Incompressible Navier-Stokes Computations for a Round-Edged Double-Delta Wing

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Numerical Results

The finite-difference solutions for $Re = 1.3 \times 10^6$ are carried out in 32-bit word arithmetic on the CDC CYBER 205 vector computer at NASA Ames Research Center. The CPU time per grid point per iteration is 37.3 μs. All steady-state solutions are calculated with local time stepping (CFL = 10). Within about 750 iterations, the L_2 norms of all residuals are reduced by three orders of magnitude for $\alpha = 12$ and 20 deg and by nearly two orders of magnitude for $\alpha = 40$ deg.

Computed total pressure contours at $x/c = 0.50$, 0.55, and 0.95 for $\alpha = 12$ deg are shown in Fig. 1. At the kink crossplane ($x/c = 0.50$), both the primary stake vortex and its induced secondary vortex above each half-wing are visible (Fig. 1a). Above the stake, the crossflow pattern is similar to that at the kink crossplane. Downstream of the kink crossplane at $x/c = 0.55$ (Fig. 1b), an additional vortex, the wing vortex, is clearly indicated. Further downstream, the weaker stake vortex moves downward and outboard and the stronger wing vortex moves upward and inboard. At $x/c = 0.95$ (Fig. 1c), the two primary vortices have almost merged into one single vortex above each half-wing. Figure 2 shows that the computational and experimental[1] vortical trajectories (local total pressure minima) of the two interacting primary vortices compare quite well with each other.

Figure 3 exhibits the distributions of spanwise surface-pressure coefficients. At $x/c = 0.55$ (Fig. 3a), the outer wing vortex induces a much higher suction-pressure peak than that of the inner stake vortex. At $x/c = 0.75$ (Fig. 3b), the predicted levels of suction pressure are lower than the experimental data[1] at $\alpha = 12$ deg; the locations of the static pressure minima are not accurately predicted either. This discrepancy can probably be attributed to the insufficient crossflow resolution. More resolution is required in the neighborhood of the vortical cores for precise predictions of surface-pressure distribution.

Figure 4 displays the lift variation with the angle of attack for the present full incompressible Navier-Stokes solutions (squares), for Fujii and Schiff's thin-layer compressible Navier-Stokes calculations[4] (triangles), and for Brennenstuhl and Hummel's wind-tunnel data[1] (circles). Both numerical and experimental results indicate that the lift variation is nonlinear with respect to the angle of attack due to the vortex formation, interaction, and breakdown. Fujii and Schiff's computations ($M_\infty = 0.3$) with thousands of iterations were carried out on a grid of 853,349 points. Their predicted lift coefficients compare very well with the experimental data up to $\alpha \approx 27$ deg; at $\alpha > 27$ deg their values are underpredicted. In the present calculations ($M_\infty = 0.0$), the asymptotic steady-state lift coefficients are obtained within 600 iterations and they are in good agreement with experimental data over the entire range of angle of attack, the predicted maximum lift coefficient up to but not including $\alpha = 40$ deg. ($C_{L_{max}} = 1.20$) at $\alpha = 30$ deg agrees closely with the measured maximum lift coefficient ($C_{L_{max}} = 1.21$) at $\alpha \approx 27$ deg. Computed results at

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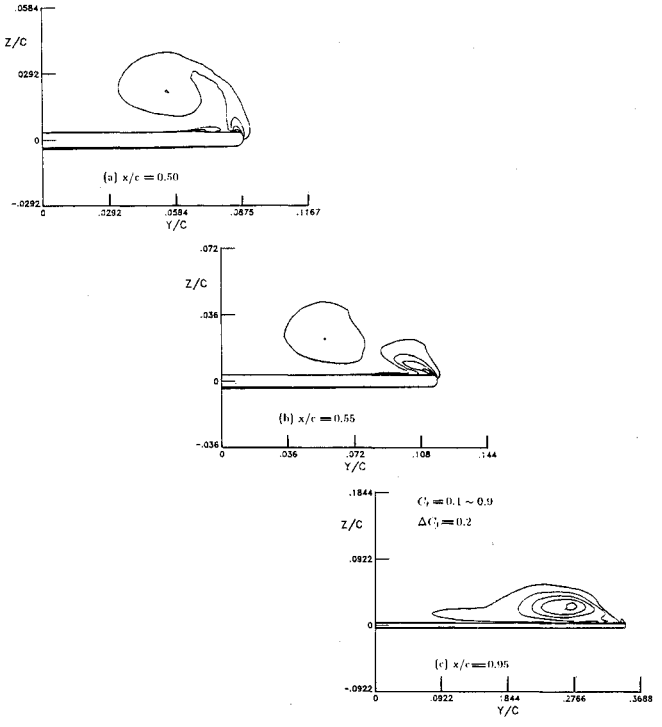

Fig. 1 Total pressure contours at $\alpha = 12$ deg.

