AN IMPLICIT METHOD FOR THREE-DIMENSIONAL VISCOUS FLOW WITH APPLICATION TO CONES AT ANGLE OF ATTACK

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An iteration method for solving the implicit difference equations associated with three-dimensional nonlinear parabolic differential equations is derived and analyzed. The method is applied to the high Reynolds number laminar viscous flow around a cone at high angle of attack. The requirements which must be met to ensure convergence of the iterations are obtained. In addition, an analysis of the stability of the difference equations is presented and discussed. The numerical results are compared with experimental data for a 10-deg cone at 12-deg angle of attack, and a 5.6-deg cone at 8-deg angle of attack. The agreement is very good.

A description of the associated computer program is contained in the appendices.
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implicit differencing
3-D parabolic differential equations
viscous flow
cone at angle of attack
convergence analysis
stability analysis
departure solution
separation
AN IMPLICIT METHOD FOR THREE-DIMENSIONAL VISCOUS FLOW WITH APPLICATION TO CONES AT ANGLE OF ATTACK

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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract No. F04701-73-C-0074. This report was prepared by the Information Processing Division, Engineering Science Operations, at the request of the Reentry Systems Division, Development Operations.

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Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

A.C. Klingler, Captain, USAF
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ABSTRACT

An iteration method for solving the implicit difference equations associated with three-dimensional nonlinear parabolic differential equations is derived and analyzed. The method is applied to the high Reynolds number laminar viscous flow around a cone at high angle of attack. The requirements which must be met to ensure convergence of the iterations are obtained. In addition, an analysis of the stability of the difference equations is presented and discussed. The numerical results are compared with experimental data for a 10-deg cone at 12-deg angle of attack, and a 5.6-deg cone at 8-deg angle of attack. The agreement is very good.

A description of the associated computer program is contained in the appendices.
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### SYMBOLS

- **h** static enthalpy \(h = \frac{h}{h_\infty}\)
- **j, k, l** finite-difference grid points in \(x, y, \phi\) directions, respectively
- **K, L** number of mesh points in \(y\) and \(\phi\) directions, respectively
- **\(\zeta'\)** length used to nondimensionalize variables
- **M_\infty** free stream Mach number
- **M_x** local streamwise Mach number \((M_x = uM_\infty / \sqrt{h})\)
- **p** dimensionless pressure \(p = \frac{\rho_\infty \sqrt{\gamma}}{\rho_\infty \sqrt{\gamma}}\)
- **Pr** freestream Prandtl number (assumed constant)
- **r** distance from a point in the flow to the axis of symmetry of the cone \((r = x \sin \theta + y \cos \theta)\)
- **Rc** free stream Reynolds number \(Rc = \frac{\rho_\infty \sqrt{\gamma} \sqrt[3]{\gamma}}{\mu_\infty}\)
- **S** Sutherland constant
- **u, v, w** dimensionless velocity components in \(x, y, \phi\) directions, respectively \((u = \frac{u}{V_\infty}, v = \frac{v}{V_\infty}, w = \frac{w}{V_\infty})\)
- **V_\infty** free stream velocity \((V_\infty = \frac{V_{\infty x}}{V_\infty}, V_{\infty y} = 1)\)
- **x, y, \phi** coordinates along the cone, normal to the cone, around the cone, respectively \((x = \frac{x}{x'}, y = \frac{y}{x'}, \phi = \frac{\phi}{x'})\)
- **\(\alpha\)** angle of attack
- **\(\gamma\)** ratio of specific heats (assumed constant)
- **\(\Delta x, \Delta y, \Delta \phi\)** mesh spacing in \(x, y, \phi\) directions, respectively
- **\(\eta\)** transformed normal coordinate \((\eta = y / \xi)\)
- **\(\theta\)** cone half angle
- **\(\mu\)** viscosity \([\mu = \sqrt{h (1+S)/(1+S/h)}]\)

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SYMBOLS (Continued)

\( \xi \) \hspace{1cm} \text{distance from shock to cone surface}

\( \rho \) \hspace{1cm} \text{density} \ (\rho = \gamma M_{\infty}^2 p/h)

Subscripts

\( \infty \) \hspace{1cm} \text{denotes free stream conditions}

\( w \) \hspace{1cm} \text{denotes conditions at the cone}

Superscripts

~ \hspace{1cm} \text{denotes dimensional quantity}

\( n \) \hspace{1cm} \text{denotes iteration number}
SECTION I
INTRODUCTION

In recent years there has been a tremendous increase in numerical solutions for three-dimensional flow problems. This increase has been due to the rapid growth in the storage capacity and speed of computers. The primary effort in computing three-dimensional flows has been in using explicit methods. Explicit methods, although relatively easy to program, consume excessive amounts of computer time due to stability restrictions on step sizes. Even a DuFort-Frankel (Ref. 1) or Crocco (Ref. 2) scheme uses a considerable amount of time when the mesh spacing is small, as is necessary for accuracy with high speed, high Reynolds number laminar flow problems. Therefore, for many flow problems it is desirable to use an implicit technique to solve the governing partial differential equations. Implicit methods have the advantage of being stable, consistent, and accurate for reasonable stepsizes. The major drawback is the size and complexity of the computer program which must be written and the storage requirements due to the necessity of solving large systems of equations. Alternating direction implicit methods (Ref. 3), although reducing the size of the system of equations which must be solved for three-dimensional problems, double the complexity of the computer code which must be developed.

In this report, a method of solving the large system of algebraic equations which result from the implicit differencing of three-dimensional flow equations is developed. For a typical problem, the implicit differencing may result in a system of 6000 or more algebraic equations. A method of solving these equations which does not require excessive computer storage and that yields accurate results is presented. The method is similar to the "predictor corrector" multiple iteration technique described by Rubin and Lin (Ref. 4).

The numerical approach begins with an implicit differencing of the system of nonlinear partial differential equations. The nonlinear algebraic
equations resulting from this differencing are first linearized, and the resulting linear algebraic equations are then solved using a Gauss-Seidel (Ref. 5) iteration method. The details of the method are given in Section II for a simple model equation. Because of the necessity of iterating, which results from the numerical approach, the convergence of the iteration should be considered. This question is also analyzed in Section II for the model equation.

In Section III, the numerical technique which is developed is applied to the solution of an approximate system of three-dimensional equations which has been developed to predict the flow fields around cones at high angles of attack. This approximate system of viscous equations has been derived from the steady Navier-Stokes equations by assuming the gradients of the shear stress in the streamwise direction are much smaller than the gradients in the normal and circumferential directions (Ref. 6). The resulting equations are similar to those developed by Lin and Rubin (Ref. 7) to solve the sharp tip, low Reynolds number region for a cone at angle of attack. The resulting system of equations is first order in x and second order in y and θ. The convergence and stability of the system of equations are discussed.

Solutions to the system of equations are presented for two cases in Section IV. The first, a 10-deg half angle cone at 12-deg angle of attack and a freestream Mach number of 8; and the second, a 5.6-deg half angle cone at 8-deg angle of attack and a freestream Mach number of 14.2. The conditions for these cases correspond closely to experimental data obtained by Tracy (Ref. 8) and Stetson and Ojdana (Ref. 9). Comparisons of the numerical results with the experimental data are shown.
SECTION II

NUMERICAL TECHNIQUE

In this section, the numerical technique is developed and analyzed. To illustrate the approach, the following three-dimensional partial differential equation is considered:

\[
\frac{\partial u}{\partial x} + a \frac{\partial u}{\partial \eta} + b \frac{\partial u}{\partial \phi} - c \frac{\partial^2 u}{\partial \eta^2} - d \frac{\partial^2 u}{\partial \phi^2} = 0 \quad c, d \geq 0
\]  

This equation is representative of the viscous flow equation. For three-dimensional steady flow, \( a = v/u, b = w/ur, c = \mu/Re_p u, d = \mu/Re_p u^2 \).

The following finite difference approximation formulas are used:

\[
\frac{\partial u}{\partial x} = \frac{(u_{j+1,k,l} - u_{j,k,l})}{\Delta x}
\]

\[
\frac{\partial u}{\partial \eta} = \frac{(u_{j+1,k+1,l} - u_{j+1,k-1,l})}{2\Delta \eta}
\]

\[
\frac{\partial^2 u}{\partial \eta^2} = \frac{(u_{j+1,k+1,l} - 2u_{j+1,k,l} + u_{j+1,k-1,l})}{\Delta \eta^2}
\]

\[
\frac{\partial u}{\partial \phi} = \frac{(u_{j+1,k,l+1} - u_{j+1,k,l-1})}{2\Delta \phi}
\]

\[
\frac{\partial^2 u}{\partial \phi^2} = \frac{(u_{j+1,k,l+1} - 2u_{j+1,k,l} + u_{j+1,k,l-1})}{\Delta \phi^2}
\]

where \( u_{j,k,l} \) is the value of \( u \) at the grid point \( j,k,l \).
In addition, in the more general case, a cross derivative term appears. For completeness the difference formula is defined.

\[
\frac{\partial^2 u}{\partial \eta \partial \phi} = \left[ (u_{j+1,k+1,l+1} - u_{j+1,k-1,l+1}) - (u_{j+1,k+1,l-1} - u_{j+1,k-1,l-1}) \right] / 4 \Delta \eta \Delta \phi
\]  

The scheme for solving the differential equation is then completely implicit. To obtain \(u_{j+1,k,l}\) (solution known at \(j\)) a linear system of equations of order \(K \times L\) must be solved.

The method proposed to solve this system of linear equations is the line Gauss-Seidel iteration method mentioned in Fox (Ref. 5) and Isaacson and Keller (Ref. 10). To be specific, suppose \(u_{j+1,k,l}^n\) is a guess to the solution of the difference equations where \(n\) denotes the iteration number. Then the correction \(\tilde{u}_{j+1,k,l}\) which must be added to \(u_{j+1,k,l}^n\) to give the solution satisfies, after rearranging

\[
\begin{align*}
- \frac{a}{2\Delta \eta} u_{j+1,k-1,l} + \left( \frac{1}{\Delta x} + \frac{2c}{\Delta \eta^2} + \frac{2d}{\Delta \phi^2} \right) u_{j+1,k,l} + \left( \frac{a}{2\Delta \eta} - \frac{c}{\Delta \eta^2} \right) u_{j+1,k+1,l} \\
= - \frac{\partial u^n}{\partial x} - a \frac{\partial u^n}{\partial \eta} - b \frac{\partial u^n}{\partial \phi} + c \frac{\partial^2 u^n}{\partial \eta^2} + d \frac{\partial^2 u^n}{\partial \phi^2} - \frac{b}{2\Delta \phi} \left( u_{j+1,k,l+1} - u_{j+1,k,l-1} \right) \\
+ \frac{1}{\Delta \phi^2} \left( \tilde{u}_{j+1,k,l+1} + \tilde{u}_{j+1,k,l-1} \right)
\end{align*}
\]  

If the underlined terms on the right hand side of Eq. (4) are ignored and the resulting equations are solved in the order \(l = 1, 2, \ldots, L\) using the boundary conditions at \(l = 1\), then the approximate solution denoted by \(\overline{u}_{j+1,k,l}\) should be close to \(u_{j+1,k,l}^n\). Taking \(u_{j+1,k,l}^{n+1} = u_{j+1,k,l}^n + \overline{u}_{j+1,k,l}^{n+1}\) as a new guess to the solution of Eq. (1) the process is repeated to obtain \(u_{j+1,k,l}\) and so on until convergence is achieved.
The above method has the advantage that \( L \) systems of order \( K \) must be solved instead of one of order \( L \times K \). This saves time and storage.

A seeming disadvantage is that iteration is required. That is, solving \( L \) systems of order \( K \) just produces a "guess" to the solution of Eq. (4). To obtain a better "guess" the \( L \) systems have to be solved again, etc.

However for nonlinear problems this is not a disadvantage. To solve a nonlinear system of equations, some form of linearization must be done (e.g., Newton-Raphson method) and then iteration is done to obtain an accurate solution. The line Gauss-Seidel method may be used to solve the linear system, and instead of iterating to convergence the first iterate is taken as the next iterate in the nonlinear sequence of iterates. Experience has shown that the convergence of the nonlinear iterates is not severely hindered by not solving exactly for the iterate.

Once the iterations have converged then the method is completely implicit and so the single linear Eq. (i) is stable and consistent. The primary question to be answered is whether or not the iterates converge. To consider the convergence question write the difference equation [Eq. (4)] as

\[
\begin{align*}
\frac{u_j^{n+1}}{j+1, k, l} + \frac{\Delta x}{2 \Delta \eta} \left( \frac{u_j^{n+1}}{j+1, k+1, l} - \frac{u_j^{n+1}}{j+1, k-1, l} \right) + \frac{b \Delta x}{2 \Delta \phi} \left( \frac{u_j^{n+1}}{j+1, k, l+1} - \frac{u_j^{n+1}}{j+1, k, l-1} \right) \\
- \frac{c \Delta x}{\Delta \eta^2} \left( u_j^{n+1} - 2 u_j^{n+1} \right) + \frac{d \Delta x}{\Delta \phi^2} \left( u_j^{n+1} - 2 u_j^{n+1} \right) = u_j, k, l
\end{align*}
\]

The above equation is a difference equation with difference index \( n \). To determine under what conditions the solution converges as \( n \to \infty \) the Fourier series method as presented in Richtmyer and Morton (Ref. 11) may be used. That is, substitute \( \lambda e^{i(m_1 \Delta \phi + m_2 k \Delta \eta)} \) for \( u_j^{n+1} \) and \( e^{i(m_1 \Delta \phi + m_2 k \Delta \eta)} \) for \( u_j^{n+1} \). The term \( u_j, k, l \) is ignored since it is independent of \( n \), and
the resulting equation is solved for \( \lambda \). The iterates will converge if \(|\lambda| < 1\).

For Eq. (5) the amplification factor \( \lambda \) is

\[
\lambda = \frac{-\left( \frac{h\Delta x}{2\Delta \phi} - \frac{\Delta x}{\Delta \phi} \right) (\cos \phi \Delta \phi + \sin \phi \Delta \phi)}{1 - \left( \frac{h\Delta x}{2\Delta \phi} + \frac{\Delta x}{\Delta \phi} \right) \cos \phi \Delta \phi + \frac{2\Delta x}{\Delta \phi} - \frac{\Delta x}{\Delta \phi} \sin \phi \Delta \eta + \left( \frac{h\Delta x}{2\Delta \phi} + \frac{\Delta x}{\Delta \phi} \right) \sin \phi \Delta \phi}
\]

(6)

After some manipulation it can be shown that \(|\lambda| < 1\) if \(\Delta x < \frac{\Delta \phi}{l b x}\).

If the values of \( u \) at \( n-1 \) were evaluated at the \( n \)th iterate instead of the \( n+1 \)th, this would be the line Jacobi elimination method (Ref. 10) and the convergence criterion would be the same. It is line Jacobi elimination that Rubin and Lin (Ref. 4) studied; however, instead of considering convergence they looked at what would happen if just one or two iterations were carried out. They found that the equations were not quite consistent and for the method to be stable as a marching scheme in \( x \) there was a restriction on \( \Delta x \) depending on the number of iterations performed. For one iteration, the stability restriction was the same as the above derived convergence restriction.

(Rubin and Lin considered the case where \( c = 0 \).) The question may be asked why it is necessary to iterate to convergence (which may require four or five iterations) instead of iterating only once or twice. Iterating to convergence produces consistency, and in nonlinear equations it is necessary to iterate several times to obtain an accurate and stable solution to the nonlinear difference equations.

The rates of convergence for the line Jacobi method and the line Gauss-Seidel method have been studied for elliptic problems (Ref. 10) and it has been found that the line Gauss-Seidel method converges twice as fast as the line Jacobi method. The results for the above simple parabolic case are analogous.

If a DuFort-Frankel scheme or a Crocco scheme or some other modified explicit formula (modified to remove the diffusive stability requirement)
is used, there are two convective stability requirements. The above scheme eliminates one convective $\Delta x$ restriction. For problems which permit very unequal meshes in the two directions, as for many flow problems, this may permit much greater step sizes.

