Surface Curvature Effects on Three-Dimensional Blunt-Body Boundary Layers

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Abstract

THE governing equations for laminar, transitional and/or turbulent, incompressible, three-dimensional boundary layers are solved numerically. The equations are developed in an orthogonal surface coordinate system and include surface curvature effects. Surface heat- and mass-transfer effects on the boundary-layer flowfield have also been included. The coordinates are generated numerically, whereas the inviscid flow is obtained from a general potential flow procedure. The only restrictions on body geometry are that it possess a blunt nose and a plane of symmetry. The boundary-layer equations, after being transformed into similarity type variables, are solved using the Krause implicit finite-difference scheme. Various test cases are presented to demonstrate the accuracy of the resulting computer program.

Contents

Theoretical Model

Second-order boundary-layer theory including the effects of longitudinal and transverse curvature is quite well developed for the two-dimensional or axisymmetric case for both compressible and incompressible flow.[1,2] These effects become important in situations where the boundary-layer thickness is small compared to a characteristic body length but may be of the same order of magnitude as the local longitudinal or transverse radius of curvature. Such situations can arise near stagnation points, near pointed noses or tails, and over very slender bodies of revolution. The current work develops a second-order theory for the three-dimensional incompressible boundary-layer flows.

The geometries considered in the current work are arbitrary blunt-nosed bodies having a plane of symmetry. Pressure distributions about these shapes are obtained from either the axisymmetric or three-dimensional Douglas-Neumann codes.[3,4]

The coordinate system used for the boundary-layer calculations is the one developed recently by Blottner and Ellis.[5] To remove the stagnation point singularity, this coordinate system uses the inviscid stagnation point as its origin. The details of the coordinate system are shown in Fig. 1. The coordinate system and its associated metric coefficients are generated numerically from either analytic or discrete data of the form $r=r(x,\phi)$.

The second-order boundary-layer equations, with the normal variation of the metric coefficients included, are derived from the full Navier-Stokes equations in the s,t,n coordinate system. The appropriate matching conditions and an integral equation for the normal pressure variation are also found. A further transformation into similarity variables is then made to the equations with $\xi=s$, $\omega=t$, $\eta=\sqrt{2u_e/\xi}\ \ n/\epsilon$, where u_e is the local edge velocity in the s direction and $\epsilon=Re^{-1/2}$. This is the final form of the equations used in the solution procedure.

The boundary-layer equations are solved with the Krause finite-difference scheme. For turbulent flows a two-layer eddy viscosity model is used based on Prandtl mixing-length theory with Van Driest or Reichardt damping near the wall. In all calculations presented, the effect of normal pressure gradient is neglected.

A rather general computer program for solving the equations has been developed that requires as input a data tape describing the body, coordinate geometries, and inviscid pressure distribution. A program for generating this tape has also been developed using the Blottner-Ellis coordinate generator[5] and incorporating the codes of Hess[3,4] for predicting the surface pressure distribution.

Results

To test the validity and accuracy of the computer program developed from the foregoing analysis, a few test cases were selected. Since the principle departure of the present analysis from previous efforts is in the inclusion of surface curvature effects, this area received most attention during the testing process. Most test cases were run at a $Re=100$ in order to produce a thick boundary layer on the body, thus amplifying the curvature effects. Calculations were made over spheres and ellipsoids at various angles of attack and a turbulent boundary-layer flow was included in one comparison.

The first test case run was that of a sphere at angle of attack. The utility of this calculation is that it can be easily compared with existing axisymmetric boundary-layer

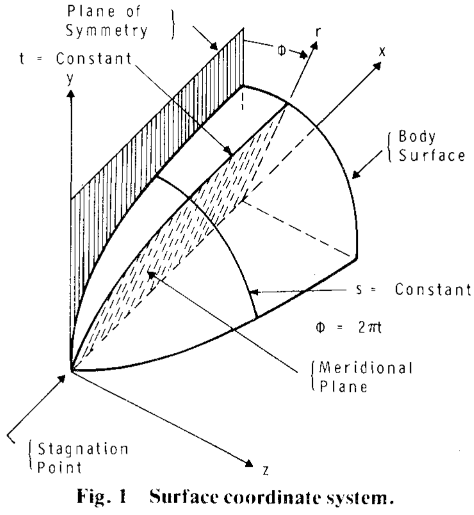

Fig. 1 Surface coordinate system.

