EULER SOLUTIONS AS LIMIT OF INFINITE REYNOLDS NUMBER
FOR SEPARATION FLOWS AND FLOWS WITH VORTICES

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Abstract

A combination of a finite volume discretisation in conjunction with carefully designed dissipative terms of third order, and a fourth order Runge Kutta time stepping scheme, is shown to yield an efficient and accurate method for solving the time-dependent Euler equations in arbitrary geometric domains. Convergence to the steady state has been accelerated by the use of different techniques described briefly. The main attempt of the present paper however is the demonstration of inviscid compressible flow computations as solutions to the full time dependent Euler equations over two- and three-dimensional configurations with separation. It is clearly shown that in inviscid flow separation can occur on sharp corners as well as on smooth surfaces as a consequence of compressibility effects. Results for non-lifting and lifting two- and three-dimensional flows with separation from round and sharp corners are presented.

Introduction

While potential flow solutions have proved extremely useful for predicting transonic flows with shock waves of moderate strength (e.g. see Ref. 1-3), typical of cruising flight of transport and some class of fighter aircraft, the approximation of ignoring entropy changes and vorticity production cannot be expected to give acceptable accuracy when the flight speed is increased into the upper transonic range or the angle of attack is reaching the manoeuvre limit.

However, for lifting flows in potential flow theory the assumption inherent to the specification of a Kutta condition are more important than the error in pressure rise across a shock (pointed out by Lock⁴).

In the first part of the present paper the recently developed finite volume method⁵ for solving the time dependent Euler equations is described briefly. Detailed analysis in Ref. 5 - 7 has proven the method to be very efficient and accurate for two- and three-dimensional transonic flows. Different acceleration techniques have been analysed to improve the efficiency further.

Previously reported results on the cylinder in compressible inviscid flow^{6,8} indicated that inviscid compressible flow can have solutions with a separated flow region on smooth surfaces if a shock produces vorticity and total pressure losses.

The studies in Ref. 6 - 7 presented results for two- and three-dimensional lifting flows which proved that no explicit Kutta condition is needed to get unique lifting Euler solutions.

The main part of the present paper shows results with no Kutta condition needed at round airfoil trailing edges, inviscid separation at sharp corners, and inviscid transonic flows for slender transonic wing-body configurations with leading edge vortices. These results confirm first results obtained by the authors in Oct. 1981 and by Rizzi¹⁰.

Euler Equation Method

The numerical method used to solve the time-dependent Euler equations is described in detail in Ref. 5. The version used for all cases discussed in the present paper is the unsplit four stage two level scheme with enthalpy forcing and local time stepping. A blend of second and fourth order differences is used to construct dissipative terms of a filter type. Additional acceleration techniques have been studied as reported on Ref. 7, but will not be discussed here.

The far field boundary conditions have been modified with respect to Ref. 5, but are constructed to be non-reflecting. All solid surfaces have no-flux boundary conditions, the wall pressure being extrapolated from the field. No special treatment is given to any wakes or vortices emanating from leading or trailing edges.

Mesh Generation

Two- and three-dimensional contour-conformal grids are constructed using standard O- or C-type procedures as reported in a comparison paper¹¹. In three-dimensional flow a mesh refinement technique has been adapted using submeshes of the actual fine mesh to accelerate convergence.

Results

The efficiency and the accuracy of the Euler solver have been confirmed by many numerical experiments. Results have been obtained on IBM and CRAY-1 computers. Some typical results are presented here. Since lifting flows for airfoils with sharp trailing edge have been reported in Ref. 6,7 we will show only one example for lifting two-dimensional flow, with a round trailing edge. Fig. 1 presents streamlines and isobars for such a transonic airfoil computed for an 128×32 O-type mesh. Without any explicit condition the trailing edge stagnation point is resolved.

Separation on a smooth surface for the circular cylinder has been presented in Ref. 6,8. Similar results on the upper surface of a supercritical compressor cascade blade have been obtained by Haase⁹. Fig. 2 presents results for a rearward facing step at $M = 0.5$. The mesh is especially constructed to resolve the region behind the

step accurately. The velocity vector plot as well as the streamlines nicely show the recirculating results for this inviscid flow computation. The mechanism for this final result without any supersonic point in the converged solution is similar to the one for the cylinder or the trailing edge flow. Due to compressibility any flow around the corner would produce a shock such that the only possible solution in the converged steady state is the one with the flow leaving the corner. Similar results can be obtained for a cavity in compressible inviscid time-dependent computations solving the Euler equations.

Three-dimensional lifting results have been obtained for a variety of wing-body combinations including ONERA M6 and DFVLR-F4. Fig. 3 presents some of the results obtained for a slender wing-body combination with leading edge vortex flow at subsonic and transonic speed with round and sharp leading edges. Compared with the wind tunnel results¹² both Mach number and leading edge type effects are nicely predicted by the computational method. Velocity vector plots nicely show the vortex position and roll-up behind the wing. A first analysis proved that the interaction of the trailing edge wake and leading edge vortex is nicely predicted within the capturing capabilities of the $81 \times 31 \times 17$ mesh being used.

Conclusions

The paper has presented an efficient solver for the full inviscid time dependent compressible Euler equations giving solutions in two- and three-dimensional flow with separation. It has been shown that this type of separated flow can occur on both round surfaces and sharp corners. In all cases compressibility is needed to allow for these solutions. All these results raise the question of the comparison between the exact inviscid solution and the limit of Navier Stokes solutions if the Reynolds number is increased to infinity.

References

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Figures

Fig. 1: Computed streamlines and isobars for an airfoil with round trailing edge

GRIDSYSTEM FOR REARWARD FACING STEP

C - MESH

STREAMLINES FOR REARWARD FACING STEP

 $M = 0.50$

Fig. 2: Euler results for inviscid flow over a rearward facing step

Fig. 3: Comparison of Euler results with experiments for leading edge vortex flow at subsonic and transonic speed