In the next section, the differencing described above is applied to a complicated system of three-dimensional viscous flow equations which have been developed to solve for the flow field around a cone at angle of attack.
SECTION III
APPLICATION TO CONE AT ANGLE OF ATTACK

A. GOVERNING EQUATIONS

The numerical technique which was developed in the previous section will be applied to a complicated system of three-dimensional viscous flow equations which have been derived to predict the flow around a cone at angle of attack. The system of equations has been derived from the steady Navier-Stokes equations by assuming the gradients of the shear stress in the streamwise direction are much smaller than the gradients in the normal and circumferential directions (Ref. 6). The coordinate system used in the development of the equations is illustrated in Figure 1.

The resulting nondimensional equations are listed below:

Continuity equation

\[
\frac{\partial \rho u_r}{\partial x} + \frac{\partial \rho v_r}{\partial y} + \frac{\partial \rho w}{\partial \phi} = 0
\]  \hspace{1cm} (7)

x-momentum equation

\[
\frac{\partial \rho u_r}{\partial x} + \frac{\partial \rho v_r}{\partial y} + \frac{\partial \rho w u_r}{\partial \phi} - \rho u_r^2 \sin \theta + r \frac{\partial p}{\partial x}
\]

\[
= \frac{r}{Re} \left\{ \frac{\partial}{\partial y} \left[ \mu \frac{\partial u_r}{\partial y} \right] + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left[ \mu \frac{\partial u_r}{\partial \phi} \right] + \frac{\mu}{r} \frac{\partial u_r}{\partial y} \cos \theta \right\}
\]  \hspace{1cm} (8)
\textbf{y-momentum equation}

\[
\frac{\partial \rho u v r}{\partial x} + \frac{\partial \rho v^2}{\partial y} + \frac{\partial \rho w}{\partial \Phi} - \rho w^2 \cos \theta + r \frac{\partial p}{\partial y} = \frac{r}{Re} \left[ \frac{4}{3} \frac{\partial}{\partial y} \left( \mu \frac{\partial v}{\partial y} \right) + \frac{1}{r^2} \frac{\partial}{\partial \Phi} \left( \mu \frac{\partial v}{\partial \Phi} \right) \right]
\]

\[
+ \frac{1}{r} \frac{\partial}{\partial \Phi} \left( \mu \frac{\partial w}{\partial \Phi} \right) - \frac{2}{3} \frac{\partial}{\partial y} \left( \mu \frac{\partial w}{\partial y} \right) \right]
\]

\textbf{\(\Phi\)-momentum equation}

\[
\frac{\partial \rho u w r}{\partial x} + \frac{\partial \rho v w r}{\partial y} + \frac{\partial \rho w^2}{\partial \Phi} + \rho u w \sin \theta + \rho v w \cos \theta + \frac{\partial p}{\partial \Phi} = \frac{r}{Re} \left[ \frac{\partial}{\partial y} \left( \frac{\mu}{r} \frac{\partial v}{\partial \Phi} \right) - \frac{2}{3} \frac{\partial}{\partial \Phi} \left( \mu \frac{\partial v}{\partial \Phi} \right) \right]
\]

\[
+ \frac{1}{r} \frac{\partial}{\partial \Phi} \left( \mu \frac{\partial w}{\partial \Phi} \right) \right]
\]

\textbf{Energy equation}

\[
\frac{\partial \rho u h}{\partial x} + \frac{\partial \rho v h}{\partial y} + \frac{\partial \rho w h}{\partial \Phi} = \frac{M_\infty^2}{r} \left[ \frac{\partial p}{\partial x} + \frac{\partial p}{\partial y} + \frac{p}{r^2} \frac{\partial p}{\partial \Phi} \right] \]

\[
+ \frac{\mu r (\gamma - 1) M_\infty^2}{Re} \left[ \left( \frac{\partial u}{\partial y} \right)^2 + \frac{1}{r^2} \left( \frac{\partial u}{\partial \Phi} \right)^2 + \left( \frac{\partial w}{\partial y} \right)^2 + \frac{4}{3} \left( \frac{\partial w}{\partial \Phi} \right)^2 \right]
\]

\[
+ \frac{4}{3} \left( \frac{\partial v}{\partial y} \right)^2 + \frac{1}{r^2} \left( \frac{\partial v}{\partial \Phi} \right)^2 - \frac{4}{3} \frac{\partial v}{\partial y} \frac{\partial w}{\partial \Phi} + \frac{2}{r} \frac{\partial v}{\partial \Phi} \frac{\partial w}{\partial y} \right]
\]

\[
+ \frac{r}{Re Pr} \left[ \frac{1}{r} \frac{\partial}{\partial y} \left( \mu \frac{\partial h}{\partial y} \right) + \frac{1}{r^2} \frac{\partial}{\partial \Phi} \left( \mu \frac{\partial h}{\partial \Phi} \right) \right]
\]

\textbf{where the perfect gas equation of state is used to relate the density to the pressure and enthalpy}

\[
\rho = \gamma M_\infty^2 \frac{p}{h}
\]
and Sutherland's law is used to relate the viscosity to the enthalpy

\[ \mu = \sqrt{h} \frac{1 + S}{1 + S/h} \]  \hspace{1cm} (13)

A constant Prandtl number and specific heat will also be assumed.

The above equations are similar to those used by Lin and Rubin (Ref. 7) except the terms associated with \( r \sim 0 \) have been dropped. These terms are important only near the tip at low Reynolds number. We will be interested in solving the higher Reynolds number cases downstream of the tip region.

The following boundary conditions at the cone surface are used.

\[ u = v = w = 0 \]

\[ h_w = \text{specified constant} \]  \hspace{1cm} (14)

\[ \left( \frac{\partial p}{\partial y} \right)_w = \frac{1}{Re} \left( \frac{4}{3} \mu \frac{\partial^2 v}{\partial y^2} + \frac{1}{r} \frac{\partial}{\partial \phi} \frac{\partial^2 w}{\partial y \partial \phi} \right) \]

The last equation has been obtained from the \( v \)-momentum equation using the condition \( (\partial v/\partial y)_w = 0 \) which is required in order that the continuity equation is satisfied at the wall.

The following difference formulas are used in the \( (\partial p/\partial y)_w \) equation:

\[ \left( \frac{\partial^2 w}{\partial y \partial \phi} \right)_w = \frac{\partial w}{\partial \phi} \bigg|_{k=2} /\Delta y \]

\[ \left( \frac{\partial^2 v}{\partial y^2} \right)_w = 2 v k=2 /\Delta y^2 \]

and are obtained from Taylor series expansions in the normal direction of \( \frac{\partial w}{\partial \phi} \bigg|_{k=2} \) and \( v k=2 \).
The Rankine-Hugoniot jump conditions are applied at the shock boundary. In the body-oriented coordinate system (Figure 1) they are

Conservation of mass equation

\[(u_\infty - \rho_K u_K) \frac{\partial \xi}{\partial x} - (v_\infty - \rho_K v_K) + (w_\infty - \rho_K w_K) \frac{1}{r} \frac{\partial \xi}{\partial \phi} = 0 \quad (15)\]

Conservation of normal momentum equation

\[\frac{u_\infty \left(\frac{\partial \xi}{\partial x}\right)^2}{\left(\frac{\partial \xi}{\partial x}\right)^2 + 1 + \left(\frac{1}{r} \frac{\partial \xi}{\partial \phi}\right)^2} + u_\infty + \rho_K \frac{1}{r} \frac{\partial \xi}{\partial \phi} = p_\infty + \left(\frac{u_K \frac{\partial \xi}{\partial x} - v_K + w_K \frac{1}{r} \frac{\partial \xi}{\partial \phi}}{\left(\frac{\partial \xi}{\partial x}\right)^2 + 1 + \left(\frac{1}{r} \frac{\partial \xi}{\partial \phi}\right)^2}\right)^2 \quad (16)\]

Conservation of tangential velocities equations

\[(u_\infty - u_K) \left[1 + \left(\frac{1}{r} \frac{\partial \xi}{\partial \phi}\right)^2\right] + (v_\infty - v_K) \frac{\partial \xi}{\partial x} - (w_\infty - w_K) \frac{1}{r} \frac{\partial \xi}{\partial \phi} \frac{\partial \xi}{\partial x} = 0 \quad (17)\]

Conservation of energy equation

\[\frac{(Y-1)M^2}{2} \frac{u_\infty}{v_\infty} v_\infty^2 + h_\infty = h_K + \frac{(Y-1)M^2}{2} \frac{u_K^2 + v_K^2 + w_K^2}{v_\infty} \quad (18)\]

The subscript K denotes the value of the variable just inside the shock. In order to uniquely determine the six unknowns $\xi$, $u_K$, $v_K$, $w_K$, $p_K$, $h_K$, the above five equations must be augmented with a sixth equation. A one-sided differencing of the continuity equation provides the sixth equation. Full justification and discussion of the above equations and boundary conditions are presented in Ref. 6).
Since the fluid flow is symmetric about the plane $\Phi = 0$ and $\Phi = \pi$, the equations used will be solved for $0 \leq \Phi \leq \pi$ where the symmetry conditions

$$
\frac{\partial}{\partial \Phi}(u, v, p, h, \xi) = 0; \quad w = \frac{\partial^2 w}{\partial \Phi^2} = 0
$$

are used at $\Phi = 0$ and $\Phi = \pi$. (Note: $\Phi = 0$ is the windward side.)

The shock distance is to be solved for from the Rankine-Hugoniot jump conditions. In a rectangular $y-\Phi$ grid the shock may not fall on a mesh point so that mesh points would have to be moved or added to accommodate the shock. Thus, the transformation $\eta = y/\xi(x, \Phi)$ is made. The resulting equations are then solved for $0 \leq \eta \leq 1$, $0 \leq \Phi \leq \pi$, where $\eta = 0$ corresponds to the cone and $\eta = 1$ corresponds to the shock. The shock distance $\xi$ appears in all the equations and in order to keep the matrix of coefficients obtained from the difference form of the equation in block tri-diagonal form, a sixth equation

$$
\frac{\partial \xi}{\partial \eta} = 0
$$

is differentiated. Thus the problem to be solved consists of six differential equations, six boundary conditions at each of the positions $\eta = 0$ and $\eta = 1$ and two symmetry conditions at $\Phi = 0$ and $\Phi = \pi$ [Eqs. (7) through (20)] in the six unknowns $u, v, w, p, h, \xi$.

If initial conditions were known, a marching scheme in $x$ could be used to solve the equations. An explicit method would not work since, as shown by Baum and Denison [Eq. (12)] for the axisymmetric problem, it is not possible to solve for $\partial u/\partial x$, $\partial v/\partial x$, $\partial w/\partial x$, $\partial p/\partial x$, $\partial h/\partial x$, at $M_x = 1$. Even if this difficulty could be overcome the diffusive stability requirement would be too strict. Since the gradients in the normal direction are much larger than in the circumferential direction, the normal mesh will be much finer than the circumferential mesh. Thus a method that is implicit in the normal direction should be more efficient than a modified explicit differencing such as DuFort-Frankel or Crocco. Accurate solutions at each $x$-station are desired.
and since the equations are very nonlinear they require iteration for accuracy. The method proposed in the previous section is most appropriate for this problem.

An alternating direction implicit technique was tried, with iteration to handle the nonlinearities. It was found that near $u = 0$ and $M_x = 1$, the equations for the implicit in $x$ step were ill-conditioned and meaningful solutions could not be obtained. The $M_x = 1$ difficulty was overcome by evaluating the $\partial p/\partial x$ term backwards in $x$ in the $x$-momentum and energy equations. However, the $u = 0$ difficulty remained.

The implicit difference equations [Eqs. (2) and (3)] are substituted into the partial differential equations and a system of nonlinear algebraic equations result. There are many ways to linearize such a system. Since convergence is guaranteed provided the initial guess is close enough, and because the convergence is quadratic, the Newton-Raphson method is used to solve these equations. That is, the nonlinear terms are expanded in a Taylor series and terms higher than first order are dropped. It is known that this iteration procedure converges provided the initial guess is close enough to the solution. It was found that linearly extrapolating the solution at the previous two $x$ stations gives a satisfactory initial guess. To see what linearization does to various terms let $\bar{t}$ represent the increment to be added to the known iterate and the superscript $n$ denote that iterate. A few sample expressions are

$$\frac{\partial p u_r}{\partial x} = \left( \frac{\partial p u_r}{\partial x} \right)^n + \bar{u} \left( \frac{p u_r}{\Delta x} \right)^n + \left( \frac{u r}{\Delta x} \right)^n \left( \frac{\partial p}{\partial p} + \frac{\partial p}{\partial h} \right) + \bar{r} \left( \frac{p u}{\Delta x} \right)^n$$

$$\frac{\partial p w}{\partial \varphi} = \left( \frac{\partial p w}{\partial \varphi} \right)^n + \bar{w} \left( \frac{\partial \varphi}{\partial \varphi} \right)^n + \frac{\partial}{\partial \varphi} \left( \frac{\partial^2 \varphi}{\partial p} + \frac{\partial^2 \varphi}{\partial h} \right)$$

$$\frac{\mu \partial^2 \varphi}{\partial \varphi^2} = \left( \frac{\mu \partial^2 \varphi}{\partial \varphi^2} \right)^n + \bar{\mu} \left( \frac{\partial h}{\partial h} \frac{\partial^2 \varphi}{\partial \varphi^2} \right)^n + \mu \frac{\partial^2 \varphi}{\partial \varphi^2}$$
The term above is \( \hat{\tau} = \hat{\xi} \eta \cos \phi \), since \( x_{i+1} \sin \theta \) is known. The linear system of equations obtained are solved for \( \bar{u}, \bar{v}, \bar{w}, \bar{p}, \hat{\xi} \), and \( \hat{\phi} \) using the line Gauss-Seidel method described in the previous section. However, only one iteration of the line Gauss-Seidel method is performed. The approximate solutions so obtained are then used to obtain the next guess to the nonlinear system.

For this flow problem the linear systems of equations that must be solved to obtain one Gauss-Seidel iterate are of order \( 6 \times \) \( K \) since there are six variables involved. The matrix of coefficients is of block tridiagonal form. An efficient method for solving such systems is presented in Isaacson and Keller (Ref. 10) and was used by Rubin and Lin (Ref. 4) and also in the present analysis.

**B. CONVERGENCE AND STABILITY**

The questions of convergence and stability must be investigated for the system of flow equations. To consider convergence, the equations are simplified. First, the equations are written in a different form by expanding the derivative expressions and subtracting the continuity equation from the momentum equation and the energy equation. For simplicity it is assumed that \( \mu/Pr = 4/3 \mu = \mu \). The viscosity is assumed to be constant and the shock distance is assumed to be known. Since the iteration is primarily for the \( \phi \) derivative terms, then all terms not involving derivatives with respect to \( \phi \) exclusively are ignored. The following equations are left.

\[
\begin{align*}
\frac{\partial u}{\partial x} + \frac{1}{Pr} \frac{\partial \bar{u}}{\partial x} + \frac{w \partial u}{ur \partial \phi} - Re \left( \frac{\partial^2 u}{\partial \phi^2} \right) &= 0 \\
\frac{\partial v}{\partial x} + \frac{w \partial v}{ur \partial \phi} - Re \left( \frac{\partial^2 v}{\partial \phi^2} \right) &= 0 \\
\frac{\partial w}{\partial x} + \frac{w \partial w}{ur \partial \phi} - Re \left( \frac{\partial^2 w}{\partial \phi^2} + \frac{h}{ur \theta^2} \right) &= 0
\end{align*}
\]

(21a)
\[
\frac{\partial p}{\partial x} + \frac{p}{u} \frac{\partial u}{\partial x} - \frac{p}{h} \frac{\partial h}{\partial x} + \frac{w}{u} \frac{\partial p}{\partial \phi} + \frac{p}{u} \frac{\partial w}{\partial \phi} - \frac{w}{u} \frac{p}{h} \frac{\partial h}{\partial \phi} = 0
\]

(21b)

\[
\frac{\partial h}{\partial x} - \frac{Y-1}{\gamma p} \frac{\partial p}{\partial x} + \frac{w}{u} \frac{\partial h}{\partial \phi} - \text{Re}^* \frac{\partial^2 h}{\partial \phi^2} - \frac{Y-1}{\gamma} \frac{w}{u} \frac{h}{p} \frac{\partial p}{\partial \phi} = 0
\]

where

\[
\text{Re}^* = \frac{1}{\text{Re}} \frac{u h}{2r^2 \gamma M^2_{\infty} p}
\]

To further simplify the analysis, assume that all coefficients of the derivative terms are constant, and that the mesh spacings are constant \(\Delta x\), \(\Delta y\), and \(\Delta \phi\) in the \(x\), \(y\), and \(\phi\) directions, respectively. After differencing and some rearranging, the line Gauss-Seidel iteration method reduces the difference equation for \(u\) at each mesh point to

\[
\begin{align*}
&u_{j+1, k, \ell} + \frac{1}{\rho u} \frac{p_{j+1, k, \ell} + w}{u} \frac{\Delta x}{2 \Delta \phi} \left( u_{j+1, k, \ell+1} - u_{j+1, k, \ell-1} \right) \hfill \\
&- \text{Re}^* \frac{\Delta x}{\Delta \phi^2} \left( u_{j+1, k, \ell+1} - 2u_{j+1, k, \ell} + u_{j+1, k, \ell-1} \right) = u_{j, k, \ell} + \frac{1}{\rho u} p_{j, k, \ell},
\end{align*}
\]

(22)

with similar expressions for the other equations, where the superscript \(n\) denotes the known iterate, the superscript \(n+1\) denotes the next (unknown) iterate, and the right hand side of the equations are at \(j\) and so are independent of the iterate.

