Technical Notes

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Vortex-Fitted Potential and Vortex-Captured Euler Solution for Leading-Edge Vortex Flow

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Introduction

PRESENTLY, there are two methods for computing the detailed flowfield about wings with leading-edge vortex flow (see Ref. 1 for a review). In the first method, potential flow is assumed and the free shear layers are modeled by vortex sheets across which the velocity potential is discontinuous. The vortex cores are modeled by isolated line vortices. The position and strength of the vortex sheets and isolated vortices are to be solved for as part of the solution. In this case one speaks of "fitting" the rotational flow regions, i.e., one has to decide a priori on their presence and account for them explicitly. This implies that the topology of the flow must be well-defined and known in advance. In addition, the computer requirements of potential flow methods are relatively modest. This method is presently relatively well-established and, in general, its results are in reasonable agreement with experimental data. The second method is based on Euler's equations in which rotational flow is allowed everywhere and vortical flow regions are "captured" implicitly as an integral part of the solution. This renders these methods rather attractive for cases where the vortex flow topology is complex or unknown entirely. The computer requirements of methods solving Euler's equations can already be met by the present generation of supercomputers. This method is currently in the development stage at various institutes and is beginning to demonstrate its potential capabilities.

The objective of the present study, a cooperative effort of NLR and FFA, is to gain some insight into a number of questions concerning the results of current Euler codes that have not yet been resolved satisfactorily. Two such questions are:

1) How realistic are the vortex layers captured in the Euler solution; are they indeed a representation by numerical and artificial viscosity effects of smeared vortex sheets?

2) How do the total pressure losses commonly observed in the solution affect the flowfield outside the vortical flow regions and, in particular, the velocity and pressure distribution on the wing surface?

To shed some light on these matters, a detailed comparison is made of the results of a potential flow method and an Euler code.

The test case chosen is a 70-deg, swept, flat-plate delta wing at 20-deg incidence in incompressible flow. This case was chosen because it demonstrates a well-developed vortical flow region above the upper surface of the wing, without the complication of vortex breakdown above the wing surface and presumably also without large secondary-separation effects, which would both violate the assumption of inviscid flow. Incompressible flow was decided upon because 1) a panel method can be used to solve the governing equation for potential flow exactly, 2) the rotational flow effects can be studied in isolation without the added complexity of compressibility effects and their possible mutual coupling, and 3) low-speed vortex flow is of practical interest in itself.

The purpose of this Note is to present the first results of a detailed comparison of numerical results of the Euler code for incompressible flow, developed at FFA, and numerical results of the panel method for computing the potential flow about wings with leading-edge vortex sheets, developed at NLR.

Computational Methods

The computational method used to solve the potential flow problem is a second-order panel method, designated VORSEP, for the three-dimensional incompressible flow about thin slender wings with leading-edge vortex sheets. In this method, the wing, leading-edge vortex sheet, and wake are modeled by a doublet distribution. The core of the leading-edge vortex is modeled by an isolated line vortex connected to the sheet by a so-called feeding sheet. The method solves for the strength of the doublet distribution and the location of the leading-edge vortex sheet, wake, and vortex core. Details of the method are provided in Ref. 2.

In the computational method used to solve Euler's equations for incompressible flow, Chorin's[3] artificial compressibility concept is employed. The resulting system of hyperbolic equations is solved by a finite-volume difference scheme, centered in space, and combined with explicit multistage time stepping developed earlier for the compressible Euler equations. The necessary artificial viscosity model contains fourth differences. (More details of the method are described in Ref. 4.) In this method rotational flow is allowed throughout the flow and vortex sheets and vortex cores are captured automatically.

