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Technical Notes

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Zonal Flow Analysis Method for Two-Dimensional Airfoils

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Introduction

A NEW general procedure for coupling potential and viscous flow calculation schemes is discussed and demonstrated for a two-dimensional airfoil simulation. The resultant two-zone method, Zonal Aerodynamics Program-2D (ZAP2D), couples a potential flow panel method[1] with a NASA Ames Research Center, two-dimensional, Navier-Stokes (NS) code, ARC2D.[2] The coupling concept is based on the premise that any computational method can only produce valid results within the approximations of the physical model employed in its construction. Therefore, the interfacing boundary surface between the potential and viscous flow code domains must be very nearly potential in order to achieve an accurate result. The primary objective of the current work is then to demonstrate the feasibility of the coupling procedure installed in ZAP2D for reducing the computational effort, i.e., grid, required by ARC2D for a given accuracy.

Zonal Concept

In this zonal approach, the flowfield is partitioned into linear potential flow and viscous flow regions. The two computational zones overlap and the innermost coupling boundary is located in the computed flowfield where the approximations inherent in both methods are valid. Figure 1 shows the zonal representation of the physical flowfield. An inner boundary S_i, which is measured by a radius, say R_i, is constructed to enclose a generally shaped body or airfoil and the fluid region near the body where viscous effects dominate. Although the body might be a complex shape, the inner boundary surface S_i would be a simple, smooth geometry. An additional outer surface S_o, which is measured by a radius, say R_o, also of simple shape, forms the computational domain of the viscous calculation. On the other hand, the potential flow domain extends from the inner boundary S_i to an infinite distance from the body surface. Consequently, the two computational domains overlap between the surfaces S_i and S_o. Since S_i should be approximately a potential flow surface, the distance between S_i and S_o should be minimized for optimum computational efficiency. Of course, the minimum overlap will be determined by numerical error limitations.

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The iterative coupling of the zonal method proceeds as follows.

1) The calculation procedure is initialized by computing the potential flow associated with the body motion. An integral panel method is used for this computation. In this first step only, the actual body surface is represented by discrete panels and the surface potential equation is solved directly by enforcing the Neumann boundary condition.

2) The velocity field V_o on the outer boundary S_o is computed from the known potential flow surface singularity solution.

3) This velocity field V_o serves as the outer boundary values for the NS calculation. Once the NS solution for the flow inside S_o is obtained, the velocity field due to the viscous solution, say V_i on S_i, which is just outside the region of viscous effects, is also known.

4) This inner boundary velocity V_i can, therefore, be used to construct the known corresponding values of the potential flow panel strengths on S_i; consequently, all further potential flow calculations require only the paneling of the smooth inner boundary S_i and not the actual body surface.

5) This iteration loop, steps 2–4, is repeated until the NS method is converged or iteration limits are achieved. Convergence should be measured by flowfield and integrated force and moment asymptotic behavior.

Results

In this work, the coupling procedure is investigated and validated for a two-dimensional NACA 0012 airfoil at an angle of attack α of 4.966 deg, a Mach number of 0.3, and a Reynolds number of 6×10^6. The two-dimensional potential flow panel code, POT2D, has been fully coupled with the thin-layer, NS code, ARC2D. The limits of the validity of the zonal procedure is established in the present work by comparing the ARC2D alone simulation for large domain size with the fully coupled ZAP2D simulation for small domain size.

An algebraic C mesh with preserved surface normals was generated for the NACA 0012 airfoil. The total number of grid points range from 12,025 (185×65) for the largest domain (outer boundary characteristic distance, $Ro = 25$ chord lengths) to 6549 (177×37) for the smallest domain (outer boundary characteristic distance, $Ro = 0.12$ chord lengths). The grid is clustered near the surface, and at least one point is embedded within the viscous sublayer. Successive grids were obtained by stripping off outer layers to ensure that the spacial distribution over the airfoil remains constant for all grids.

Figure 2 illustrates the effect of domain size on the section lift C_l, drag C_d, and moment C_m coefficients. In this figure,

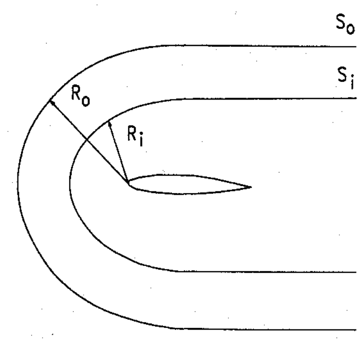

Fig. 1 Zonal representation of the physical flowfield.

