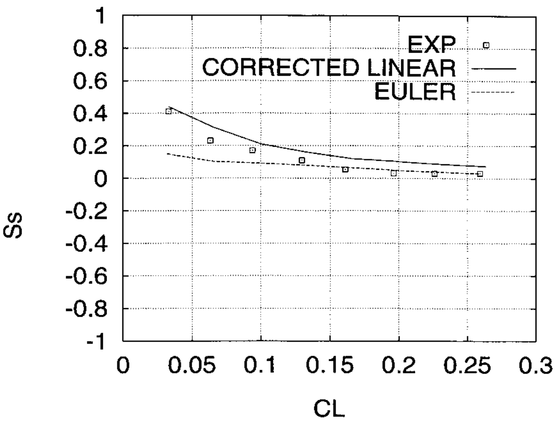

Fig. 5 Carlson arrow wing, M_∞ = 2.05, suction parameter vs lift coefficient.

A better understanding of the results can be obtained by introducing the suction parameter:

$$S_s = \frac{C_L \cdot \tan(C_L/C_{L\alpha}) - \Delta C_D}{C_L \cdot \tan(C_L/C_{L\alpha}) - C_L^2/(\pi \cdot AR)}$$

With such parameter the computed drag is compared with the upper bound (i.e., drag of a flat wing with no thrust and vortex forces) and the lower bound obtained in case of a wing with an elliptical span load distribution and the full amount of theoretical leading-edge thrust. These two limit cases are obtained for $S_s = 0$ and $S_s = 1$, respectively. Figure 5 shows that the Euler solution provides a reasonable level of suction for the highest incidences. Although the values of S_s are wrong at low incidences, the discrepancies in terms of the axial coefficient are still low. This fact can be explained by noting that when lift tends to zero, also the difference between the upper and lower bound is vanishing. These results are in disagreement with the Euler computation presented by Carlson[1] for the same wing configuration and obtained by a space-marching method. Present results seem to explain this difference by the poor accuracy at the leading edge of the pressure distribution in the Carlson[1] solution.

Conclusions

The main results of the present study can be summarized as follows:

1) Central space discretized schemes can provide reasonable flow solutions and included the primary vortex effects; the numerical model can influence the solution accuracy (for supersonic flow in particular it is strongly affected by wall boundary conditions).

2) Force coefficients obtained by pressure integration are in good agreement with the experiments.

3) The behavior of the axial force vs incidence reveals the capability of the Euler flow model to predict leading-edge thrust.

4) Euler simulation can effectively support the supersonic wing design since nonlinear semiempirical correction depends on the availability of large experimental database and is limited to specified families of wing planform.

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Computation of Vortex Breakdown on a Rolling Delta Wing

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Introduction

REFERENCE 1 presents a detailed description of the computation of several different "roll-and-hold" maneuvers (see Table 1) for an 80-deg sweep delta wing at 30-deg angle of attack. This Note focuses on one interesting feature observed for case III, dynamically induced vortex breakdown of the upward-moving edge vortex during a portion of the roll maneuver. Dynamic motion has clearly been shown to influence vortex breakdown over delta wings. Experimental investigations of delta-wing rock by both Arena[2] and Ng et al.[3] show large hysteresis loops in vortex breakdown location due to time lags in the motion of the breakdown position. Ericsson and Hanff[4] report that the dynamic effect of vortex breakdown in experiments by Hanff[5] on a 65-deg sweep rolling delta wing is controlled to a large extent by roll-rate induced camber. Pitching motions also exhibit a lag of the vortex breakdown[6] as compared to the static situation. Gursul et al.[7] have also shown in experiments with an unsteady freestream that breakdown can occur on a delta wing with increasing unsteady effects, even if no breakdown is observed in a steady freestream, similar to the situation arising in this Note.

Discussion

For the rolling motion of case III the right vortex (upward motion) exhibits a small region of vortex breakdown near the trailing edge during a portion of the roll maneuver. Figure 1 tracks the location of the vortex burst point (defined as the location of the forward stagnation point) from the initial appearance of burst at a roll angle $\phi \approx 7.77$ deg, to when the vortex burst disappears, $\phi \approx -30.95$ deg. The vortex burst crosses the wing trailing edge at a roll angle, $\phi = 3.22$ deg. The maximum upstream penetration of the breakdown is $X/L = 0.914$ at $\phi = -17.28$ deg. The burst point also shows a spanwise motion across the wing due to the rolling motion.