Comparison of Computed Results

Panel Scheme—Spatial Mesh

The panel method solution has been obtained employing a panel scheme consisting of 13 spanwise strips of 36 panels each, 468 panels in total. The surface of the wing is represented by 10 strips of 20 panels each, 200 panels in total, providing sufficient resolution of the suction peak on the upper surface of the wing. The angular extent of the leading-edge vortex sheet is such that one complete turn of the sheet is modeled, yielding an accurate representation of the interac-

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tion of the vortex sheet with the flow over the wing's upper surface. The near wake is represented relatively crudely by three spanwise strips only, precluding an accurate representation of the so-called trailing-edge vortex. However, it has been verified numerically that the influence of the near-wake panel scheme on the wing pressure distribution is relatively small. The total number of unknown parameters solved for is 1030. On the NLR CYBER 170-855 (2 mflops), the solution requires about 400 s of CPU time per iteration, while 4-5 iterations are required for convergence. The panel scheme used in the present investigation is much finer than normally used in applications of free vortex sheet codes.

The grid used to solve Euler's equations is an O-O type, obtained with the method of Ref. 5. The mesh is constructed with a polar singular line at the apex, a parabolic singular line at the tip of the trailing edge, 80 cells around the half-span (40 each on the upper and lower chords), 40 in the chordwise direction, and 24 in the normal direction, i.e., a mesh of 76,800 cells in total. In the grid generation for this delta wing, the corner of the wing tip had to be streamlined slightly. The Euler computations were carried out on the CYBER 205 in 32-bit precision. After 800 iterations, using 400 s of CPU timer, a steady solution was obtained. The program processes the data at a rate of 6×10^{-6} s/grid point/iteration for a sustained rate of over 125 mflops.

Lift and Drag Coefficients

The lift coefficient computed by numerical integration of the pressure distribution is equal to 0.97 according to the potential flow method and 0.91 according to the Euler code. The drag coefficient obtained was 0.35 and 0.33 for panel and Euler codes, respectively.

Vortex Sheet Shape—Vorticity Magnitude Contours

In Fig. 1 the shape of the vortex sheet and the vorticity contours are superimposed for three cross-flow planes. Note that the vortex sheet shapes are cross sections with planes $x/c=\text{const}$, while the vorticity contours are projections on these planes of the surface of constant mesh coordinates intersecting the wing at the corresponding streamwise station. The computed geometry of the vortex sheet turns out to be very nearly conical up to 70% of the root chord.

The shape of the region of vortical flow, as computed by the Euler code and visualized by vorticity magnitude contours, is as expected. The vortex core is a more or less elliptical cone, flattened near the wing upper surface, containing highly concentrated vorticity. Due to the artificial viscosity implied in the numerical method to solve Euler's equations, the vortex sheet is spread over a number of cells. This means that, in general, the vortical flow region as computed by the Euler code occupies a larger region than enclosed by the vortex sheet computed by the panel method. It follows from Fig. 1 that, in this respect, the two solutions agree quite well, except at the first station, $x/c=0.3$, where the vortical flow region computed by the Euler code is somewhat larger and more inboard than indicated by the vortex sheet solution.

In the vortex sheet solution the surface vorticity γ is largest near the leading edge where the vortex sheet is most curved. In

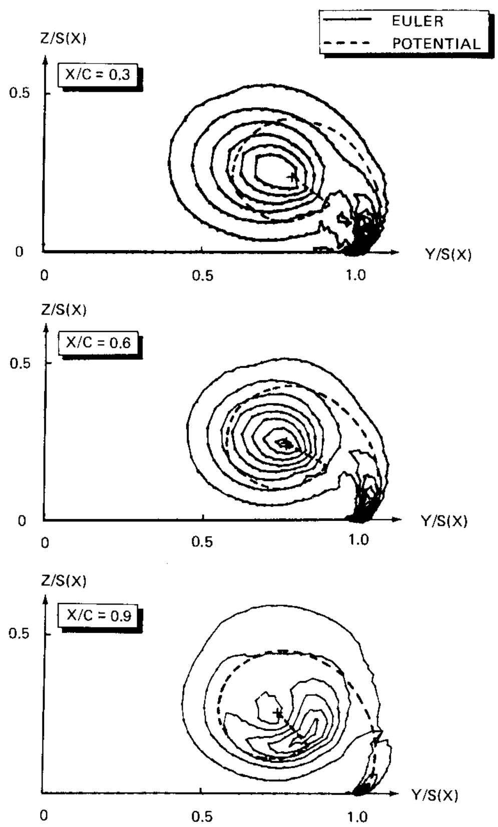

Fig. 1 Comparison of vortex sheet position and vorticity magnitude contours.