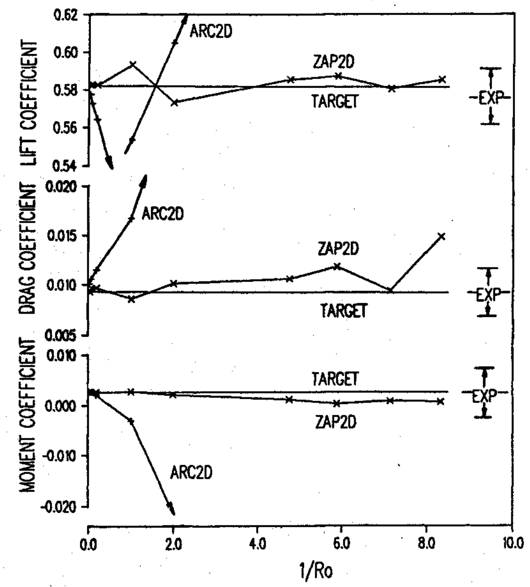

Fig. 2 Computed force and moment variation with domain size for NACA 00122 airfoil at Mach 0.3, α = 4.966 deg.

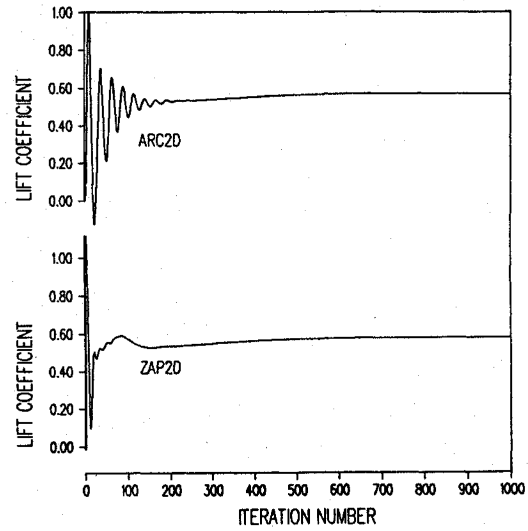

Fig. 3 Comparison of ZAP2D (R_o = 0.14) and ARC2D (R_o = 25) computed C_l iteration history at Mach 0.3, α = 4.966 deg.

the ZAP2D simulation is compared with the ARC2D-alone simulation as well as with the experimental data.[3] These ARC2D calculations do not include the point vortex correction since zonal performance improvements for general programs are of interest and also such a simple correction is not possible in three-dimensional flows. In addition, the computational trends of ARC2D for domains smaller than 25 chords are shown here for comparison only since the smaller domains are not recommended practice.[4] In fact, ARC2D (with or without the point vortex correction) diverges for grid domains smaller than R_o = 0.5. Finally, the target values for C_l, C_d, and C_m, shown in Fig. 2, are the respective ZAP2D computed values for a domain of 25 chord lengths (R_o = 25) and therefore represent zero error trend lines.

The deviation of the ZAP2D computed C_l is less than about 1% from its target value for all grid domains (each division represents a change of approximately 1.7% in C_l). Furthermore, the entire computed C_l trend is within 2% of the experimental value, which itself has a possible data scatter[5] of approximately ±2.5%, as indicated in the figure. Finally, although not shown explicitly in the figure, the ZAP2D calculation converges to the ARC2D solution (point vortex correction active) for domain sizes ≤ 4 chords ($1/R_o$ = 0.25).

Similar results are illustrated in Fig. 2 for sectional drag and sectional pitching moment about the quarter chord, respectively. The computed C_d variation from its target value is < 25 drag counts for all domains with the exception of the smallest one (R_o = 0.12) where it slightly exceeds 50 drag counts. Also, the computed C_d values for domains reduced to 0.14 chord lengths are within the possible scatter (±25 drag counts[5]) of the experimental data. Finally, for all domains, the ZAP2D computed pitching moment compares very well with its target value and with the experimental data. The experimental scatter of the pitching moment data is estimated to be C_m = ±0.005.[5] Consequently, for this case, the ZAP2D calculations of C_l, C_d, and C_m are effectively independent of finite domain size for grid sizes reduced to at least R_o = 0.14 chords. Finally, although not shown explicitly here, the off-body flowfield calculations also indicate domain independence.

The numerical stability and convergence characteristics are shown in Fig. 3, where the time history of C_l is compared for the first 1000 iterations for ARC2D (R_o = 25) and ZAP2D (R_o = 0.14). The ZAP2D time history demonstrates that the coupling procedure is, in fact, a stabilizing influence because it allows for a large reduction of grid domain. As the domain size is reduced, information is passed more quickly throughout the flowfield and the oscillatory behavior evident in the ARC2D-alone simulation is vastly reduced in the ZAP2D simulation.

Conclusions

The primary objective of this work is to demonstrate the feasiblity of a new potential/viscous coupling procedure for reducing computational effort while maintaining solution accuracy. The closed-loop, overlapped, velocity-coupling concept has been used in a new two-dimensional panel/Navier-Stokes zonal method. A thorough study of grid domain sizes from 25 to 0.12 chord lengths and comparison with experimental data has demonstrated that the grid domain size can be reduced for the zonal code to about 0.14 chord lengths with < 1–2% loss in accuracy compared with the large domain result. Finally, this reduction in grid requirement along with a significant improvement in the numerical convergence behavior obtained with the zonal method has reduced the required CPU time for this case by a factor of about 4.

Further work with ZAP2D addresses the effects of higher angles of attack and Mach numbers on the two-zone method and its comparative computational requirements.[6,7]

Acknowledgment

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