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Table 1 Roll maneuver parameters

Case	ϕ_i[a]	ϕ_f[b]	Φ[c]
I	0	45	0.0233
II	0	45	0.0467
III	45	−45	−0.0467

[a]Initial roll angle. [b]Final roll angle. [c]Roll rate.

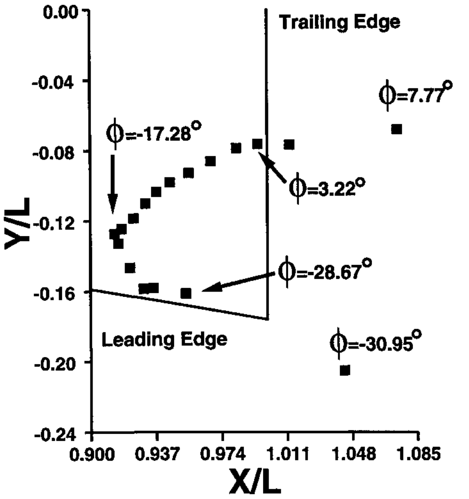

Fig. 1 Motion of right vortex burst point during roll maneuver for case III.

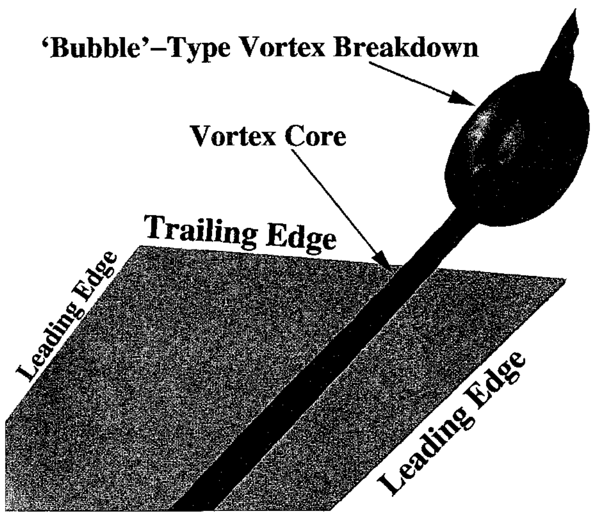

Fig. 2 Isosurface of total pressure at $\phi = -15$ deg.

The structure of the vortex breakdown at a roll angle $\phi = -15$ deg can be seen in Figs. 2 and 3. Figure 2 shows an isosurface of low total pressure. The vortex core is clearly seen as a thin, straight cylindrical region. At the point of vortex burst the vortex core swells to form a bubble-like structure, which then terminates by reforming a cylindrical core downstream of breakdown. This indicates that the breakdown observed is a "bubble"-type breakdown. This observation is further confirmed by plotting restricted particle traces on a plane passing through the core of the vortex and the breakdown bubble (Fig. 3). This figure shows that the breakdown bubble is characterized by a forward and rear saddle and a stable and unstable focus. This topology for the breakdown bubble is consistent with the flow topology for a bubble-type breakdown over a pitching delta wing observed in the computations of Visbal[8] and the experiments of Lin and Rockwell.[9]

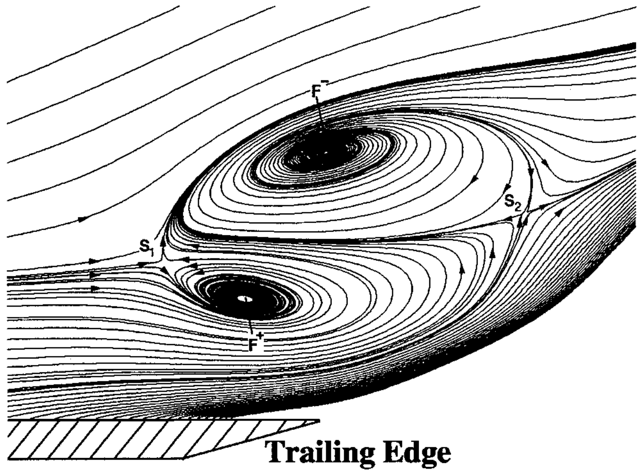

Fig. 3 Restricted particle traces on a longitudinal plane along the vortex core, $\phi = -15$ deg.