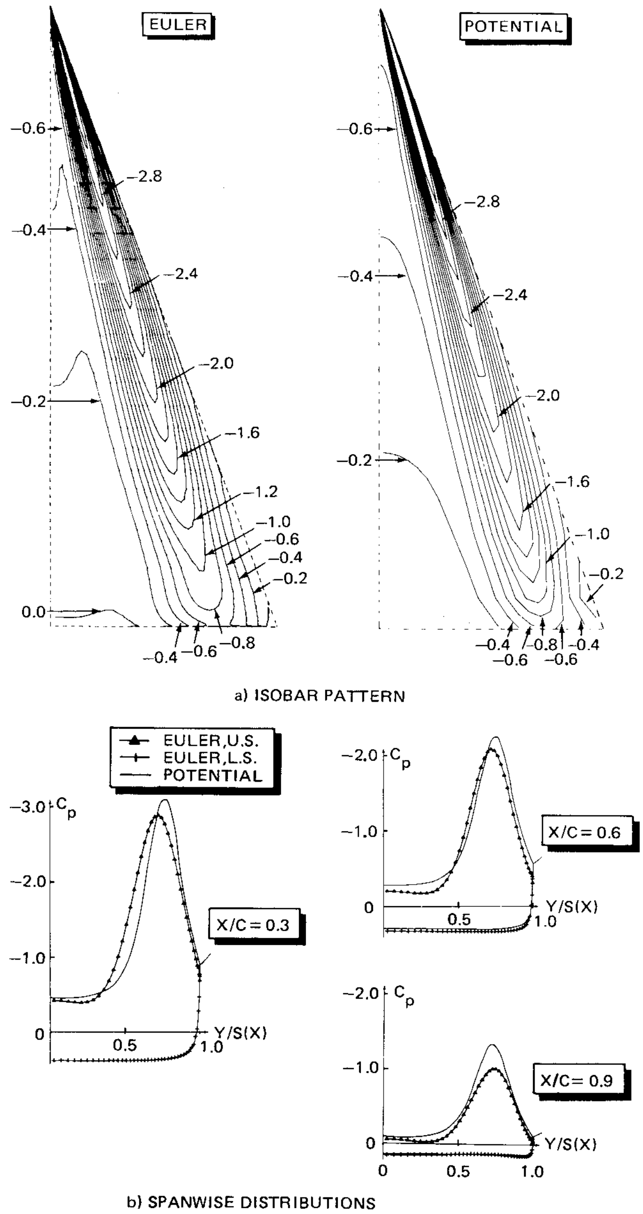

Fig. 2 Comparison of surface pressure distributions.

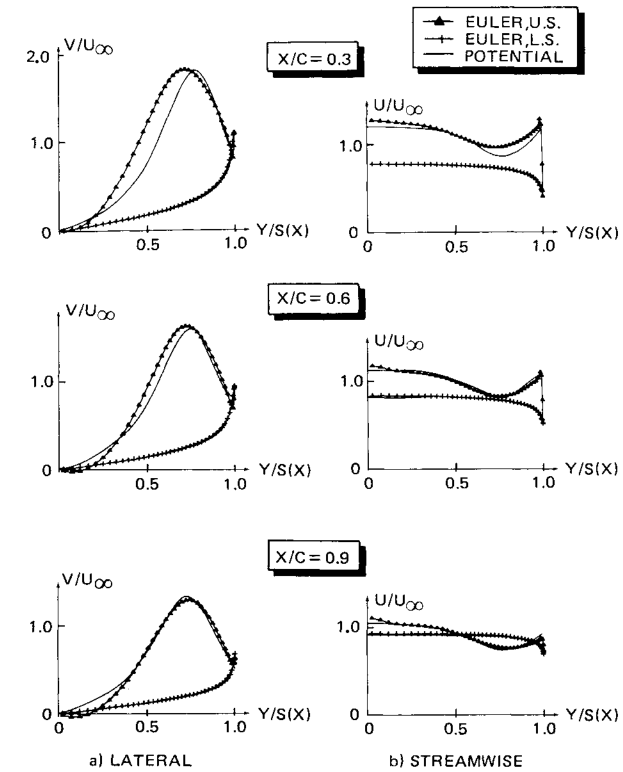

Fig. 3 Comparison of surface velocity components.