The convergence of the solution of the system of difference equations represented by Eq. (22) can be determined using the Fourier series method as presented in Ref. 11. The solutions will converge if the eigenvalues of the associated amplification matrix are less than one in absolute value. To
obtain the eigenvalues substitute \( u_0 e^{iml\Delta \phi} \) and \( \lambda u_0 e^{iml\Delta \phi} \) for \( u^n_{j+1, k, l} \) and \( u^{n+1}_{j+1, k, l} \), and similarly for \( v, w, p, h \); this gives five linear equations in \( u_0, v_0, w_0, p_0, \) and \( h_0 \), and the eigenvalues of the amplification matrix are those values of \( \lambda \) for which the determinant of the coefficient matrix is zero.

For the above system it has been found in regions of the flow where \( M_x \) is near one or less than one, that some of the eigenvalues of the amplification matrix are greater than one, in absolute value, independent of \( \Delta x \) and \( \Delta \phi \). However, if the \( \partial p/\partial x \) term in the \( x \)-momentum and energy equation are differenced backwards in \( x \), i.e.

\[
\frac{\partial p}{\partial x} = \frac{p_j, k, l - p_{j-1}, k, l}{\Delta x}
\]  

(23)

as suggested by Ohrenberger and Baum (Ref. 13), or set equal to zero as suggested by Rubin and Lin (Ref. 14), then convergence criteria can be obtained. Doing either of the above modifications causes the difference expressions representing the underlined terms in Eq. (21) to be independent of the iteration index \( n \). Thus, the first and second difference equations are uncoupled from the rest of the system and are similar to the simple equation in Section II. Therefore \( |\lambda| < 1 \) if

\[
\Delta x < \left| \frac{ut}{w} \right| \Delta \phi
\]  

(24)

The remaining three equations are studied using the Fourier series method. If the determinant of the associated three by three matrix of coefficients is set equal to zero, it can be found that a third value of \( \lambda \) is the same as the first two above, and so Eq. (24) must be satisfied. The remaining two values satisfy a complicated quadratic equation. To simplify the analysis the first and second derivative terms are handled separately. For second derivative terms only, it can be easily shown that both roots of the
quadratic equation are less than one in absolute value. For first derivative terms only, it can be shown after considerable effort that the two roots of the quadratic equation are less than one in absolute value if and only if

\[
\Delta x < \frac{\frac{1}{2} \left| \nabla \right| \Delta \phi}{\left| w \right| (1 + \frac{1}{w}) + \sqrt{\left(1 - \frac{1}{w}\right)^2 w^2 + \frac{4h}{\gamma M_w}}}
\]

(25)

The results as represented by Eqs. (24), (25) apply to the simplified linear system Eq. (21). It has been found numerically that the restriction for the actual nonlinear system of equations [Eqs. (7) through (20)] is qualitatively like Eqs. (24), (25). Quantitatively the restriction is similar to Eq. (24).

Once the solution can be obtained at \( x_{j+1} \), the question of whether the scheme is stable for marching in the \( x \) direction must be answered. To analyze the stability, the following system is considered.

\[
\begin{align*}
\frac{\partial u}{\partial x} + \frac{1}{\rho u} \frac{\partial p}{\partial x} - \text{Re} \left( \frac{\partial^2 u}{\partial \phi^2} + r^2 \frac{\partial^2 u}{\partial y^2} \right) &= 0 \\
\frac{\partial v}{\partial x} \text{Re} \left( \frac{\partial^2 v}{\partial \phi^2} + r^2 \frac{\partial^2 v}{\partial y^2} \right) &= 0 \\
\frac{\partial w}{\partial x} \text{Re} \left( \frac{\partial^2 w}{\partial \phi^2} + r^2 \frac{\partial^2 w}{\partial y^2} \right) &= 0 \\
\frac{\partial p}{\partial x} + p \frac{\partial u}{\partial x} - p \frac{\partial h}{\partial x} &= 0 \\
\frac{\partial h}{\partial x} - \gamma \frac{1}{\rho} \frac{\partial p}{\partial x} - \text{Re} \left( \frac{\partial^2 h}{\partial \phi^2} + r^2 \frac{\partial^2 h}{\partial y^2} \right) &= 0
\end{align*}
\]

(26)
The above equations are differenced implicitly and the resulting equations are studied using the Fourier series technique. The equations are stable if the eigenvalues of the amplification matrix are less than or equal to one in absolute value. The second and third equations are uncoupled from the system. It can easily be shown that they are unconditionally stable.

For the remaining three equations one of the eigenvalues is \( \lambda = 1 \), and another is

\[
\lambda = \frac{1}{1 - 2 \Re \left( \frac{\cos_1(\Delta \Phi - 1) \frac{\Delta x}{\Delta y^2} + (\cos_2(\Delta \phi) - 1) \frac{r^2 \Delta x}{\Delta y^2}}{\Delta y^2} \right)}
\]  

(27)

which is less than or equal to one in absolute value.

Since the first four eigenvalues are less than or equal to one in absolute value, the stability of the system of Eq. (26) depends on the magnitude of the fifth and final one. Three different cases are considered depending on how the \( \partial p/\partial x \) term in the x-momentum and energy equations is differenced. In

the first case, if \( \partial p/\partial x \) is set to zero as suggested by Rubin and Lin (Ref. 14), then the fifth eigenvalue is the same as Eq. (27). Thus, the difference equations are unconditionally stable as a marching scheme in x.

The second case corresponds to evaluating \( \partial p/\partial x \) backwards in x [Eq. (23)], as suggested by Ohrenberger and Baum (Ref. 13). If \( M_x \geq 1 \) then it can be shown that the magnitude of the eigenvalue is less than or equal to one. However, if \( M_x < 1 \), which occurs near the cone due to the boundary condition \( u = 0 \), the following restriction must be satisfied to ensure that the absolute value of the eigenvalue is less than or equal to one.

\[
\Delta x \geq \left( \frac{1}{\Delta y^2} - 1 \right) \frac{1}{2 \Re \left( \frac{(1 - \cos_1 \Delta \phi - 1) \frac{1}{\Delta y^2} + (1 - \cos_2 \Delta \phi) \frac{r^2}{\Delta y^2}}{\Delta y^2} \right)}
\]

(28)
The third case corresponds to taking $\partial p/\partial x$ implicitly. For this case it is found that $\Delta x$ must be twice as big as for the previous case where $\partial p/\partial x$ was evaluated explicitly. This implies that if a different method were used to solve the implicit equations (the proposed Newton-Gauss-Seidel method does not converge when $\partial p/\partial x$ is differenced implicitly as mentioned previously) a numerical solution to the fluid flow equations could be obtained if $\Delta x$ were chosen sufficiently large. A lower bound restriction on the marching stepsize has also been found for certain stiff ordinary differential equations by Curtiss and Hirschfelder (Ref. 15) in order to suppress so-called departure solutions. The case here is analogous to the ordinary differential equation case. The departure is characterized by the leeward surface pressure oscillating or rapidly increasing, and has been observed by Baum and Denison (Ref. 12), Rubin and Lin (Ref. 14), and Tyson (Ref. 16). Tyson experimentally found that a large stepsize was necessary to suppress the departure solutions.
SECTION IV
NUMERICAL RESULTS

To demonstrate the validity of the technique, solutions have been compared with experimental data obtained by Tracy (Ref. 8) on a sharp 10 deg half angle cone at an angle of attack of 12 deg. The parameters used in the calculation are given in Table I. These correspond closely to the experimental data. Initial conditions, which would normally come from a solution to the nose region, are needed before an exact comparison can be obtained. Since the nose solution was not available, the following technique was used to generate the required initial conditions. Starting at zero, the angle of attack was slowly increased while marching along the cone until 12 deg was reached at an \( x = x_0 \). The calculations are then continued at a constant 12 deg angle of attack, and the solution is allowed to relax to the desired sharp cone results. Because of the method used to generate the initial conditions, the calculations are not expected to agree with the data at the same \( x \) station. However, the calculation should relax to results which are similar to the data (except the difference in local Reynolds number) as the solution continues downstream.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol and Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cone half angle</td>
<td>( \theta = 10 ) deg</td>
</tr>
<tr>
<td>angle of attack</td>
<td>( \alpha = 12 ) deg</td>
</tr>
<tr>
<td>freestream Mach number</td>
<td>( M_\infty = 8 )</td>
</tr>
<tr>
<td>freestream Reynolds number</td>
<td>( Re = 1.1 \times 10^6 / \text{ft} )</td>
</tr>
<tr>
<td>freestream Prandtl number</td>
<td>( Pr = 0.75 )</td>
</tr>
<tr>
<td>ratio of specific heats</td>
<td>( \gamma = 1.4 )</td>
</tr>
<tr>
<td>Sutherland constant</td>
<td>( S = 2 )</td>
</tr>
<tr>
<td>freestream dimensionless pressure</td>
<td>( P_\infty = 0.0112 )</td>
</tr>
<tr>
<td>static enthalpy at the cone</td>
<td>( h_\infty = 5.5 )</td>
</tr>
</tbody>
</table>
Figures 2, 3 show the experimental surface pressure and heat transfer around the cone at \( x = 0.33 \) ft and the calculated results at \( \bar{x} = x/x_0 = 8.5, 25, \) and 50. The calculated heat transfer results illustrate that at \( \bar{x} = 8.5 \) the effect of the initial conditions at \( x = x_0 \) have not yet relaxed. At \( x = 25 \) and 50 the calculations appear to be approaching a relaxed result and the agreement with the heat transfer data is very good.

In Figure 4, a comparison between the measured and calculated bow shock and viscous layer thickness around the cone is given. The data were taken at \( x = 0.286 \) ft, the calculated results at \( \bar{x} = 50 \) are shown. Finally in Figure 5, the calculated velocity vectors on the leeward side projected normal to the streamwise direction are shown. The separated flow region on the leeward side is clearly shown by this figure.

The above results were obtained by evaluating \( \partial p/\partial x \) explicitly. Runs were also made with \( \partial p/\partial x = 0 \) and the results differed very slightly from those presented.

A comparison of actual convergence and stability restrictions with the analytical restrictions for this case is presented in Figure 6. From Eq. (24) with \( \Delta \Phi = 10 \) deg and taking 1 as a lower bound for \( |u/w| \) we see that

\[
\frac{\Delta x}{x} < 0.03 \tag{29}
\]

is necessary for convergence. Equation (28) implies that the biggest restriction occurs for small \( u \), that is near to the cone. To simplify the expression, suppose that \( \cos m_1 \Delta \Phi \) and \( \cos m_2 \Delta y \) are zero. This is not strictly valid; however, we are looking for an approximate answer. Making this assumption may not give us precise quantitative results but hopefully qualitative results will be obtained. For the case run, \( \Delta y << r \Delta \Phi \). The nearest point to the cone that is solved for corresponds to \( y - \Delta y \). The functions \( p \) and \( \mu \) evaluated at \( \Delta y \) are approximately constant as functions of \( x \). Also it
Figure 2. Geometry of the Flow for Tracy's Case, $\alpha = 12$ deg
Figure 3. Circumferential Surface Pressure Distribution for Tracy's Case, $\alpha = 12$ deg
Figure 4. Circumferential Heat Transfer Distribution for Tracy's Case, \( \alpha = 12 \) deg
\[ \frac{\Delta x}{x} = 0.03 \]
\[ \frac{\Delta x}{x} = 16 \frac{\Delta y}{x} \]

C CONVERGED STABLE SOLUTION
NC NO CONVERGENCE
D CONVERGED BUT DEPARTURE SOLUTION
O SLOWLY OSCILLATING SOLUTION

Figure 6. Comparison of Analytical and Numerical Results
has been observed that the ratio $\Delta y/u$ where $u$ is evaluated at $y = \Delta y$ is almost constant as a function of $x$. Thus Eq. (28) is approximately

$$\frac{\Delta x}{x} = \left[ \frac{\frac{\text{Re}}{\rho}}{\frac{\text{Pr}}{\mu}} \right] \frac{\Delta y}{x}$$

(30)

where the expression in brackets in Eq. (30) is approximately constant. In addition, since the transformation $y = \eta \xi$ is made, $\Delta y = \Delta \eta \xi$; and since $\xi$ increases approximately linearly with $x$, then $\Delta y/x$ remains constant as $x$ increases. Equation (30) then implies that for an initially chosen $\Delta y$, $\Delta x$ must increase linearly as $x$ increases. Therefore if $\Delta y$ is chosen so that Eqs. (30), (29) are satisfied initially, they will be satisfied for all $x$ provided $\Delta x$ increases proportionally to $x$.

Tracy's case was run with $\Delta x/x = 0.03$ and a $\Delta \eta$ spacing such that initially $\Delta y/x = 0.0006$. The expression in brackets in Eq. (30) is equal to 16 so that Eq. (30) is satisfied. With $\Delta \Phi = 10$ several different values for $\Delta x$ and $\Delta y$ were used to determine how accurate the derived inequalities are. The results are shown in Figure 6. The shaded region is the predicted area where convergent stable solutions should be obtained. The actual region of convergent stable solutions is somewhat different. However, the qualitative results are correct. It was found that increasing $\Delta x$ slowed down the convergence of the iterative procedure to obtain the solution at an $x$ station until finally it did not converge. Decreasing $\Delta x$ sped up the convergence but produced solutions that departed as a function of $x$. Increasing $\Delta y$ led to departure solution and decreasing $\Delta y$ led to stable solutions. For a few cases the results for the surface pressure on the leeward side (the most critical for departure) at $\alpha = 12$ deg are shown in Figure 7.

A second case has been run to compare with experimental data obtained by Stetson and Ojdana (Ref. 9) on a sharp 5.6 deg half angle cone at an angle of attack of 8 deg. The parameters used in the calculation are given in Table II. Figure 8 shows the wall pressure distribution on the leeward side at $x = 17$. Stetson's case was run with $\partial p/\partial x = 0$. Analysis of the restrictions
Figure 7. Leeward Surface Pressure for Different Values of $\Delta x$ and $\Delta y$
Figure 8. Circumferential Surface Pressure Distribution for Stetson's Case, $\alpha = 8$ deg
on $\Delta x$ for $\partial p/\partial x$ evaluated explicitly as was done for Tracy's case led to $\Delta x$ spacings that were much too small in the sense that too many $y$ mesh points were required and the storage capability of the computer was exceeded. Numerical experimentation verified that the solution could not be obtained for any permissible mesh spacing when $\partial p/\partial x$ was evaluated explicitly.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol and Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cone half angle</td>
<td>$\theta = 5.6$ deg</td>
</tr>
<tr>
<td>angle of attack</td>
<td>$\alpha = 8$ deg</td>
</tr>
<tr>
<td>freestream Mach number</td>
<td>$M_\infty = 14.2$</td>
</tr>
<tr>
<td>freestream Reynolds number</td>
<td>$Re = 0.83 \times 10^6$/ft</td>
</tr>
<tr>
<td>freestream Prandtl number</td>
<td>$Pr = 0.75$</td>
</tr>
<tr>
<td>ratio of specific heats</td>
<td>$\gamma = 1.4$</td>
</tr>
<tr>
<td>Sutherland constant</td>
<td>$S = 4$</td>
</tr>
<tr>
<td>freestream dimensionless pressure</td>
<td>$p_\infty = 0.00354$</td>
</tr>
<tr>
<td>static enthalpy at the cone</td>
<td>$h_w = 32.398$</td>
</tr>
</tbody>
</table>
SECTION V

COMPUTER PROGRAM

A computer program has been developed for the CDC/7600 computer that solves the above equations. Provision has been made for variable grid sizes in both the $y$ and $\Phi$ directions and this feature has been used heavily. The iteration logic has been structured so that when the solution along a $\Phi$ line converges to the desired number of figures, that line is dropped from the iteration loop. This saves considerable time since a few $\Phi$ lines require as many as seven iterations to converge to five figures while most $\Phi$ lines require only two or three iterations.

