Prediction of Vortical Flows on Wings Using Incompressible Navier-Stokes Equations

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Abstract

STEADY-STATE Navier-Stokes solutions are obtained for a round-edged double-delta wing using an upwing-relaxation finite-difference algorithm. The effects of grid density and Reynolds number on integral values and static pressure distributions are studied. Computed longitudinal aerodynamic coefficients are in good agreement with available experimental data, but the magnitudes of suction-pressure peaks are underpredicted in the vicinity of the trailing edge.

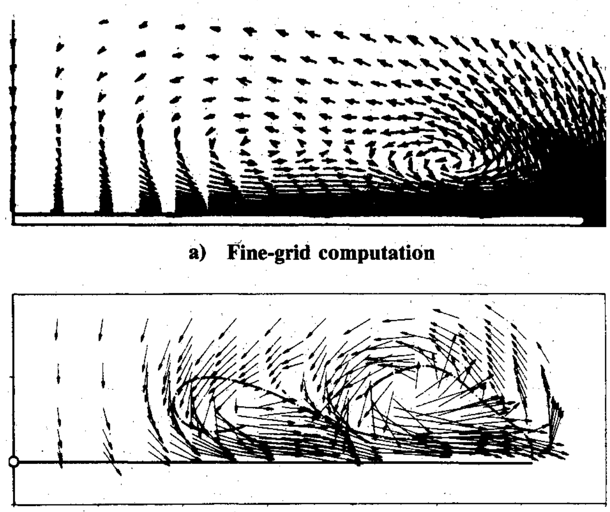
Contents

An incompressible Navier-Stokes solver has been developed to obtain steady-state finite-difference solutions to the three-dimensional, incompressible Navier-Stokes equations using the concept of artificial compressibility.[1,2] Since the numerical scheme employs upwind differencing, it is inherently dissipative. The solver has been successfully applied to three slender delta-like wings.[3] In this paper, the flow over a 80-60-deg round-edged double-delta wing is investigated.

Three elliptic grids are generated for the double-delta wing.[3] They are 1) coarse grid ($65 \times 65 \times 59$), 2) medium grid ($81 \times 119 \times 59$), and 3) fine grid ($97 \times 167 \times 59$). Each three-dimensional grid is composed of 59 crossplanes that are perpendicular to the longitudinal axis of the wing.

Crossflow velocity vectors at $x = 0.75$ (crossplane at 75% root chord) are shown in Figs. 1 for $\alpha = 12$ deg and $Re = 1.3 \times 10^6$ (based on the wing root chord). Fine-grid computations are shown in Fig. 1a. Both strake (inner) and wing (outer) vortices are indicated clearly by the flow directions. Underneath the two vortices and above the upper wing surface, large velocity components are observed, which are caused by the ground or image effect of the vortices due to the existence of the solid wing surface. Comparison with the experiment[4] (Fig. 1b) shows that major features of vortical interaction have been simulated.

Computed spanwise surface static pressure distributions are in fairly good agreement with available measured data, except for the vicinity of the trailing edge.[3] The effects of grid refinement on the spanwise surface static pressure distributions at $x = 0.75$ for $\alpha = 12$ deg and $Re = 1.3 \times 10^6$ are shown in Fig. 2. Coarse-grid calculations predict the lowest suction-pressure peak. Medium-grid results indicate that the wing vortex is located inboard, the effect of the secondary separation is visible, and the suction-pressure peak is higher. Fine-grid computations show that the wing vortex is located further inboard and match better with the experimental data.[4] Computed magnitudes of suction-pressure peaks are underpredicted due to the lack of grid resolution in the vortical flow region. Note



a) Fine-grid computation

b) Experiment[4]

Fig. 1 Crossflow velocity vectors at $x = 0.75$: $\alpha = 12$ deg, $Re = 1.3 \times 10^6$.

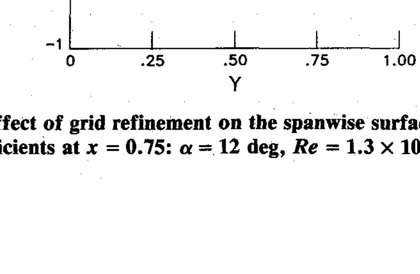


Fig. 2 Effect of grid refinement on the spanwise surface static pressure coefficients at $x = 0.75$: $\alpha = 12$ deg, $Re = 1.3 \times 10^6$.

