type that occurred on the 80- and 85-deg delta wings, was observed on the 75-deg wing. Instead, the moment driving the wing rock was supplied entirely by the undamping generated by the attached leading-edge vortices (see Fig. 8). The amplitude-limiting mechanism was vortex breakdown, just as in the case of the 80-deg delta wing.[3]

Why do the 75- and 85-deg delta wings exhibit asymmetric, single-sided wing rock while the 80-deg delta wing does not?

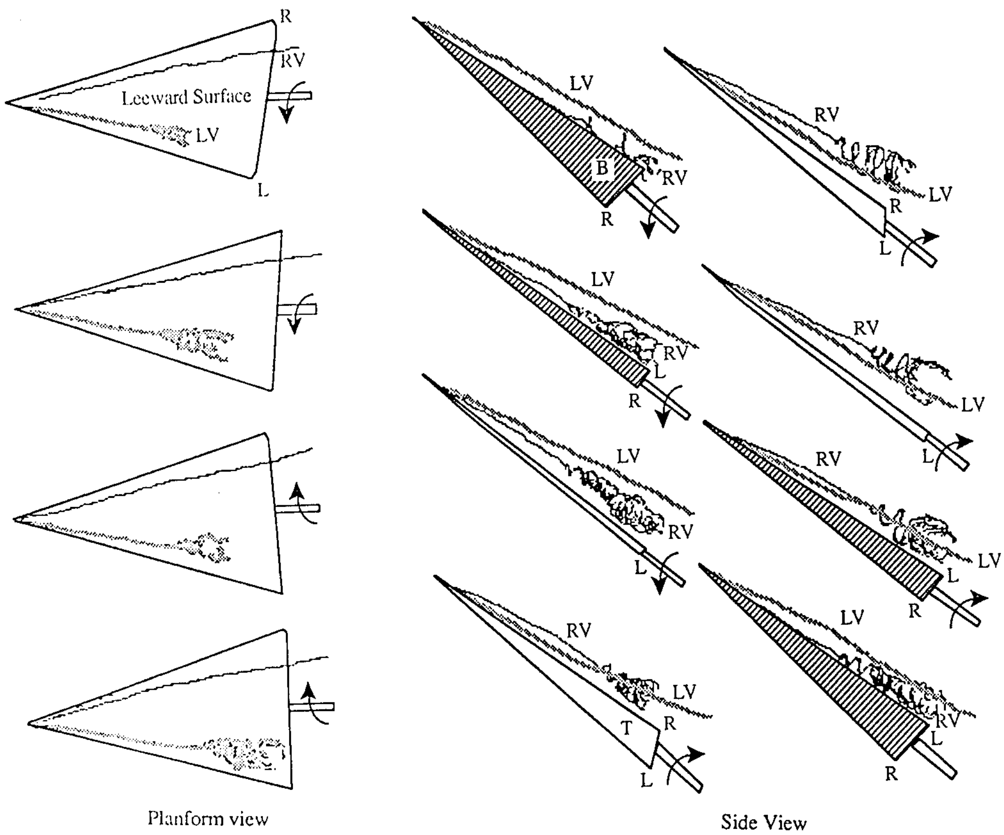

Fig. 10 Wing rock motion of 75-deg delta wing at $\alpha = 35$ deg.[8]

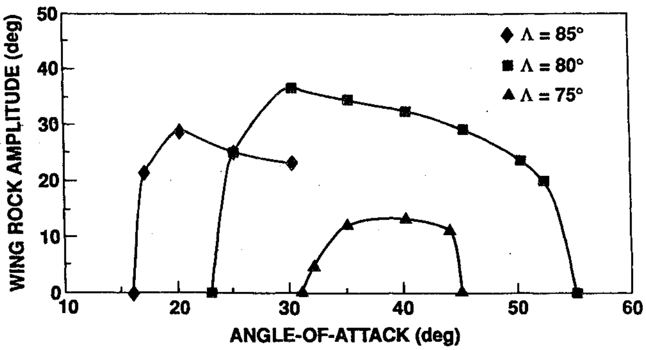

Fig. 11 Measured wing-rock amplitude as a function of angle of attack.[8]

It could, of course, be a matter of slight differences in how the windward side tube outlets were located. However, a more likely reason is that only the narrow 85-deg delta wing exhibited the flow asymmetry generated by a windward side protuberance (the pair of tube outlets), and that the reason for the single-sided wing rock of the 75-deg delta wing is the occurrence of vortex breakdown. Figure 7 shows that vortex breakdown will have a large statically destabilizing effect, which could prevent the return to $\phi = 0$ of the time-average roll angle.

Going back to Fig. 9, one observes that for the 75-deg delta wing, vortex breakdown should occur on both wing halves, already at $\Phi = 0$, when alpha is increased beyond $\alpha = 37$ deg. This is also what was observed at $\alpha = 40$ deg in the test.[8] Vortex breakdown occurred on both wing halves. Longitudinally the breakdown movement was larger in this case than for the single-sided case at $\alpha = 35$ deg. This type of wing rock persisted until the angle of attack approached $\alpha = 45$ deg, when vortex breakdown occurred very close to the apex and the rocking motion became damped.

This demonstrated existence of single-sided wing rock has far-reaching consequences in regard to advanced aircraft performing high alpha maneuvers. It indicates that slender wing rock will occur much more frequently than what has been assumed,[14] based upon the "crowding" theory.[2,4]

Figure 11 shows the magnitude of the wing-rock limit-cycle amplitude measured for the three delta wings tested.[8] It can be seen that the single-sided wing rock mechanism can generate significant roll amplitudes, $\Delta\phi \leq 30$ deg for $\Lambda = 85$ deg and $\Delta\phi \leq 15$ deg for $\Lambda = 75$ deg. That is, the phenomenon is of importance for high-agility fighter aircraft.

Conclusions

A re-examination of wing rock in view of recent experimental results leads to the following conclusions:

1. Asymmetric liftoff of the leading-edge vortices on slender delta wings does not start the wing rock observed in experiments. It is, however, the mechanism leading to the observed very large limit-cycle amplitudes in roll. The magnitude of the wing rock amplitude is limited by breakdown of the vortex that is not lifted-off.
2. Slender wing rock is not critically dependent upon interaction between the two leading-edge vortices on a delta wing, but can be generated by the vortex-induced rolling moment on one wing half, usually involving both vortex liftoff and vortex breakdown.
3. As a consequence of the characteristics outlined above, slender wing rock is a phenomenon of much more concern than previously thought to the designer of high agility aircraft and aerospace vehicles in general, operating at high angles of attack.

Acknowledgment

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