For 50 points in the $y$ direction and 23 points in the $\Phi$ direction the program requires 35,000 words of storage. It takes 30 sec to obtain the solution accurate to five figures at one $x$ station. Eleven percent of this time is spent evaluating all the derivative expressions, 33 percent is spent computing the Jacobian coefficient matrix, and 56 percent is spent solving the linear equations. For Tracy's case it took about 120 steps to go from $\overline{x} = 1$ to $\overline{x} = 50$.

For convenience in programming the derivatives were defined as

\[
\frac{\partial u^n}{\partial \Phi} = \left( \frac{u^n_{j+1,k+1} - u^n_{j+1,k-1}}{2 \Delta \Phi} \right)
\]

\[
\frac{\partial^2 u^n}{\partial \Phi^2} = \left( \frac{u^n_{j+1,k+1} - 2u^n_{j,k+1} + u^n_{j,k-1}}{\Delta \Phi^2} \right)
\]

The right hand side of Eq. (4) became

\[
- \frac{\partial u^n}{\partial x} - a \frac{\partial u^n}{\partial \eta} - b \frac{\partial u^n}{\partial \Phi} + c \frac{\partial^2 u^n}{\partial \eta^2} + d \frac{\partial^2 u^n}{\partial \Phi^2}
\]
where the underlined terms in Eq. (4) have been ignored. It is seen that it is necessary to store only two planes of the solution, one at $j$ and one for the current iterate at $j+1$. The $n+1$ iterate is stored on top of the $n$ iterate as it is computed.
SECTION VI
DISCUSSION AND CONCLUSIONS

A method for solving the implicit difference equations describing the three-dimensional flow around a cone at angle of attack has been described and analyzed. These equations which are derived and discussed in Ref. 6 constitute a system of three-dimensional nonlinear parabolic equations. The technique for solving these equations has been shown to be accurate and efficient in both running time and computer storage.

The numerical method is not restricted to steady flow problems but could easily be applied to two-dimensional time dependent calculations.

An analysis of the numerical aspect of departure solutions has been presented. Methods that have been proposed by other authors to suppress the departure solutions have been verified and in some cases qualified. In addition, it has been shown that departure solutions can be suppressed even if the streamwise pressure derivative is included, if the steps ze is large enough.

Results have been compared with experimental data and the agreement is very good.
REFERENCES


APPENDIX A
PROGRAM INPUT INSTRUCTIONS

The input is divided into two sections, namelist input and formatted input. Parameters describing the problem are read using NAMELIST/INPUT/.

GAMMA = \( \gamma \)
MINF = \( M_\infty \)
THETAC = \( \theta \)
REINF = Re
PRINF = Pr
ALFA = \( \alpha \)
PINF = \( p_\infty \)
SPROP = S
NJ = number of x-stations
NK = number of y-stations at which initial conditions are specified
NL = number of \( \phi \)-stations at which initial conditions are specified
M\( \phi \)D = .TRUE. or .FALSE. depending on whether the input mesh distribution is to be modified or not. Default is .FALSE.
ITAPE = 0, no output on TAPE2, this is the default
= N, output solution on TAPE2 every Nth x-step

The rest of the input is read using format control.

IREAD (112)

IREAD > 0 read initial profile from TAPE3, used for restart purposes. The first profile on TAPE 3 at an x station bigger than or equal to X(1) is selected as the initial profile.

IREAD \leq 0 read initial profile from cards
If IREAD ≤ 0 then the cards with the solution are input

\[
\text{FI}(L), \ ZI(1, L) \ (2E12.5)
\]

repeat \( NL \) times

\[
\text{FI}(L) \text{ is a } \phi \text{ station in degrees} \\
ZI(1, L) \text{ is the shock distance at } \phi \\
ET(K), \ U(K, L), \ V(K, L), \ W(K, L), \ P(K, L), \ H(K, L), \ K=1, NK(6E12.5) \\
\text{FT}(K) \text{ is a distance from the body (≠y not } y/\text{shock}) \\
U, V, W, P, H \text{ are values of } u, v, w, p, h \text{ at } ET(K), \ FI(L)
\]

\( X(J) \) \( J=1 \) or \( J=1, \) \( NJ(6E12.5) \)

\( X(J) \) is an \( X \)-station along the body. If \( J=1 \) then the rest of the points are obtained using \( X(J+1) = c \times X(J) \) where

\( c \) is a constant > 1. \( X(1) \) is the position of the initial profile.

The following cards describe \( v \) and \( h \) at the body:

\( L \ (112) \)

\( L \) is the index of a \( \phi \) station

\( J, \ VB(J, L), \ HB(J, L) \ (112, \ 2E12.5) \)

\( J \) is the index of an \( X \) station

\( VB(J, L) \) is the value of \( v \) at the body at \( X(J), \ FI(L) \)

\( HB(J, L) \) is the value of \( h \) at the body at \( X(J), \ FI(L) \)

This card is repeated with \( N \) increasing from 1 to \( NJ \).

If any \( J \) stations are skipped then linear interpolation is used to obtain \( VB \) and \( HB \) at the skipped stations.

There then follows a card with another \( L \) value and cards with \( J, \ VB, \) and \( HB \). These groups are repeated with \( L \) increasing from 1 to \( NL \). If any \( L \) stations are skipped then linear interpolation is used to obtain \( VB \) and \( HB \) at the skipped stations.
If MOD=.TRUE., more cards are needed.

NEWK, NEWL (215)

NEWK is a new value for NK, and indicates that the input η
distribution is to be changed. If the η distribution is not to
be changed then leave NEWK blank.
NEWL as with NEWK but for NL and φ.

If NEWK > 0

ETNEW(K) K=1, NEWK (6D12.4).
The numbers must increase from 0. The input numbers
are scaled by the program to go from 0. to 1, by dividing
by ETNEW (NEWK)

If NEWL > 0

FINEW(L) L=1, NEWL (6D12.4)
These are the new φ stations in degrees. They must
increase from 0 to 180 deg.
The name list input is printed out. If the initial profiles were read from cards then the card images are printed.

The x-stations at which the solution will be obtained are printed.

The input profiles are printed and if the mesh distribution was changed, then the new initial profiles are printed.

The profiles are printed at each x-station as they are obtained. Preceding each station printout is printed the iteration and convergence history for that x-station. The variables printed are ITER and INS(L), L = 1, NL. If all $\phi$-rays have converged then ITER = 0, otherwise ITER = 1. If the Lth $\phi$-ray has converged then INS(L) = 0, otherwise INS(L) = 1.

The parameters read in with name list are written on TAPE4, followed by the profiles at each x-station. The data are written without format control and can be used to supply initial conditions.

If ITAPE > 0 then the profiles are written on TAPE2 at each ITAPEth x-station. TAPE2 can be set up as the punch file.
APPENDIX C

EXAMPLE PROBLEM

The input necessary to run Tracy's case (see Table 1) is given in Appendix D. The sequence numbers on the initial condition profiles are not required, they are included on the sample deck to aid in ordering the cards if they get mixed up.

The output from the program is presented in Appendix E. The solution has been printed at only a few mesh points.

After running much further along the cone the solution profiles obtained would be similar to those shown in Figures C-1, C-2, C-3, C-4, and C-5.
CALCULATED RESULTS

X = 50X₀

Figure C-1. Streamwise Velocity Profiles for Tracy's Case, φ = 12 deg
CALCULATED RESULTS

$X = 50X_0$

**Figure C-2.** Normal Velocity Profiles for Tracy's Case, $\alpha = 12$ deg
Figure C-3. Circumferential Velocity Profiles for Tracy's Case, $\alpha = 12$ deg
Figure C-4. Pressure Profiles for Tracy's Case. 
\( \alpha = 12 \text{ deg} \)
CALCULATED RESULTS
\[ x = 50X_0 \]

Figure C-5. Enthalpy Profiles for Tracy's Case.
\[ \alpha = 12 \text{ deg} \]
APPENDIX D

INPUT FOR TRACY'S CASE
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*Input*

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| $N$ | 11.0 |
| $NK$ | 50.0 |
| $NL$ | 19.0 |

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APPENDIX E

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**Note:** The table above represents a solution at a specific point (X = 0.00000E+01) with various parameters (Y, U, W, M, P, M TOTAL) showing the distribution or values at that point. The values are given in scientific notation for clarity and precision.
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## Solution at \( x = 0.50000\times 10^{-01} \)

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### Shocks Distance = \( 208.25\times 10^{-02} \)
The text contains values and formulas, possibly related to a physics or engineering context. The table includes columns for AT, CFINF, STINF, SHOCK DISTANCE, and other variables. The table entries are numerical values with units or dimensions implied by the context. The formulas seem to be related to calculations involving shock waves or similar phenomena, given the context of the variables involved.
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<td>0.29649E-03</td>
<td>0.16422E+00</td>
<td>0.23644E-02</td>
<td>0.12936E+15</td>
</tr>
<tr>
<td>0.32148E-03</td>
<td>0.19539E+00</td>
<td>0.27550E-02</td>
<td>0.32089E+15</td>
</tr>
<tr>
<td>0.37171E-03</td>
<td>0.21897E+00</td>
<td>0.37643E-02</td>
<td>0.43329E+15</td>
</tr>
<tr>
<td>0.42583E-03</td>
<td>0.25031E+00</td>
<td>0.48285E-02</td>
<td>0.55909E+15</td>
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<tr>
<td>0.50286E-03</td>
<td>0.28793E+00</td>
<td>0.62829E-02</td>
<td>0.58078E+15</td>
</tr>
<tr>
<td>0.55855E-03</td>
<td>0.32639E+00</td>
<td>0.80101E-02</td>
<td>0.61342E+15</td>
</tr>
<tr>
<td>0.61134E-03</td>
<td>0.36319E+00</td>
<td>1.01520E-01</td>
<td>0.79464E+15</td>
</tr>
<tr>
<td>0.67916E-03</td>
<td>0.40171E+00</td>
<td>1.20280E+01</td>
<td>0.98026E+15</td>
</tr>
<tr>
<td>0.66698E-03</td>
<td>0.38447E+00</td>
<td>1.15683E-01</td>
<td>0.11212E-14</td>
</tr>
</tbody>
</table>
PROGRAM ADFAI (INPUT, OUTPUT, TAPES=INPUT, TAPE6=OUTPUT).
&TAPE2, TAPE3, TAPE4)
C THIS IS THE MAIN ROUTINE.
C THE MAXIMUM SIZE OF ALL ARRAYS IS SPECIFIED IN THE
C DIMENSION STATEMENT. IF MAXJ, MAXK, MAXL DENOTE THE
C UPPER BOUNDS FOR J, K, AND MAXL DENOTES THE LARGER
C OF MAXJ AND MAXK THEN THE ARRAYS ARE DIMENSIONED
C DEFINED (MAXKXMAXL, 1)
C ARCFD (MAXK, 1.0)
C TMAXX), F (MAXK, X (MAXJ))
C NETF (MAXK, INFET (MAXK))
C VB (MAXJ, MAXK, XB (MAXK, MAXL))
C COEFF (MAXJ, MAXK, DEL ((MAXK-1)!, RESIDE (MAXK-1)!,
C WORK3 (1, 1), WORK2 (1), WORK1 (1), WORK4 (1),
C IF MAXK IS GREATER THAN 100 THEN THE DIMENSION OF Y IN
C BLANK COMMON SHOULD BE MAXK.
C
C TAPE2 IS AN OUTPUT UNIT; SEE SUBROUTINE OUTPUT.
C TAPE3 AND TAPE4 ARE INPUT AND OUTPUT UNITS,
C SEE SUBROUTINES BCIC AND OUTPUT.
C
C PROBLEM PARAMETERS ARE READ USING NAMELIST IN THE MAIN
C ROUTINE. FOR OTHER INPUT SEE SUBROUTINE BCIC.
C
C THERE ARE A FEW UNCONVENTIONAL (AND FRUSTRATING IF FORGOTTEN)
C THINGS IN THE PROGRAM. SEE SUBROUTINES FLFCLC, IMPETA, BCIC,
C AND OUTPUT, THE COMMENTS ARE INDICATED WITH ASTERISKS ****
C REAL ME, MINT
C LEVEL 2, DEPVAR, ABCFD, COEFF, WORK1,
C LEVEL 2, UVPJ1, UVPJ2, UVPJ3, UVPJ4, UVPJ5, UVPJ6, UVPJ7, UVPJ8, UVPJ9,
C & UVPJ10, UVPJ11, UVPJ12, UVPJ13, A, B, C, D, DELU, DELV, CELW, DELH,
C & DELP, DELZ
C LEVEL 2, UNEW, VNEW, WNEW, PNEW, HNEW, ZNEW, HBKNEW, VBKNEW, ETNEW, FNEW
C THE ARRAY UVPHZ IS NEEDED ONLY BECAUSE THE CCC7600 JUMBLES
C LARGE CORE ARRAYS WHEN THEY ARE INPUT OR OUTPUT WITHOUT
C FORMAT CONTROL. THE ARRAY IS USED IN SUBROUTINES BCIC AND
C OUTPUT. HERE IT SHOULD BE DIMENSIONED UVPHZ (MAXKXMAXL, 6).
C COMMON /OUTDEP/ UVPHZ (50, 20, 6)
C DIMENSION DEPVAR (1000, 18)
C DIMENSION ABCFD (50, 120)
C DIMENSION
COMMON /VARY/XM1,XJ,XJ01,DX,DXJ1,JM1,J,JP1
COMMON /PUNCH/ ITAPE
LOGICAL MOD

C THE FOLLOWING PARAMETERS ARE INPUT WITH NAMELIST
C GAMMA = RATIO OF SPECIFIC HEATS
C MINF = FREESTREAM MACH NUMBER
C THETAC = CONE HALF-ANGLE (DEG)
C REINF = FREESTREAM REYNOLDS NUMBER (1/FT)
C PRINF = FREESTREAM PRANDTL NUMBER
C ALFA = ANGLE OF ATTACK (DEG)
C PRINF = DIMENSIONLESS FREESTREAM PRESSURE
C PROP = SUTHERLAND CONSTANT USED IN VISCOSITY LAW
C NJ = NUMBER OF X-STATIONS
C NK = NUMBER OF Y-STATIONS
C NL = NUMBER OF PHI-STATIONS
C MOD = .TRUE. OR .FALSE. DEPENDING ON WHETHER THE INITIAL
C CONDITIONS ARE TO BE MODIFIED OR NOT, DEFAULT=.FALSE.
C ITAPE = 0 NO OUTPUT ON TAPE2, THIS IS THE DEFAULT VALUE
C = N OUTPUT SOLUTION ON TAPE2 EVERY NTH X-STATION.