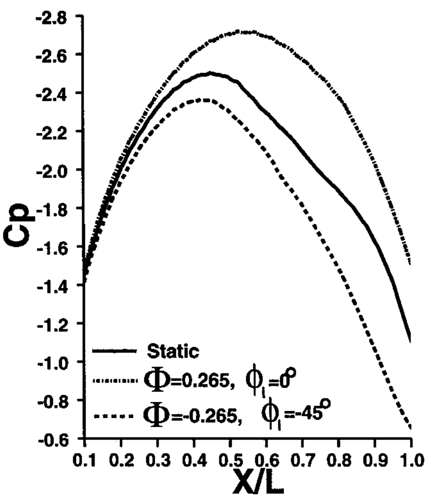

Fig. 4 Variation of pressure along the vortex core, $\phi = 26$ deg.

Since the breakdown that occurs is rather mild, with the maximum extent of breakdown being approximately 0.2 and a maximum reverse-flow, axial velocity of −0.475, it is difficult to identify the precise cause of the vortex breakdown. Several factors contribute to vortex breakdown, however. Lambourne and Bryer[10] have shown that longitudinal camber has a large effect on the breakdown of a vortex over a delta wing, with positive camber delaying breakdown and negative camber promoting breakdown. Ericsson[4] points out that roll-rate induced camber delays vortex breakdown on the downstroking span and promotes it on the upstroking span of a rolling delta wing. The roll-rate induced camber is given by the following relation:

$$|\Delta\alpha_{LE}| = |\Phi| \tan \Lambda \sec \alpha \quad (1)$$

For case III this gives $|\Delta\alpha_{LE}| = 3.1$ deg or $|\Delta\alpha_{LE}|/\alpha = 0.1$, whereas the effects of Lambourne and Bryer were for $|\Delta\alpha_{LE}|/\alpha = 1$. While the value of $|\Delta\alpha_{LE}|/\alpha$ is smaller by an order of magnitude than that of Lambourne and Bryer, the effect they showed on breakdown was very large. Therefore, it seems reasonable that even this small camber effect could contribute to inducing the mild breakdown observed here.

Another contributing factor to the appearance of the vortex breakdown is convective time lags along the vortex core. The importance of time-lag effects in the dynamics of a rolling motion have been discussed by several authors.[2,3,11,12] Figure 4 plots the pressure along a streamline that follows the core of the right vortex at a roll angle of 26 deg for case II, case III, and the static case. Both Lambourne and Bryer[10] and Gursul et al.[7] have shown that an adverse pressure gradient along the vortex core is one of the driving factors of vortex breakdown. All three cases show an initial region of expansion (favorable pressure gradient) followed by a region of compression (adverse pressure gradient). The pressure in the forward-rolling case shows a smaller region of adverse pressure gradient than the static case, while the backward-rolling case shows a larger region of adverse pressure gradient. Furthermore, the pressure increase for the backward-rolling case, $\Delta Cp = 1.7$ is greater than both the static case, $\Delta Cp = 1.42$, and the forward-rolling case, $\Delta Cp = 1.2$. This difference in behavior between the forward- and backward-rolling cases persists as the roll angle continues to decrease and vortex breakdown occurs. The more extensive and larger adverse pressure region due to the lag in the adjustment of the pressure along the vortex core tends to promote breakdown of the vortex. Conversely, the less extensive and smaller adverse pressure region in the forward-rolling case tends to further delay any appearance of breakdown.

Finally, the initial roll angle for the maneuver must also play a role in whether or not breakdown is observed, since vortex breakdown does not occur in the upward-moving edge vortex for case II with an initial roll angle, $\phi_i = 0$ deg, but does occur in the upward-moving edge vortex for case III, $\phi_i = 45$ deg. The influence of initial roll angle can be explained in part by quasistatic effects. For a delta wing at nonzero roll angle, an effective angle of attack and sweep angle can be defined from geometric considerations as follows[13]:

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

$$\Lambda_{\text{eff}} = \Lambda \pm \tan^{-1}(\tan \alpha \sin \phi) \tag{3}$$

For positive roll angles this leads to smaller effective sweep angles for the leading edge that is rolled down, and larger effective sweep angles for the edge that is rolled up. The effective angle of attack of the wing is also reduced. For case II where $\phi_i = 0$ deg, the upward-moving leading edge has increasing effective sweep and reduced effective angle of attack as the wing rolls, both tending to delay breakdown. Alternately, for case III where $\phi_i = 45$ deg, the upward-moving leading edge starts with a much lower effective sweep angle, $\Lambda_{\text{eff}} = 58$ deg, which tends to promote breakdown. Since the effect of the loss in effective angle of attack tends to be less dominant than the lowering of the effective sweep angle, this leading-edge vortex should be more susceptible to the dynamic effects that promote breakdown than the vortex in case II.

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