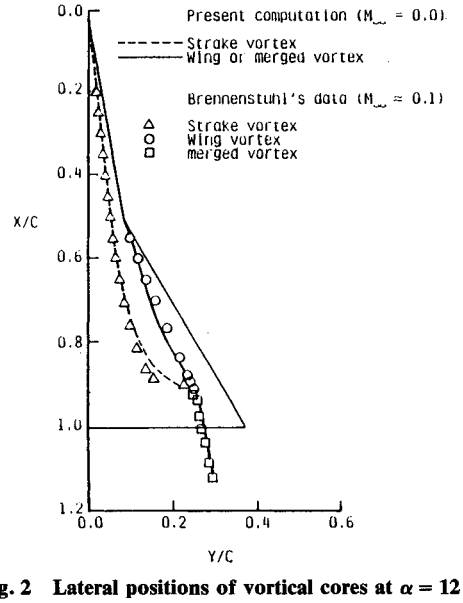

Fig. 2 Lateral positions of vortical cores at $\alpha = 12$ deg.

$\alpha = 40$ deg reveal a clear bubble-type vortex breakdown. The breakdown zone (reversal-flow region) extends from $x/c \approx 0.6$ to the trailing edge. Although large scale vortical structures are well simulated, further computational efforts with greater mesh resolution are needed to fully resolve the detailed structure of the vortical flow. This will, hopefully, also remove the differences between prediction and experiment in Fig. 3b and in Fig. 4 for $\alpha = 40$ deg.

Conclusions

The complex vortical flow over a round-edged double-delta wing has been simulated numerically by solving the incompressible Navier-Stokes equations via an upwind-relaxation finite-difference scheme. Key features of both vortical interation and vortex breakdown are simulated. Computed lift

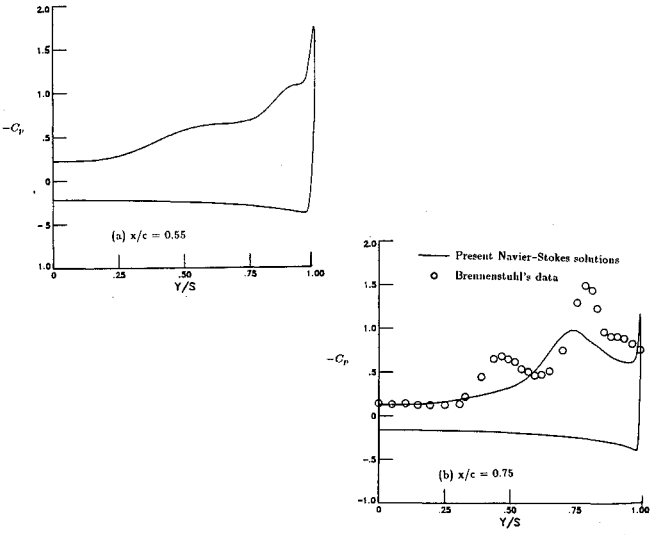

Fig. 3 Spanwise surface-pressrue distributions at $\alpha = 12$ deg (s = local semispan).

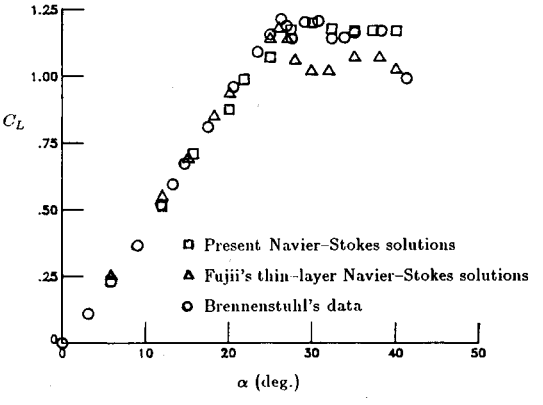

Fig. 4 Lift variation with angle of attack.

coefficients and lateral trajectories of the vortical cores are in reasonably good agreement with experimental data. Future efforts will concentrate on obtaining a better agreement between computational and experimental surface-pressure distributions.

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