NAMELIST /INPUT/ GAMMA,MINF,THETAC,REINF,PRINF,ALFA,
                 PRINF,PROP,NJ,NK,NL,MOD,ITAPE

J = 0
MOD = .FALSE.
ITAPE=0
READ (5,INPUT)
WRITE (6,INPUT)
THETAC=THETAC*.0174532925199433
ALFA=ALFA*.0174532925199433
REINF=REINF/REINF
PROP=PROP/PRINF
MF=(GAMMA-1.)/MINF*MINF
VELINF = 1.
HBA= 1. + ME/2.
REEME=ME*REINF
GM2=GAMMA*MINF*MINF
COCTC=COSI(THTAC)
SINTC=SINI(THTAC)
COSTC=COSI(ALFA)
SINTC=SINI(ALFA)
CTCA=COSI*CTSA
STSA=SINTC*CTSA
STCA=SINTC*COSA1F
CTSA=COSTC*STSA

C OBTAIN THE BOUNDARY CONDITIONS AND THE INITIAL CONDITIONS.
CALL BCIG (NJ, NK, NL, U, V, W, H, P, ZI, UJMH1, VJMH1, WJMH1, HJMH1, PJMH1, ZIJMH1)

C REWIND 3
NEWK = NK
NEWL = NL
IF (.NOT. MOD) GO TO 100

C OUTPUT THE INITIAL CONDITIONS BEFORE THEY ARE MODIFIED.
CALL OUTPUT (NK, NL, X, IL, ET, FI, U, V, W, H, P, ZI)

C IF THE SOLUTION IS TO BE MODIFIED READ IN A NEW VALUE FOR
C NK AND/OR NL.
READ (5, 5010) NEWK, NEWL

5010 FORMAT (2I5)
IF (NEWK .LE. 0) GO TO 50
NEWK = NEWK

C READ IN A NEW NORMAL DISTRIBUTION.
READ (5, 5020) (ETNEW(K), K=1,NEWK)

5020 FORMAT (6E12.4)
DO 40 K = 1, NEWK
ETNEW(K) = ETNEW(K) / ETNEW(NEWK)
40 CONTINUE

ETNEW(1) = 0.0
ETNEW(NEWK) = 1.0
GO TO 55

55 CONTINUE
DO 52 K = 1, NK
ETNEW(K) = ET(K)
52 CONTINUE
IF (NEWL .LE. 0) GO TO 70
NEWL = NEWL

C READ IN A NEW CIRCUMFERENTIAL DISTRIBUTION (CEC).
READ (5, 5020) (FNEW(L), L=1, NEWL)
DO 60 L = 1, NEWL
FNEW(L) = FNEW(L) * .01745329252
60 CONTINUE

FNEW(1) = 0.0
FNEW(NEWL) = 180.00 * .01745329252
GO TO 75

75 CONTINUE
IF (NEWL .LE. 0) GO TO 72
NEWL = NEWL

C INTERPOLATE TO OBTAIN THE SOLUTION AT THE NEW MESH.
DISTRIBUTION FOR EACH OF THE INPUT PLANES.

CALL MODIFY (NK, NL, NEWNK, NEWNL, ET, FI, ETNEW, FINEW, 0.0)

CALL MODIFY (NK, NL, NEWNK, NEWNL, ET, FI, ETNEW, FINEW, UVP)

CALL MODIFY (NK, NL, NEWNK, NEWNL, ET, FI, ETNEW, FINEW, NJ, HB)

NK = NEWNK
NL = NEWNL

WRITE (6, INPUT)

CONTINUE

REWIND 6

WRITE (4) GAMMA, MINF, THE TAC, REINF, PRINF, ALFA, PINF, SPROP, NJ, NK, NL

OUTPUT THE INITIAL CONDITIONS

CALL OUTPUT (NK, NL, X(I), ET, FI, U, V, W, H, P, ZI)

NKM1 = NK - 1
NKM2 = NKM1 * 2
NL5 = NL * 5

CALL FLOFDINJ, NK, NL, NKM1, NKM2, NL5, U, V, W, H, P, ZI, UJP1, VJP1,

WJP1, HJP1, PJP1, ZIJP1, UJM1, VJM1, WJM1, HJM1, PJM1,

ZIJM1, VB, HB,

DELU, DELV, DELW, DELH, DELP, DELT1,

INETF1, INFET1, KSUP, PMJ1F1,

ET, FX, AX, BX, CY, CZ, DELERTSIDE, WCRK1, WCRK2,

WORK3, WORK4

STOP

END

SUBROUTINE FLOFD (INJ, NK, NL, NKM1, NKM2, NL5, U, V, W, H, P, ZI, UJP1, VJP1,

WJP1, HJP1, PJP1, ZIJP1, UJM1, VJM1, WJM1, HJM1, PJM1,

ZIJM1, VB, HB,

DELU, DELV, DELW, DELH, DELP, DELT1,

INETF1, INFET1, KSUP, PMJ1F1,

ET, FX, AX, BX, CY, CZ, DELERTSIDE, WCRK1, WCRK2,

WORK3, WORK4)

C THIS SUBROUTINE COMPUTES THE INITIAL GUESS TO THE SOLUTION

C AT THE NEXT X-STATION, AND CONTROLS THE MARCHING IN X.

REAL MINF

LEVEL 2, U, UJP1, UJM1, V, VJP1, VJM1, W, WJP1, WJM1, P, PJP1, PJM1,

G220C
C**********THE FOLLOWING CARD MUST BE SET CORRECTLY FOR EACH RUN.**********
C**********THE NUMBER PLT ON IT MUST BE EQUAL TO THE X-STEP TAKEN TO***
C**********GET TO THE PLANE OF INITIAL CONDITIONS READ IN FROM THE***
C**********PREVIOUS X-STATION. THIS IS SO THE INITIAL BACKWARDS**********
C**********EVALUATION OF DX/NX WILL BE CORRECT.**********************

XJ = X(J1) - 0.0012
XJPI = X(J1)
200 CONTINUE
JMJ = J-1
JPJ = J+1
XJM = X(J)
XJ = XJPI
XJPI = X(JPJ)
DXJM1 = XJ - XJM1
DX = XJPI - XJ
DO 25 LDUM=1,NL
C obtam the initial guess
DO 20 K=1,NK
UJP(K,LDUM) = U(K,LDUM) + (U(K,LDUM) - UJM1(K,LDUM)) * DX/CXJM1
VJP(K,LDUM) = V(K,LDUM) + (V(K,LDUM) - VJM1(K,LDUM)) * DX/CXJM1
WJP(K,LDUM) = W(K,LDUM) + (W(K,LDUM) - WM1(K,LDUM)) * DX/CXJM1
HJP1(K,LDUM) = H(K,LDUM) + (H(K,LDUM) - HM1(K,LDUM)) * DX/CXJM1
PJP1(K,LDUM) = P(K,LDUM) + (P(K,LDUM) - PM1(K,LDUM)) * DX/CXJM1
ZJP1(K,LDUM) = Z(K,LDUM) + (Z(K,LDUM) - ZJM1(K,LDUM)) * DX/CXJM1
C
20 CONTINUE
25 CONTINUE
DO 30 L=1,NL
INETF1(L) = 1
30 CONTINUE
DO 275 ITGR=N1,N4C
ITER = 0
C
CALL THE SUBROUTINE THAT ADVANCES THE SOLUTION TO THE
C
NEXT X-LOCATION USING A METHOD THAT IS IMPLICIT IN ETA.
C
AND ITERATIVE IN PHI.
C
CALL IMPETA(INJ,NK,NL,HKMI,NKMI,NKMI6,J,VL,W,KZI,UIP1,VJP1,WJP1,
& HJP1,PJP1,ZIJP1,UIJ1,VJMI,WJMI,HJMI,PJMI,ZIJMI1,
& I,J,K,L)
& DEU,DEUL,DELV,DELW,DELP,DELZ1,
& INETF1,
& ET,F1,X,A,B,C,D,DEL,RTSINE,WCRT1,WCRT2,WCRT3,WCRT4
WRITE (6,6973) ITER,(INETF1(KJ),KJ=1,NL)
IF (ITER.LT.O) GO TO 287
IF (ITER.EQ.0) GO TO 276
275 CONTINUE
276 CONTINUE
6973 FORMAT (* ITER,INS *,4012)
287 CONTINUE
C
OUTPUT THE SOLUTION AT X(J+1).
C
CALL OUTPUT(NK,NL,XJP1,E1,F1,UIP1,VJP1,WJP1,HJP1,PJP1,
& ZIJP1)
& IF (ITER.LT.O) RETURN
J=J+1
IF (J.GE.NJ) GO TO 300
C
REDEFINE THE SOLUTION AT X(J) AND X(J-1).
DO 290 L=1,NL
DO 290 K=1,NK
QZ1=U(K,L)
U(K,L)=UJP1(K,L)
UJMI(K,L)=QZ1
QZ1=V(K,L)
V(K,L)=VJP1(K,L)
VJMI(K,L)=QZ1
QZ1=W(K,L)
W(K,L)=WJP1(K,L)
WJMI(K,L)=QZ1
QZ1=H(K,L)
H(K,L)=HJP1(K,L)
HJMI(K,L)=QZ1
290 CONTINUE
295 CONTINUE
02650 02660 02670 02680 02690
02700 02710 02720 02730 02740
02750 02760 02770 02780 02790
02800 02810 02820 02830 02840
02850 02860 02870 02880 02890
02900 02910 02920 02930
02940 02950 02960 02970 02980
02990 03000 03010 03020 03030
03040 03050 03060 03070 03080
QZ1 = P(K, L)
QK1 = P(JP1(K, L))
PJM1(K, L) = QZ1
QZ1 = ZI(K, L)
ZI(K, L) = Z1JP1(K, L)
ZI(JM1, L) = ZI(JM1, L)

CONTINUE
GO TO 200
CONTINUE
RETURN

SUBROUTINE IMPETA (NJ, NK, NL, NM1, NM2, U, V, W, H, P, ZI, UJ1, VJP1, WJP1, HJP1, PJP1, Z1JP1, UJ1, VJ1, W1J1, H1J1, P1J1)
& J, UP1, VJ1, WJP1, HJP1, PJP1, Z1JP1, UJ1, V1J1, W1J1, H1J1, P1J1)
& J, UJ1, VJ1, WJP1, HJP1, PJP1, Z1JP1, UJ1, V1J1, W1J1, H1J1, P1J1)
& J, Z1JP1, UP1, VJ1, WJP1, HJP1, PJP1, Z1JP1, UJ1, V1J1, W1J1, H1J1, P1J1)
& J, Z1JP1, UP1, VJ1, WJP1, HJP1, PJP1, Z1JP1, UJ1, V1J1, W1J1, H1J1, P1J1)
& J, DELU, DELV, DELW, DELH, DELP, DELZI,
& J, INETFI,
& J, ET, FI, X, A, B, C, D, E,
& J, WORK1, WORK2,
& J, WORK3, WORK4
& J, WORK1, WORK2,
& J, WORK3, WORK4

THIS SUBROUTINE CONTROLS THE IMPLICIT IN ETA STEPS.

REAL MJL1, MJL1, MJL1, MJL1
REAL MNL1, MNL1, MNL1
REAL MRL1, MRL1, MRL1
REAL MNL1, MNL1

LOGICAL SUBSN, SUBP1
LOGICAL LINL

LEVEL 2, UJP1, UJ1, VJP1, VJ1, WJP1, W1J1, HJP1, H1J1, PJP1, P1J1,
& J, UJP1, UJ1, VJP1, VJ1, WJP1, W1J1, HJP1, H1J1, PJP1, P1J1,
& J, UJP1, UJ1, VJP1, VJ1, WJP1, W1J1, HJP1, H1J1, PJP1, P1J1,
& J, A, B, C, D, E, WORK1,
& J, UJP1, UJ1, VJP1, VJ1, WJP1, W1J1, HJP1, H1J1, PJP1, P1J1,
& J, UJP1, UJ1, VJP1, VJ1, WJP1, W1J1, HJP1, H1J1, PJP1, P1J1,
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& J, UJP1, UJ1, VJP1, VJ1, WJP1, W1J1, HJP1, H1J1, PJP1, P1J1,
& DRUE, DRUHE, DRUHE, DRUHE, DRUHE, DRUHE, DRUHE, 0.3530
& ORUURX, DRUHE, ORUURX, DRUHE, ORUURX, DRUHE, ORUURX, 0.3540
& ORUHRX, ORUHRX, ORUHRX, ORUHRX, DRUHE, DRUHE, DRUHE, 0.3550
& DRUHRX, DRUHRX, DRUHRX, DRUHRX, DRUHRX, DRUHRX, DRUHRX, 0.3560
& DRUHRX, DRUHRX, DRUHRX, DRUHRX, DRUHRX, DRUHRX, DRUHRX, 0.3570
& D2UDE, D2UDE, D2UDE, D2UDE, D2UDE, D2UDE, D2UDE, 0.3580
& D2UDE, D2UDE, D2UDE, D2UDE, D2UDE, D2UDE, D2UDE, 0.3590
COMMON DHCPX, DHCPX, DHCPX, DHCPX, DHCPX, DHCPX, DHCPX, 0.3600
COMMON ALPHAX, ALPHA2, ALPHAX, ALPHAX, ALPHAX, ALPHAX, 0.3610
& BETA2, EPS2, BETA2, EPS2, BETA2, EPS2, BETA2, 0.3620
& XM1, XM1, XM1, XM1, XM1, XM1, XM1, 0.3630
COMMON SUBSON, SUBSON, SUBSON, SUBSON, SUBSON, SUBSON, SUBSON, 0.3640
COMMON KM1, KM1, KM1, KM1, KM1, KM1, KM1, 0.3650
COMMON /CONST/COSTC, SIMTC, REINF, PRINF, ME, REINF, PRINF, ME, CM2, 0.3660
& MINF, ALPHA1, ALPHA2, ALPHA3, GAMMA1, GAMMA2, GAMMA3, 0.3670
& COMMON /VARY/XJM1, XM1, XM1, XM1, XM1, XM1, XM1, XM1, DDR, 0.3680
& COMMON /ITERATE/I, ITER, ITER, ITER, ITER, ITER, ITER, 0.3690
COMMON /QZBODY/ QZ1, QZ2, QZ3, QZ4, QZ5, QZ6, 0.3700
& , QZ33, QZ42, 0.3710
EQUIVALENCE (DF, DFIL) 0.3720
DATA LFLAG/-1/ 0.3730
LFLAG=LFLAG 0.3740
L=0 0.3750
IF (LFLAG.EQ.-1) L=L+1 0.3760
IF (NL.EQ.2) DF1LP1=F1(L+LFLAG1+LFLAG)+F1(L+LFLAG1+LFLAG)+F1(L+LFLAG1+LFLAG)+F1(L+LFLAG1+LFLAG) 0.3770
DO 200 LDUM=1,NL 0.3780
ISOLV = 0 0.3790
L=L+LFLAG 0.3800
LM1=L-LFLAG 0.3810
LP1=L-LFLAG 0.3820
LINL=FALSE 0.3830
IF (LNEE1.AND. L.NE.NL) OR NL.EQ.1 LINL = TRUE 0.3840
C OBTAIN THE COEFFICIENTS FOR THE FI DERIVATIVES. 0.3850
C IF L = 1 OR NL THEN ALL PHI DERIVATIVES EXCEPT THESE 0.3860
C INVOLVING L AND THE SECOND DERIVATIVES MUST BE ZERO. 0.3870
C DEFINE PARAMETERS SO THAT THIS HAPPENS AND SO THAT THERE 0.3880
C ARE NO PROBLEMS WITH SUBSCRIPTS OR DIVISION BY ZERO. 0.3890
C WHEN NL.NE.1 AND L=1 OR NL THEN LP1 IS USED IN OBTAINING 0.3890
C THE NONZERO PHI DERIVATIVES. LM1 IS SET TO 1 AND IS NOT 0.3900
C INVOLVED WITH NONZERO TERMS. LP1 MUST BE DEFINED PROPERLY. 0.3910
LM1=1 0.3920
LP1=1 0.3930
IF (NL .NE. 1 .AND. L .EQ. 1) LP1=L+1
IF (NL .NE. 1 .AND. L .EQ. NL) LP1=L-1
C SET DFIL I= DELTA PHI) SC THAT CRSS DERIVATIVE TERMS ARE
C HANDLED PROPERLY IN SETUP.
DFIL = 1.E+60
BETA1=0.
BETA2=0.
BETA3=0.
EPS1=0.
EPS2=0.
EPS3=0.
IF (NL .EQ. 1) GO TO 40
RDIFIL = 1. / (FI(LP1)-FI(L))
RDFS2 = 2. * RDIFIL * RDIFIL
GO TO 40
30 CONTINUE
DFIL=DFILP1
DFILP1=FI(LP1)-FI(L)
RDIFIL=2. / (FI(LP1)-FI(LM1))
EPS1=RDIFIL/DFIL
EPS2=EPS1-EPS3
EPS3=RDIFIL/DFILP1
BETA1=-DFILP1*EPS1*5
BETA2=-BETA1-BETA3
40 CONTINUE
IF (INETFIL(L) .EQ. 0) GO TO 127
INETFIL = 0
C OBTAIN THE STARTING VALUES OF THE PARAMETERS.
DETKP1=ET(2)-ET(1)
R=XJP1*SINTC+ET(1)*Z1*JP1(1,L)*COSTC
RKP1=XJP1*SINTC+ET(2)*Z1*JP1(2,L)*COSTC
CALL PROP (HJP1(1,L),JP1(1,L),RHO,DRP,D_DP,RHP,)
6 MU,D_MH,CON,DCH)
CALL PROP (HJP1(2,L),JP1(2,L),RHPK1,DRPKP1,)
5 DRHKP1,MUKP1,D_MHKP1,CONPKP1,DCHKP1)
C THIS IS THE ETA LOOP FOR A SPECIFIC VALUE OF FI.
C THE LIMITS ARE FROM 2 TO NK-1 SINCE THE BOUNDARY CONDITIONS
C SEPARATELY.
DO 100 K=2,NKM1
KM1=K-1
KPI=K+1
C OBTAIN THE COEFFICIENTS FOR THE ETA DERIVATIVES.
O4400
DETK = DETKP1
DETK1 = ET(KP1) - ET(K)
RD2ETK = 2. / ET(KP1) - ET(KP1)
GAMMA1 = RD2ETK / DETK
GAMMA2 = GAMMA1 - GAMMA3
ALPHA1 = DETKP1 / GAMMA1 * 4.5
ALPHA3 = DETK * GAMMA3 * 4.5
ALPHA2 = ALPHA1 - ALPHA3