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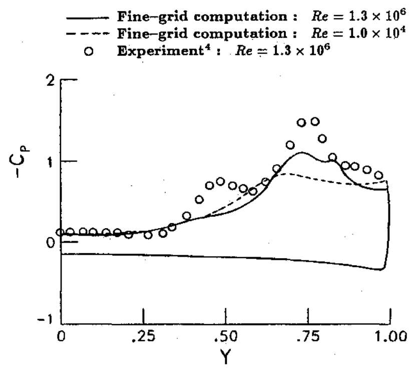
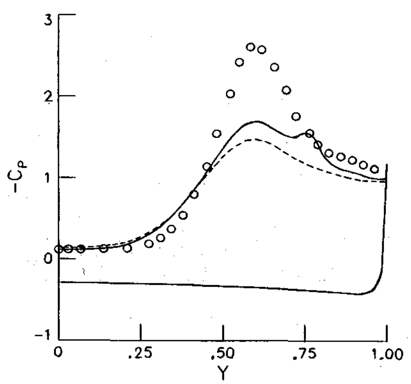
Table 1 Grid effects

Grid	C_L	C_D	C_M	α, deg
65 × 65 × 59	0.501	0.112	−0.098	12
81 × 119 × 59	0.518	0.118	−0.106	12
97 × 167 × 59	0.529	0.120	−0.106	12
Experiment[4]	0.525	0.121	−0.107	12
65 × 65 × 59	0.880	0.328	−0.168	20
81 × 119 × 59	0.919	0.342	−0.177	20
97 × 167 × 59	0.938	0.351	−0.186	20
Experiment[4]	0.935	0.354	−0.180	20



a) $\alpha = 12$ deg



b) $\alpha = 20$ deg

Fig. 3 Effect of Reynolds number on the spanwise surface static pressure coefficients at $x = 0.75$.

that the predicted pressure distributions on the lower surface are not affected by grid refinement.

Comparison of lift C_L, drag C_D, and pitching moment C_M coefficients at $\alpha = 12$ and 20 deg is shown in Table 1 for different grid levels. Note that the pitching moment coefficient is referred to the quarter chord of the mean aerodynamic chord. Both fine- and medium-grid computations for the lift, drag, and pitching moment coefficients are in good agreement with the experimental data.[4] Although coarse-grid results indicate underpredicted aerodynamic coefficients, these results are reasonably good for engineering purposes.

Table 2 Reynolds number effects

Re	C_L	C_D	C_M	α, deg
1.0×10^4	0.453	0.356	−0.097	12
1.3×10^6	0.529	0.120	−0.106	12
1.0×10^4	0.782	0.576	−0.164	20
1.3×10^6	0.937	0.351	−0.186	20

Fine-grid computations with Reynolds numbers of 1.0×10^4 and 1.3×10^6 are presented in Figs. 3 for $\alpha = 12$ and 20 deg. Spanwise surface static pressure distributions at $x = 0.75$ indicate that with increasing Reynolds number the wing vortex lies further outboard, the induced suction-pressure peak rises higher, and the effect of secondary separation due to the wing vortex becomes stronger. The variation in the spanwise vortical core positions with Reynolds number is very similar to that shown in Thompson's[5] towing-tank results ($Re = 7.0 \times 10^3 \approx 1.0 \times 10^5$) and Brennenstuhl and Hummel's[4] wind-tunnel results ($Re = 1.3 \times 10^6$). For $\alpha = 20$ deg, predicted magnitudes of suction-pressure peaks are much lower than the measured data. This suggests that much finer grids are required to resolve the interaction of the leading-edge vortices at higher angles of attack. In addition, the magnitude of the suction-pressure peak due to the secondary separation induced by the merged vortex is predicted too high because the laminar flow calculations are inadequate near the trailing edge.

Comparison of aerodynamic coefficients for the two Reynolds numbers is shown in Table 2 for $\alpha = 12$ and 20 deg. As Reynolds number is increased, the magnitudes of the lift and pitching moment coefficients increase, but the value of drag coefficient decreases.

Although important flow characteristics of vortical interaction have been successfully simulated, even the fine-grid computations underpredict the magnitudes of suction-pressure peaks in the vicinity of the trailing edge. Additional computations employing finer grid resolutions in the vortical flow region are required. Since the actual flow is transitional or fully turbulent, a proper turbulence model that is applicable to a rotational flow such as a vortex is urgently needed.

Acknowledgment

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