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Index categories: Boundary Layers and Convective Heat Transfer—Laminar; Boundary Layers and Convective Heat Transfer-Turbulent; Computational Methods.

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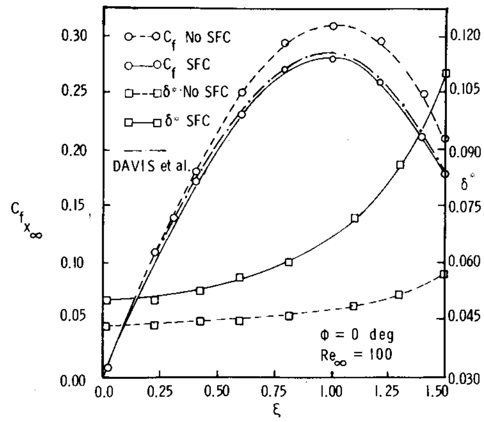

Fig. 2 Skin friction and displacement thickness along windward streamline for a sphere at $\alpha = 2$ deg.

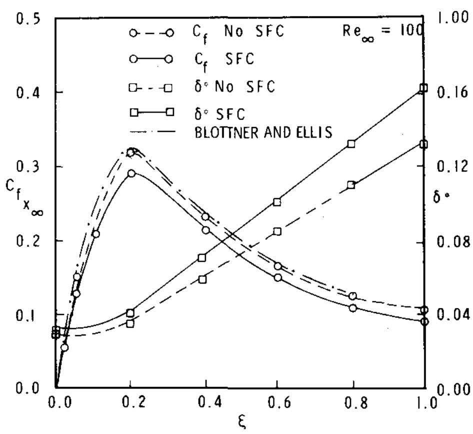

Fig. 3 Skin friction and displacement thickness along the leeward streamline of a 4:1 ellipsoid at $\alpha = 10$ deg.

calculations. Calculations were made for a unit sphere at $\alpha = 2$ deg, $Re_\infty = 100$. The results were compared with those of Davis et al.[2] where the previous results were obtained with an axisymmetric boundary-layer code with body longitudinal and transverse curvature effects included (SFC). Figure 2 shows the development of the skin friction and displacement thickness along the windward symmetry plane of the sphere. The skin-friction comparison between the present method and that of Davis et al.[2] for the SFC case is excellent.

Calculations were then made over a 4:1 ellipsoid at $\alpha = 10$ deg and $Re_\infty = 100$. The semimajor axis of the body was inclined at angle of attack and was 4-ft long. Figure 3 illustrates the development of the streamwise skin-friction

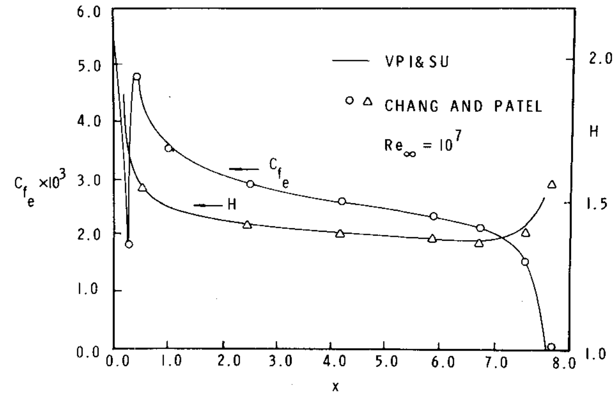

Fig. 4 Laminar, transitional and turbulent boundary layer over a 4:1 ellipsoid at zero lift.

coefficient and δ^* along the leeward streamline, $\phi = 180$. The curvature effects tend to decrease the skin friction and increase the displacement thickness.

The last comparison is shown in Fig. 4, in which the skin friction and shape factor H predicted by the present method are compared with Chang and Patel[6] for laminar, transitional, and turbulent flow over a 4:1 ellipsoid at zero angle of attack at $Re_\infty = 10^7$. The agreement is excellent. Experimental boundary-layer data were not available at angle of attack for comparison with predictions from the present code.

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