C
OBTAIN THE NEEDED PARAMETERS.
C
**********THE CONDITION DP / DETA = 0 CAN BE INVOKED BY SETTING**********
C
**********SUBSON = .TRUE., IT IS SUPPRESSED WHEN SUBSON = .FALSE. *****
C
SUPSON = .FALSE.
C
**********SET SUBP1 = .TRUE. IF DP / DX IS TO BE EVALUATED EXPlicitly.*****
C
**********OR SET TO ZERO. FOR DP / DX IMPLICIT SET SUBP1 = .FALSE. *****

S'BP1  = .TRUE.
RKM1 = R
R = RK1

RM1 = XJ * SINTC + ET(K) * (K) * GCSTC
RK1 = XJ1 * SINTC + ET(KP1) * (K) * GCSTC
RHM1 = RH0
RHO = RMHK1
CGM1 = CON
CON = CONKP1
MUKM1 = MU

MUKP1 = MUKP1
DCHM1 = DCH
DCH = DCHKP1

DMKP1 = DMK1
DRKP1 = DRKP1

DRKP1 = DRKP1

CALL PROP (HJP1(KP1, L), PJP1(KP1, L), RHGP1)

CALL PROP (H(KP1, L), P(KP1, L), RHOJ1, OZI, OZ2, MUJ, OZ3, CNJ, C24)

CALL PROP (HJP1(KP1, L), PJP1(KP1, L), RHLM1, OZI, OZ2, MLK1, CZ3, CNK1, C24)

CALL PROP (HJP1(KP1, L), PJP1(KP1, L), RHLN1, OZI, OZ2, MALP1, CZ3, CNL1, OZ4)

C
COMPUTE SOME TERMS COMMON TO MANY OF THE DERIVATIVE
C
EXPRESSIONS.

QZ1 = ALPHA1 * RHM1
QZ2 = ALPH A2 * RHO
QZ3 = ALPH A3 * RHOKP1
QZ4 = QZ1 * UJP1(KM1, L)
QZ5 = QZ2 * UJP1(K, L)
QZ6 = QZ3 * UJP1(KP1, L)
QZ7 = QZ1 * VJP1(KM1, L)
QZ8 = QZ2 * VJP1(K, L)
QZ9 = QZ3 * VJP1(KP1, L)
QZ10 = QZ1 * WJP1(KM1, L)
QZ11 = QZ2 * WJP1(K, L)
QZ12 = QZ3 * WJP1(KP1, L)

C
COMPUTE THE DERIVATIVES.

DHDX = (HJP1(K, L) - H(K, L))/DX
DROD = ALPHA1 * RHOKM1 + ALPH A2 * RHO + ALPH A3 * RHCKP1
DROF = BETA1 * RHNLM1 + BETA2 * RHO + BETA3 * RHALP1
DROD = (RHO-RH0M) / DX
DUDX = (UJP1(K, L) - U(K, L))/DX
DVDX = (VJP1(K, L) - V(K, L))/DX
DWDX = (WJP1(K, L) - W(K, L))/DX
DCDC = ALPHA1 * CONKM1 + ALPHA2 * CON + ALPHA3 * CCNKPI
DCDF = BETA1 * CNLM1 + BETA2 * CON + BETA3 * CNLP1
DDLM1 = 0.
DDUL1 = 0.

F-13
DDLM1 = 0.
DDUL1 = 0.

IF (SUBP1) = (PI(K, L) - PJM1(K, L))/DJM1
C********** TO SET DP/DX TO ZERO INSERT DPDX = 0. HERE. **********

DRUUE = QZ4 * QZ5 * QZ6
DRCUE = QZ4 * HJP1(KM1, L) + QZ5 * HJP1(K, L) + QZ6 * HJP1(KP1, L)
DrURH = (RHO * UJP1(KM1, L) * RM1 + QZ5 * HJP1(KM1, L) + R * QZ6 * HJP1(KM1, L) + RKP1
DrURRH = (RHO * UJP1(KM1, L) * RM1 + QZ5 * HJP1(KM1, L) + R * QZ6 * HJP1(KM1, L) / DJM1)/DX
DrURU = QZ4 * HJP1(KM1, L) + QZ5 * UJP1(KM1, L) + QZ6 * UJP1(KM1, L)
DrURV = QZ4 * UJP1(KM1, L) * RM1 + QZ5 * UJP1(KM1, L) * R * QZ6 * UJP1(KM1, L) / DJM1)/DX
DrUUE = QZ4 * VJP1(KM1, L) + QZ5 * VJP1(KM1, L) + QZ6 * VJP1(KM1, L)
DrUVU = QZ4 * VJP1(KM1, L) * RM1 + QZ5 * VJP1(KM1, L) * R * QZ6 * VJP1(KM1, L) / DJM1)/DX
DrUUE = QZ4 * VJP1(KM1, L) + QZ5 * VJP1(KM1, L) + QZ6 * VJP1(KM1, L)
D2WDEF=(ALPHA1*WJP1(KM1,LP1)+ALPHA2*WJP1(KL1)+ALPHA3*WJP1(KP1,LP1))*RCFIL  05730
D2WDF=QZ15*WJP1(K,L1)+QZ14*WJP1(K,L1)+QZ13*WJP1(K,L1)  05740
D2ZIDF=RDFS2*(ZIJP1(K,L1)-ZIJP1(K,L1))  05750
GO TO 5  05760
CONTINUE  05770
IF L DOES NOT = 1 OR NL THEN EVALUATE W-CERIVATIVES AND CROSS DERIVATIVES STANDARDLY.  05780
QZ13=BETA1*RHLMI1*WJP1(K,L1)  05800
QZ14=BETA2*RHO*WJP1(K,L1)  05810
QZ15=BETA3*RHLI1*WJP1(K,L1)  05820
D2HDF=BETA1*(ALPHA1*HJP1(KM1,L1)+ALPHA2*HJP1(KL1)+ALPHA3*HJP1(KP1,LP1))  05830
+ALPHA3*HJP1(KP1,LP1))  05840
D2HDF=EPS1*HJP1(K,L1)+EPS2*HJP1(K,L1)+EPS3*HJP1(K,L1)  05850
D2UDF=BETA1*(ALPHA1*UJP1(KM1,L1)+ALPHA2*UJP1(KL1))  05860
+ALPHA3*UJP1(KP1,LP1))  05870
D2UDF=EPS1*UJP1(K,L1)+EPS2*UJP1(K,L1)+EPS3*UJP1(K,L1)  05880
D2VDF=BETA1*(ALPHA1*VJP1(KM1,L1)+ALPHA2*VJP1(KL1)+ALPHA3*VJP1(KP1,LP1))  05890
+ALPHA3*VJP1(KP1,LP1))  05900
D2VDF=EPS1*VJP1(K,L1)+EPS2*VJP1(K,L1)+EPS3*VJP1(K,L1)  05910
D21DF = EPS1 * WJP1(K, L), EPS2 * HJP1(K, L), EPS3 * WJP1(K, L), 06170
D221DF = EPS1 * Z1JP1(K, L), EPS2 * Z1JP1(K, L), EPS3 * Z1JP1(K, L), 06180

RS CONTINUE 06190
C CALL THE SUBROUTINE THAT SETS UP THE MATRIX ELEMENTS 06200
C FOR EACH VALUE OF K. 06210
C CALL SETUP [NK, NKML, UJP1(1, L), VJP1(1, L), WJP1(1, L), JJP1(1, L), 06220
& PJPI(1, L), Z1JP1(1, L), 06230
& ET, A, B, C, F]. 06240
C CHECK FOR CONVERGENCE. 06250
SUMF = F(1, K) * F(1, K) + F(2, K) * F(2, K) + F(3, K) * F(3, K) 06260
+ F(4, K) * F(4, K) + F(5, K) * F(5, K) + F(6, K) * F(6, K) 06270
IF (SUMF .GT. 6.E-17) ISOLV = ISOLV + 1 06280
IF (SUMF .LT. 6.E-14) GO TO 95 06290
INETHIL = 1 06300
IF (ITER .NE. -1) ITER = 1 06310
95 CONTINUE 06320
100 CONTINUE 06330
C OBTAIN THE PARAMETERS AND DERIVATIVES NEEDED IN THE 06340
C SHOCK BOUNDARY CONDITION EQUATIONS. 06350
ALPHA2 = 1. / (ETINKL - ETINKML) 06360
ALPHA1 = -ALPHA2 06370
PHI = F(1, L) 06380
RKML = RK 06390
R = RKP1 06400
RM = XJ * SINTC + ETINKL * ZI(NK, L) * COS(TC 06410
RMKML = RH0 06420
RH0 = RH0KP1 06430
CALL PROPS (H(NK, L), P(NK, L), RH0, JML, DZ1, DZ2, DZ3, DZ4, DZ5, DZ6) 06440
CALL PROPS (HJP1(NK, L), PJPI(NK, L), RMNL1, DZ1, DZ2, DZ3, DZ4, DZ5, 06450
DZ6) 06460
CALL PROPS (HJP1(NK, L), PJPI(NK, L), RMNL1, DZ1, DZ2, DZ3, DZ4, DZ5, 06470
DZ6) 06480
B. DRHKL = DRH 06490
DR = DHKPL 06500
DRKML = DRK 06510
DRPKL = DRP 06520
DZDX = (Z1JP1(NK, L) - Z1JP1(NK, L)) / DX 06530
DZDF = BETA1 * Z1JP1(NK, L) + BETA2 * Z1JP1(NK, L) * BETA3 * Z1JP1(NK, L) 06540
QZ1 = ALPHA1 * RMKL 06550
QZ2 = ALPHA2 * RH0 06560
QZ4 = QZ1 * UJP1(NKML1) 06570
QZ5 = QZ2 * UJP1(NKML1) 06580
QZ7 = QZ1 * VJP1(NKML1) 06590
QZ8 = QZ2 * VJP1(NKML1) 06600
C (BETA1*WJPI(2,L)*L+L+6)*BETA2*WJPI(2,L)+BETA3*WJPI(2,L)*L)*REC

DWE = WJPI(2,L)*REC

DZJF = BETA1*WJPI(1,L)*L+L+6)*BETA2*WJPI(1,L)+BETA3*WJPI(1,L)*L

D2DWE = D2*VJPI(2,L)*REC

C OBTAIN THE COEFFICIENTS FOR THE BODY BOUNDARY
C CONDITION EQUATIONS
C CALL BODYEC (NK, 1, WJPI(1,L), VJPI(1,L), WJPI(1,L), HJPI(1,L), P1(1,L), ZIPI(1,L),
C ET, A, B, C, F, VBJP1, HBJP1)
C CALL THE ROUTINE THAT COMPUTES THE INCREMENTS TO BE
C ADDED TO THE SOLUTION AT X(j).
C
127 CONTINUE
147 CONTINUE
IF (ISOLV.EQ.0) GO TO 195
C COMPUTE THE SOLUTION AT X(j+1).
DO 150 K=2,NK
UJPI(K,L) = UJPI(K,L) + DELU(K)
VJPI(K,L) = VJPI(K,L) + DELV(K)
WJPI(K,L) = WJPI(K,L) + DELW(K)
HJPI(K,L) = HJPI(K,L) + DELH(K)
IF (HJPI(K,L, L, C) .GT. 1) THEN
PJPI K,L) \( \text{PJP1(K,L) = PJPI(K,L) + DELP(K)} \)
ZIPI(K,L) = ZJPI(K,L) + DELZ(K)
150 CONTINUE
ZIPI(1,L) = ZJPI(2,L)
167 CONTINUE
UJPI(1,L) = Q
VJPI(1,L) = VBJP1
WJPI(1,L) = C
HJPI(1,L) = HBJP1
C THE VARIABLES QZ1-QZ6 WERE COMPUTED IN SUBROUTINE BDCYEC
C AND PASSED THROUGH COMMON QZ.
C PJP1(1,L) = PJP1(1,1) + DELZ1(2)*Q2*DELV1*Q3*DELV1*Q3*Z33
C + DELP2*Q4*DELW2*Q2*Q6*Q2
195 CONTINUE
200 CONTINUE
RETURN
END
C THIS SUBROUTINE MODIFIES THE COEFFICIENTS AT K=2 TO TAKE
C INTO ACCOUNT THE BOUNDARY CONDITIONS AT THE BDCY (K=1).
C THE VALUES OF THE SUBSCRIPTS ON THE PARAMETERS ARE
C

WITH RESPECT TO K=1.

REAL MU,ME
REAL MINF
LOGICAL SUBSON,SLBP1
LEVEL 2,3,4
DIMENSION UNK1,VNK1,HNK1,P(NK1),Z1(NK1),ET(NK1)
DIMENSION A(6,6,NK1),B(6,6,NK1),C(6,6,NK1),F(6,NK1)

COMMON DQ1(17),DPDE,DQ2(43),DWE,DWDF,DIF,DQ3(7),D2VE,DC4(3)

& D2DEF,DQ5(9)

COMMON ALP(61),
BET2,EPS2
E
RKM,RHOKPI,RJP1,RHOKMI,RHO,RHKPI,CCA,MU,PHI

COMMON /CONST/COSTC,SINTC,REINF,PRINF,ME,RREIAF,RRPARE,RRREME,GM2,

MINF,AFAF,SINALF,CXCA,STSA,STCA,CTS,PRINF,BAR,SPROP

COMMON /VARY/XM1,XJ,XJP1,DX,XJM1,JMI,J,JPI

COMMON /QBODY/QZ1,QZ2,QZ3,QZ4,QZ5,QZ6

& QZ7=VBJP1-V(1)
QZ8=HBJP1-H11

IF (VBJP1.EQ.0.) GO TO 50

C

IF V AT THE CONE DOES NOT = 0, USE THE CONTINUITY EQUATION.

CZ1=1./DRP*VBJP1*RJP1)
CZ2=RHOKPI*V(2)*ET(2).*COSTC
CZ3=RHOKPI.*RJP1
CZ4=V(2)*RJP1*DRPK1
CZ5=V(2)*RJP1*DRPK1
CZ6=RHOKPI*ET(2)*RJP1-VBJP1*RJP1*(RHO*DRH*G28)

GO TO 75

50 CONTINUE

C

IF V AT THE CONE = 0, USE THE V-MOMENTUM EQUATION.