the Euler code solution, a similar behavior, i.e., a narrow region of high spatial vorticity (although somewhate blurred in Fig. 1), is observed.

Surface Pressure Distribution

A comparison of the computed pressure distributions is presented in Fig. 2. It shows the upper-surface isobar pattern and the spanwise pressure distribution at three stations $x/c = \text{const}$. In both computed isobar patterns the low-pressure region underneath the leading-edge vortex has qualitatively the same shape, position, and width. The upper wing surface suction peaks (characteristic for leading-edge vortex flow), predicted by the two methods agree quantitatively quite satisfactorily. At the first station shown, $x/c = 0.3$, there is a slight shift in the position of the suction peak. This appears to be associated with the differences in the vortical flow patterns already presented in Fig. 1. In general, the height of the suction peak, its position, and its width as predicted by both methods are in close agreement, much closer than has been achieved previously (on a coarser and less tuned mesh; see, Ref. 1).

On the lower wing surface the two pressure distributions are virtually identical. The characteristic differences in the two computed pressure distributions that remain to be explained are 1) the apparent mismatch in the pressure at the leading edge as computed by the Euler code compared to the one computed by the panel method (the latter extrapolated to the leading edge, both from the wing upper surface to the leading edge as well as from the vortex sheet to the leading edge), and 2) the difference in behavior of the pressure distribution near the plane of symmetry: in the potential flow solution the pressure decreases monotonically between the plane symmetry and the position of minimum pressure, while in the case of the Euler-equation solution the pressure slightly increases before it starts decreasing toward the position of minimum pressure.

Part of the discrepancy at the leading edge may be due to the circumstance that in the Euler solution the vortex layer, containing flow with total pressure losses, is smeared (even at the leading edge), while in the potential flow solution the vortex layer is an infinitesimal thin sheet. Part of the discrepancy near the plane of symmetry may be atributed to the different way the symmetry condition is imposed in the panel and Euler methods, i.e., exactly by mirroring and numerically along the grid boundary, respectively.

However, the spurious suction spike at the leading edge, as has occurred in earlier applications of both the Euler and Navier-Stokes codes to delta wing vortex flow, is absent in the present Euler solution.

Surface-Velocity Distribution

The lateral and streamwise components of the velocity at the wing surface are presented in Figs. 3a and 3b, respectively. The correlation of the results of the Euler code and the panel method may be inferred from the preceding comparisons. At the first station shown the discrepancy is largest; the peak is shifted in the inboard direction. In the potential flow solution the flow attaches onto the upper wing surface in the plane of symmetry and is directed in the outboard direction all along the upper surface. In the Euler equation solution the attachment line on the aft part of the wing is not in the plane of symmetry but at a position between 15 and 25% semispan, quite similar to a potential flow solution at a lower incidence. Outboard of this position the flow is directed toward the leading-edge. Inboard of the attachment line the flow is directed toward the plane of symmetry.

Concluding Remarks

Comparison of the results of a potential flow method and an Euler code presented in this Note demonstrates the capabilities of the present Euler code to simulate the leading-edge vortex flow about slender delta wings. The two results correlate qualitatively quite satisfactorily. This relates in particular to 1) the location and extent of the vortical flow region, i.e., fitted vortex sheet and captured vortex layer, and 2) the surface pressure and velocity distribution at points outside the vortical flow region.

It appears that, for the Euler solution, the density of the spatial mesh used as well as the choice of the dissipation terms have a large effect on the results obtained. High accuracy in the Euler solution is probably obtained with spatial grids of 10^5 points or more.

Acknowledgment

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