QZ1=1.
QZ2=0.
QZ3=0.
QZ4=1.
QZ5=0.
QZ6=PR(11)-Z1(1)
QZ1 = ET(2)-ET(1)))/Z1(1)
QZ2 = DRP*RREINF*#MU/3.*RJP1*(D2DEF-BETA2*DNECE11
QZ3 = -RREINF*8.#MU/3./ET(2)-ET(1))*(ET(2)-ET(1))
QZ33 = 0.
QZ4 = Z1(1)/ET(2)-ET(1))
QZ42 = RREINF*#MU/3.*RJP1/(Z1(1)*BETA2-D2DEF*ICF1/ET(2)-ET(1))
QZ5 = 0.
QZ6 = 2.65000*PHI-REINF*(Q2V*F*MU.*MU/3.
C = +MU/3.*RJPI)*Q11+Q2WDEF-Q2LDF+Q2PE)
75 CONTINUE
DO 100 II=1,6
QZ9=Q11*Q12+Q12
BB=(11,1,2)=BB(11,1,2)+Q29*Q22
BB(11,3,2)=BB(11,3,2)+Q29*Q23
BB(11,5,2)=BB(11,5,2)+Q29*Q24
BB(11,6,2)=BB(11,6,2)+Q29*Q25
BB(11,4,2)=BB(11,4,2)+Q29*Q26
BB(11,3,2)=BB(11,3,2)+Q29*Q23
F(11,2)=F(11,2)+Q29*Q26-A(11,3,2)*Q27-A(11,6,2)*Q28
100 CONTINUE
DO 300 II=1,6
DO 200 II=1,6
A(11,12,2)=0.
200 CONTINUE
300 CONTINUE
RETURN
END
SUBROUTINE SHOKBC (NK, NKM1, U, V, H, P, Z1, T1, A, B, C, F)
THIS SUBROUTINE COMPUTES THE COEFFICIENTS FOR THE
SHOCK BOUNDARY CONDITION EQUATIONS.
LEVEL 2, U, V, H, P, Z1, T1, A, B, C, F
REAL MU, MU, ME
REAL MIN, MAX
LOGICAL SUBSON, SUP1
DIMENSION (UNK), (V(NK)), (H(NK)), P(NK), Z1(NK), T1(NK)
DIMENSION A(6,6,NK), B(6,6,NK), C(6,6,NK)
COMMON DQ1, DQ2, DRHKPI, DRHKPI, DRHKPI, DRHKPI, DRHKPI, DRHKPI
& DRHKPI, DRHKPI, DRHKPI, DRHKPI, DRHKPI, DRHKPI, DRHKPI, DRHKPI
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F(1,NK)=-QFRE-Z1(NK)*QRIW+ET(NK)*QZIDF+QDHE
0810C
E=-Z1(NK)*QRF+ET(NK)*QZIDX+QDHE
0820C
B(2,1,NK)=QZ13/NX
0830C
B(2,2,NK)=-1.
0840C
B(2,3,NK)=-QZ1Dx
0850C
B(2,4,NK)=-QZ12
0860C
B(4,1,NK)=QZ14*ET(NK)*COST
0870C
B(4,3,NK)=QZ1D
0880C
B(4,4,NK)=R
0890C
F(4,NK)=QZ13*QZIDF-QZ14*R
0900C
B(5,2,NK)=2.*QRO*QF(NK)-(QRO+1.)*QUNF
0910C
B(5,3,NK)=2.*QRO*QV(NK)-(QRO+1.)*QVINF
0920C
B(5,4,NK)=2.*QRO*QW(NK)-(QRO+1.)*WINF
0930C
B(5,5,NK)=DRP+QZ11
0940C
B(5,6,NK)=URH*QZ11
0950C
F(5,NK)=-QRO+QZ11+1.*QZ10
0960C
B(6,2,NK)=ME*QV(NK)
0970C
B(6,3,NK)=ME*QV(NK)
0980C
B(6,4,NK)=ME*QW(NK)
0990C
B(6,5,NK)=1.
0900C
F(6,NK)=H(NK)-ME*QZ9/2.+HBAR
0910C
B(3,2,NK)=QRO*(L*QV)(6.*QZ6-4.*QZ9)+2.*QVINF*(QZ4+QZ5)
0920C
B(3,3,NK)=QRO*(QV)(6.*QZ7-4.*QZ9)+2.*QVINF*(QZ3+QZ5)
0930C
B(3,4,NK)=QRO*(QW)(6.*QZ8-4.*QZ9)+2.*QVINF*(QZ2+QZ4)
0940C
B(3,5,NK)=QRO*(QW)(6.*QZ9-4.*QZ9)+2.*QVINF*(QZ2+QZ4)
0950C
B(3,6,NK)=ORH*QZ15
0960C
F(3,NK)=QRO*QZ15-L*QV*QZ12+QVINF*QZ13+QVINF*QZ14+QVINF*QZ14
0970C
B(1,3,NK)=DRP+QZ15-QZ9+1.+2.*QZ10
0980C
B(1,6,NK)=QRF+QZ15
0990C
F(2,NK)=F(2,NK)\*QZ13\*QZ10
0900C
B(1,1,NK)=B(1,1,NK)\-ET(NK)*QRF+Qbeta2
0910C
B(1,4,NK)=B(1,4,NK)\+ZI(NK)*QRO+Qbeta2
0920C
B(1,5,NK)=B(1,5,NK)\+DRP+ZI(NK)*QW(NK)*Qbeta2
0930C
B(1,6,NK)=B(1,6,NK)\+ORH+ZI(NK)*QW(NK)*Qbeta2
0940C
B(4,1,NK)=B(4,1,NK)\+QZ13*Qbeta2
0950C
RETURN
0960C
END
0970C
SUBROUTINE SETUPE (NK,NKLM,UV,W,H,P,ZI,ET,AB,CF)
0980C
THIS SUBROUTINE SETS UP THE COEFFICIENT MATRIX FOR THE
0990C
Q15 = Q12 * RHOKP1 * RKP1
Q16 = -Q12 * ET(K) * RHOKP1 * DZIDF
Q17 = Q12 * (V(KP1) * KPI - ET(K) * DZIDF * W(KP) + CZIDX * U(KP1) * RKP1))
Q18 = K * A * ET(K) * DZIDF * ET(K) * DZIDF
Q19 = DZIDF * DMDF
Q20 = DZIDF * DUDF
Q21 = 2 * ET(K) * H * DZIDF * (DZIDF - Z1(K) / DF)
Q22 = -Z1(K) * ET(K) * (MU * DZIDF + QZ19)
Q23 = R * Z1(K) * (R * U(K) * V(K) / D - W(K) * W(K) * C) * C * C * C * C * C * C * C
Q24 = Q12 * R * R / 3.
Q25 = K
Q26 = Z1(K) * (V(K) * COSTC + U(K)) * (SINTC + R / DX)
Q27 = R * Z1(K) * (Q26 + Q10A) * W(K)
Q28 = R * R + 4 * ET(K) * DZIDF * ET(K) * DZIDF / 3.
Q29 = ET(K) * Z1(K) * COSTC * R / 3.
Q30 = (MU / DF - 2 * DMDF) / 3.
Q31 = Q21 * ET(K) * DZIDF * Z1(K) * (MU / DF + DMDF) / 3.
Q32 = DWDE * Q28 - ET(K) * DZIDF * (2 * DWDF - Z1(K) * R / CVDE) / 3 * R * Z1(K) * DVDF
Q33 = ALPHA1 * (R * U(K) * V(K)) * ET(K) * (DZIDF * W(KM1) + R * K * W(K) * W(K) * C * D * D)
Q34 = ALPHA2 * (R * ET(K) * DZIDF * W(K) + R * U(K) * W(K) * C * D)
Q35 = ALPHA3 * (R * (V(K) * ET(K) * DZIDF * W(KP1) + RKP1 * U(KP1) * CZIDX))
Q36 = R * R * K * (R * L_K) * (Z1(K) / DX - ALPHA2 * ET(K) * DZIDF)
Q37 = +ALPHA2 * (V(K) * R * ET(K)) * DZIDF * W(K)
Q38 = -MU * (Q28 + DWE - Z1(K) * ET(K) * DZIDF + DUDF)
Q39 = DWE * DWE + DWE * DWE
Q40 = DUDF * DUDF + DWE * DWE * DWE * DWE
Q41 = ET(K) * DZIDF * (DWE * DUDE + DWE * DWE * DWE)
Q42 = Q18 * Q39 + Z1(K) * ET(K) * Q24 + Q20 - R * Q41
Q43 = ((ET(K) * DZIDF * DWE) * 2) / 3.

THE SHOCK EQUATION

A11,1_K = ALPHA1
A11,2_K = 0
A11,3_K = 0
A11,4_K = 0
A11,5_K = 0
A11,6_K = 0
B11,1_K = ALPHA2
B11,2_K = 0
B11,3_K = 0
B11,4_K = 0
B11,5_K = 0

A12,1_K = 10010
A12,2_K = 10020
A12,3_K = 10030
A12,4_K = 10040
A12,5_K = 10050
A12,6_K = 10060
B12,1_K = 10070
B12,2_K = 10080
B12,3_K = 10090
B12,4_K = 10100
B12,5_K = 10110
B12,6_K = 10120
B(1.6, K) = C
C(1.1 + K) = ALPHAS
C(1.2 + K) = 0
C(1.3 + K) = 0
C(1.4 + K) = 0
C(1.5 + K) = C
C(1.6 + K) = 0
F(1 + K) = 0.

THE U-MOMENTUM EQUATION
A(2, 1 + K) = QZI!U(KMI)
A(2, 2 + K) = QZ0!RHOKM1!V(KMI)RKM1!ET(K)W(KPI)C2ICF1!QZ2!U(KMI)
A(2, 3 + K) = QZ3!U(KMI)
A(2, 4 + K) = QZ4!U(KMI)
A(2, 5 + K) = QZ5!U(KMI)RPKM1!QZ0!R!DZIDV!ET(K)
A(2, 6 + K) = QZ5!U(KMI)R!RHOKM1
B(2, 1 + K)

\[ \text{IF DP} \neq \text{DX} \text{ IS EVALUATED EXPLICITLY OR SET TO ZERO RECEIVE IN B2SK} \]

\[ \text{IF (SUBP)} \]

\[ \text{CS} (2.5 + K) = \text{DKP}!QZ10\!R\!R!ET(K) \neq \text{0, -ALPHAS!ET(K)CZIDV} \]
B(2.6 + K) = DHCP!QZ11
C(2.1 + K) = QZ13!U(KPI)
C(2.2 + K) = QZ12!RHOKP1!V(KPI)RKP1!ET(K)!W(KPI)!CZICF1

\[ \text{IF DP} \neq \text{DX} \text{ IS EVALUATED EXPLICITLY OR SET TO ZERO RECEIVE IN B2SK} \]

\[ \text{NOW THE VISCOS U TERMS} \]
A(2.2 + K) = A(2.2 + K)!MDM!ALPHAS!OMDE!QZ18!ALPHAS!QZ22!REINF
A(2.6 + K) = A(2.6 + K)!ALPHAS!OMHM1!OMDE!QZ18!ET(K)!ZI(K)QZ20!REINF
F \left( 3 \times K \right) = F \left( 3 \times K \right) + \left( \left( \text{DMDF} \times \text{DVDE} + \text{MU} \times \text{DVDE} \right) \times Q \right) \left( 3 \times K \right)

\begin{align*}
&+ \text{ALPHA} \times \left( \text{VW} \times \text{QDIZ \times C270} \right) \times \text{QDIZ} \times \text{QDIZ} \\
&\text{NOW THE VISCOS TERMS} \\
&A \left( 4 \times 3 \times K \right) = A \left( 4 \times 3 \times K \right) - \text{DIZDF} \times \left( \text{QDIZ} + \text{ALPHA} \times \text{MU} \times \text{ALPHA} \times \text{CMCE} \right) \times \text{QDIZ} \times \text{QDIZ} \\
&\text{REINF} \\
&A \left( 4 \times 4 \times K \right) = A \left( 4 \times 4 \times K \right) - \left( \text{MU} \times \text{ALPHA} \times \text{C270} + \text{ALPHA} \times \text{CMCE} \right) \times \text{QDIZ} \times \text{QDIZ} \times \text{QDIZ} \\
&\text{REINF}
\end{align*}
A(4, 6, K) = ALPHAL*DM*HMK1*Q32/REINF
6(4, 1, K) = R(4, 1, K)*DQ6.DE*DVDF*MU*O2WDEF/3.
6 = -ET(K)*COST*(DVDF*O2WDEF*(ET(K)*QZDIF*CMCF*)/3.
6 = +2.*ZI(K)*QZDIF/3.
6 = -MU*(2.*R*O2WDEF-ET(K)*QZDIF*C2VCE/3.
6 = -2.*R*O2WDEF*O2DE.
6 = -ET(K)*QZDIF*((MU*QZ29*ALPHAL*MU).
6 = +ZI(K)*QZ29*ALPHAL*QZ32.
6 = +O2WDEF*O2WDEF-ET(K)*QZDIF*C2VCE).
6 = +O2WDEF-ET(K)*QZDIF.*QZDIF*QZDIF-ZI(K)*O2WDEF/4.3.
6 = -ET(K)*QZDIF*O2WDEF/4.3/3.
6 = -R*O2WDEF*O2DE.
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6 = -R*O2WDEF*O2DE.
NOW THE VISCOS DISSIPATION TERMS

A(6, 2, K) = A(6, 2, K) - QZ37*ALPHA1*ME/REINF
A(6, 4, K) = A(6, 4, K) - QZ38*ALPHA1*ME/REINF
B(6, 1, K) = B(6, 1, K) - 2.*MU*(R*ET(K)*CCSTC*QZ39 + ZI(K)*QZ40-QZ41)

ADD THE CONTRIBUTIONS FROM THE PHI-DERIVATIVE TERMS.
QX1 = ET(K)*((DZIDF*2.*ET(K)*DMDE+4.*MU) - ZI(K)*CMCF*BETA2
- EPS2*ZI(K)*MU)*REINF
QX2 = R*ZI(K)*ZI(K)*BETA2
QX3 = ZI(K)*BETA2*(ZI(K)*DMF-ET(K)*DZIDF*(DMDE+2.*MU*ALPHA2))
QX4 = QX2*K(K)
QX5 = QX4*RHO
QX6 = QX4*U(K)
QX7 = QX4*V(K)
QX8 = QX4*W(K)
QX9 = QX4*H(K)
QX10 = 2.*ET(K)*MU*ZI(K)*DZIDF*REINF*BETA2
QX11 = QX10*ALPHA1
QX12 = QX10*ALPHA3
QX13 = R*MU*ZI(K)*REINF*BETA2
QX14 = QX13*ALPHA1
QX15 = QX13*ALPHA3
QX16 = 2.*ET(K)*CON*ZI(K)*DZIDF*RPRF*BETA2
A(2, 2, K) = A(2, 2, K) + QX11
B(2, 1, K) = B(2, 1, K) - R*ZI(K)*ET(K)*DRWUE*BETA2 - CX1*DUCE
+ REINF*BETA2*ET(K)*(ZI(K)*DMCE*DUCE
+ 2.*MU*(ZI(K)*2*DUDEF-ET(K)*CZIDF*DUCE))
B(2, 2, K) = B(2, 2, K) + QX5 - QX3
B(2, 4, K) = B(2, 4, K) + QX2*RHO*U(K)
B(2, 5, K) = B(2, 5, K) + ORP*QX6
B(2, 6, K) = B(2, 6, K) + ORH*QX6
C(2, 2, K) = C(2, 2, K) + QX12
A(3, 3, K) = A(3, 3, K) + QX11
A(3, 4, K) = A(3, 4, K) - QX14/3.
B(3, 1, K) = B(3, 1, K) - F*ZI(K)*ET(K)*DRWUE*BETA2 - CX1*CVDE
+ REINF*BETA2*ET(K)*(ZI(K)*DMCE*CVCF
C(3, 2, K) = C(3, 2, K) + QX12
A(3, 3, K) = A(3, 3, K) + QX11
A(3, 4, K) = A(3, 4, K) - QX14/3.
B(6,6,K) = B(6,6,K) + ORH*QX5 + QX5 + RPRL*F1(K)
E 1BETA2*Z1(K)*IDCF+DCH+DHF-E(T(K)*DZIF+SCCE
E 1EPS2Z1(K)*CONI
C (6,6,K) = C(6,6,K) + QX6*ALPHA3
ADD IN SOME TERMS TO THE ENERGY EQUATION THAT HAD BEEN FORGOTTEN
QZ43 = 2.0*MU*(QZ24*DVE - E(T(K)*DZIF+Z1(K)*DVF+R*DVE/3.1)
QZ44 = 2.0*MU*(Z1(K)*DVF - E(T(K)*DZIF+DVF/3.1)
QZ45 = -E(T(K)*DZIF+DVF*QVE - K*(DVE+DHF+2.3 - DVE*DVF)
QZ46 = QZ24*DVE*DVF+Z1(K)*Z1(K)*DVF+DVF
E 1*Z1(K)*DVF*DVF+DVF*DVF+DVF
A(6,3,K) = A(6,3,K) - QZ43*ALPHA1*REME
A(6,4,K) = A(6,4,K) - QZ44*ALPHA1*REME
B(6,1,K) = B(6,1,K) - 2.0*MU*(R*ET(K)*CSTC*DVE+DVE*4.0)
B(6,1,K) = B(6,1,K) - 2.0*MU*(R*ET(K)*CSTC*DVE+DVE*4.0)
E 1*Z1(K)*DVF*DVF+DVF+QZ43
E 1*Z1(K)*DVF*DVF+DVF+QZ43
E 1*Z1(K)*DVF*DVF+DVF+QZ43
R(6,3,K) = B(6,3,K) - QZ43*ALPHA1*REME
R(6,4,K) = B(6,4,K) - QZ44*ALPHA1*REME
B(6,4,K) = B(6,4,K) - QZ44*ALPHA1*REME
E 1*Z1(K)*DVF*DVF-ET(K)*DZIF+DVE+4.0
E 1*Z1(K)*DVF*DVF-ET(K)*DZIF+DVE+4.0
B(6,6,K) = B(6,6,K) - DN4*QZ6*REME
C(6,3,K) = C(6,3,K) - QZ43*ALPHA1*REME
C(6,4,K) = C(6,4,K) - QZ44*ALPHA1*REME
F(6,K) = F(6,K) + MU*Z6*PRME
IF (NOT SUBSON). RETURN
C IF PF/DETA IS SET TO ZERO, REDEFINE A FEW COEFFICIENTS,
90 500 I=1+6
A(3,6,1) = A(5,6,1)
B(3,6,1) = B(5,6,1)
C(3,6,1) = C(5,6,1)
A(5,6,1) = C(0)
B(5,6,1) = C(0)
C(5,6,1) = C(0)
500 CONTINUE
A(5,5,1) = C(0)
B(5,5,1) = C(0)
C(5,5,1) = C(0)
F(3, K) = F(5, K)
F(5, K) = P(K+1) - P(K)
RETURN
END
SUBROUTINE BCIU(NJ, NK, NL, U, V, W, P, XI, UJMI, VJMI, WJMI, HJMI, DJMI, ZJMI, ETMI, XBM, HBM)
    & C
    & C THIS SUBROUTINE READS IN THE MESH DISTRIBUTION FOR X, ET, AND FI. THE BOUNDARY CONDITIONS AND THE INITIAL CONDITIONS
    & C ARE ALSO READ IN.
    & C TAPE 3 IS THE INPUT TAPE WHEN THE INITIAL CONDITIONS ARE READ FROM TAPE
    & C
    REAL MU
    LEVEL 2, U, UJMI, V, VJMI, W, WJMI, H, HJMI, P, PIJMI, X, ZJMI
    ELEMENT U(NK, NL), UJMI(NK, NL), V(NK, NL), VJMI(NK, NL), W(NK, NL), WJMI(NK, NL), H(NK, NL), HJMI(NK, NL), P(NK, NL), PIJMI(NK, NL), ZI(NK, NL), ZJMI(NK, NL), ET(NK, XI(NL), X(BM, NL), H(BM, NL)
    COMMON QZI, IQZI

C************ IF THE PLANE OF INITIAL CONDITIONS IS TO BE READ FROM TAPE ************
C************ THEN THE DIMENSIONS OF U/WPHZ MUST BE WHATEVER THEY WERE ************
C************ WHEN THE SOLUTION WAS ORIGINALLY WRITTEN ON THE TAPE ************
COMMON /OUTDEP/ U/WPHZ(150, 20, 6)
 JJ=C
II=0
READ (5, 102C) IREAD
IF (IREAD.GT.0) GO TO 105
DO 100 L=1, NL
  C READ IN A VALUE FOR FI AND THE CORRESPONDING VALUE
  C FOR ZI. (ZI IS NOT A FUNCTION OF ETA.)
  C
  READ (5, 101C) FI(L), ZI(L)
  FI(L) = FI(L) + 0.00658252519943
  C READ IN THE INITIAL VALUES OF THE SOLUTION. (THE VALUES AT
  C X=X(1)) ALONG A RAY NORMAL TO THE BODY.
  C READ (5, 101C) (ET(K), U(K), V(K), W(K), P(K), H(K), F(K), X(K), Z(K), X=1, NK)
  WRITE(6, 101C) (ET(K), U(K), V(K), W(K), P(K), H(K), F(K), X(K), Z(K), X=1, NK)
  QZI = 1./ZI(L)
  DO 50 K=1, NK
    ET(K) = ET(K)*QZI
  50 CONTINUE
100 CONTINUE
105 CONTINUE
C READ IN THE DISTRIBUTION OF X-STATIONS ALONG THE BODY
C AT WHICH THE SOLUTION WILL BE OBTAINED.
NJGRS=NJ
IF (NJ.GT.6) NJOR6=6
READ (5,1010) (X(J),J=1,NJOR6)
IF (NJ.LE.2) GO TO 180
IF (X(2).LT.X(1).AND.NJ.GT.6) READ (5,1010) (X(J),J=7,NJ)
C C IF ALL OF THE X-STATIONS ARE TO BE READ IN, READ IN THE REST
C OF THEM
C IF (X(2).LT.X(1)) GO TO 180
C
C THE REST OF THE X-STATIONS CAN BE GENERATED FROM THE FIRST
C ONE. EACH SUCCESSIVE X-STATION IS MADE PROPORTIONAL TO THE
C PREVIOUS ONE.
C
C 175 J=2,NJ
C
C**********THE PROPORTIONALITY CONSTANT (THE NUMBER CLOSE TO 1.) ON THE
C**********NEXT CARD MUST BE CHANGED HERE TO WHATEVER IS NEEDED.**********
C
175 CONTINUE
180 CONTINUE
WRITE (6,1010) X
IF (IREAD.LE.0) GO TO 145
C C READ IN THE INITIAL PLANE FROM TAPE3.
C
F-36
EPS = 1.E-10
read (3) QZ,IO2
READ (3) XX,ET,FI,UVPHZ
IF (X(1)-EPS.GT.XX) GO TO 140
C
130 CONTINUE
READ (3) XX,ET,FI,UVPHZ
IF (X(1)-EPS.LT.XX) GO TO 140
C
140 CONTINUE
DO 122 L=1,NL
DO 122 K=1,NK
UK(K,L) = UVPHZ(K,L,1)
VK(K,L) = UVPHZ(K,L,2)
WK(K,L) = UVPHZ(K,L,3)
PK(K,L) = UVPHZ(K,L,4)
HK(K,L) = UVPHZ(K,L,5)
ZIK(K,L) = UVPHZ(K,L,6)
C
122 CONTINUE
BACKSPACE 3
BACKSPACE 3
READ (3) XX,ET,FI,UVPHZ
DO 128 L=1,NL
DO 128 K=1,NK
UJM1(K,L) = UVWPHZ(K,L,1) 15410
VJM1(K,L) = UVWPHZ(K,L,2) 15420
WJM1(K,L) = UVWPHZ(K,L,3) 15430
PJMN(K,L) = UVWPHZ(K,L,4) 15440
HJM1(K,L) = UVWPHZ(K,L,5) 15450
ZJM1(K,L) = UVWPHZ(K,L,6) 15460
128 CONTINUE 15470
145 CONTINUE 15480
C READ IN THE VALUES OF V AND H ALONG THE EDGY AT VARIOUS 15490
C L-J (ETA-X) GRID POINTS. LINEAR INTERPOLATION WILL BE USED 15500
C TO OBTAIN VALUES OF VB AND HB WHERE THEY ARE NOT SPECIFIED. 15510
200 CONTINUE 15520
READ (5,102C) L 15530
250 CONTINUE 15540
READ (5,102C) J,VB(J,L),HB(J,L) 15550
VB2=VB(J,L) 15560
HB2=HB(J,L) 15570
IF (J-J,J,LE,1) GO TO 400 15580
JM1=J-1 15590
JJP1=J+1 15600
QZ1=1./[X(JJ)-X(JJ)] 15610
QZ2=(HB2-HB1)*QZ1 15620
QZ1=(VB2-VB1)*QZ1 15630
DO 300 II=JJP1,JM1 15640
QZ3=X(JJ)-X(JJ) 15650
VB1=VB1+QZ1*QZ3 15660
HB1=HB1+QZ2*QZ3 15670
300 CONTINUE 15680
400 CONTINUE 15690
VB1=VB2 15700
HB1=HB2 15710
JJ=J 15720
IF (J,LT,NJ) GO TO 250 15730
IF (L-LL.LE,1) GO TO 700 15740
LM1=L-L 15750
LLP1=LL+1 15760
DO 600 II=1,NJ 15770
VB1=VB1(QL,LL) 15780
HB1=HB(II,LL) 15790
QZ1=L/(FII)+FLII) 15800
QZ2=(HB(II,LL)-HB1)*QZ1 15810
QZ1=(VB(II,LL)-VB1)*QZ1 15820
DO 500 (II,LL) 15830
QZ3=FI(II)-FII) 15840
VB(II,12)=VB+Q21*Q23
HB(II,12)=HB1*Q21*Q23
500 CONTINUE
600 CONTINUE
700 CONTINUE
LL=L
IF (LL.LT.NL) GO TO 200
1010 FORMAT (6E12.5)
1620 FORMAT (11L12,5E12.5)
IF (IRJAN.GT.0) RETURN
C     DEFINE THE SOLUTION SO THAT THE X-DERIVATIVES FOR THE
C     FIRST X-STEP WILL BE ZERO.
DO RCO 12=1,NL
DO RCO II=1,NI
UJM1(II,12)=UJ(II,12)
VJM1(II,12)=VJ(II,12)
WJM1(II,12)=WJ(II,12)
HJM1(II,12)=HJ(II,12)
PJM1(II,12)=PJ(II,12)
C     Z1 IS NOT A FUNCTION OF ETA (i.e. II).
Z1(II,12)=Z1(1,12)
Z1JM(II,12)=Z1J(II,12)
800 CONTINUE
RETURN
END
SUBROUTINE LEQ(A,B,NEQS,NSOLNS,IA,IR,DET)
CLEQ LINEAR EQUATIONS SOLUTIONS FORTRAN II VERSION
C     SOLVE A SYSTEM OF LINEAR EQUATIONS OF THE FORM AX=B BY A MODIFIED
C     GAUSS ELIMINATION SCHEME
C     NEQ= NUMBER OF EQUATIONS AND UNKNOWNS
C     NSOL= NUMBER OF VECTOR SOLUTIONS DESIRED
C     IA = NUMBER OF ROWS OF A AS DEFINED BY DIMENSION STATEMENT ENTRY
C     IR = NUMBER OF ROWS OF R AS DEFINED BY DIMENSION STATEMENT ENTRY
C     ADET = DETERMINANT OF A, AFTER EXIT FROM LEC
C     DIMENSION A(IA,IA),B(IB,IB)
C     NSIZ = NEQS
C     NBSIZ = NSOLNS
C     START SYSTEM REDUCTION
NUMSYS=NSIZ-1
DO 14 IA=1,NUMSYS
   NN=IA+1
   BIG=A(IA,IA)
NBSRW=I
BG=1*G/1G
C ELIMINATE UNKNOWNS FROM FIRST COLUMN OF CURRENT SYSTEM
10 DO 13 K=NN+NSIZ
C COMPUTE PIVOTAL MULTIPLIER
PMULT=A(K,1)*BG
C APPLY PMULT TO ALL COLUMNS OF THE CURRENT A-MATRIX ROW
DO 11 J=NN+NSIZ
11 A(K,J)=PMULT*A(J,1)+A(K,J)
C APPLY PMULT TO ALL COLUMNS OF MATRIX B
DO 12 L=1NBSIZ
12 B(K,L)=PMULT*B(L,1)+31K,L)
13 CONTINUE
14 CONTINUE
C DO BACK SUBSTITUTION
C WITH A-MATRIX COLUMN = NCOLB
50 DO 15 NCOLB=1,NBSIZ
C DO FOR ROW = NROW
DO 19 I=1NSIZ
NROW=NSIZ+1-I
TEMP=0.0
C NUMBER OF PREVIOUSLY COMPUTED UNKNOWNS = NXS
NXS=NSIZ-NROW
C ARE WE DOING THE BOTTOM ROW
IF(NXS)<16,17,16
C NO
16 DO 18 K=1,NXS
KK=NSIZ+1-K
18 TEMP=TEMP+B(KK,NCOLB)*A(NROW,KK)
19 B(NROW,NCOLB)=B(NROW,NCOLB)-TEMP/A(NROW,NROW)
C HAVE WE FINISHED ALL ROWS FOR B-MATRIX COLUMN = NCOLB
19 CONTINUE
C YES
C HAVE WE JUST FINISHED WITH B-MATRIX COLUMN NCOLB=NSIZ
15 CONTINUE
C YES
C WE ARE ALL DONE NOW
C WHEN...
RETURN
END
SUBROUTINE MODIFY(NK,NL,NEWK,NEWL,ET,FI,FNEW,FINEW,
& U,UNEW,UNEWF,V,VNEW,VNEWF,WNEME,WNEWF,
& P,PNEW,PNEWF,H,HNEW,HNEWF,
& ZI,ZINEW,ZINEWF,
C C

C THIS SUBROUTINE USES QUADRATIC INTERPOLATION TO OBTAIN THE
C INITIAL CONDITIONS AT A NEW MESH DISTRIBUTION.
C
C LEVEL 2, LNEW, VNEW, PNEW, HNEW, ZNEW,
C LNEW, VNEW, PNEW, HNEW, ZNEW,

DIMENSION ET(NK,FNL), ETNEW(NEWNK), ETNEW(NEWNL),
V(NK,NL), VNEW(NEWNK,NL), VNEWF(NEWNK,NEWNL),
W(NK,NL), WNEW(NEWNK,NL), WNEWF(NEWNK,NEWNL),
P(NK,NL), PNEW(NEWNK,NL), PNEWF(NEWNK,NEWNL),
H(NK,NL), HNEW(NEWNK,NL), HNEWF(NEWNK,NEWNL),
Z(NEWNK,NEWNL), ZNEW(NEWNK,NEWNL), ZNEWF(NEWNK,NEWNL),
PBNEW, HBNW,

DIMENSION VB(NJ,NL), HB(NJ,NL)
DIMENSION VBNEW(NJ,NEWNL), HBNEW(NJ,NEWNL)
DATA IN12/0/
IN12 = IN12 + 1
DO 100 KK=1, NEWNK
   INTERPOLATE IN ETA.
   IF (KK.EQ.1 .OR. KK.EQ.NEWNK) GO TO 60
   K=K-1
50 K = K + 1
   IF (K.GT.NK) GO TO 2000
   IF (ETNEW(KK).GT.ET(K)) GO TO 50
   KM1 = K - 1
   K3 = K-2
   IF (K.EQ.2 .OR. K.EQ.NK) GO TO 55
   IF (ETNEW(KK)-ET(K3).GT.ET(K+1)-ETNEW(KK)) K3=K+1
   GO TO 57
   CONTINUE
   IF (K.EQ.2) K3=3
   CONTINUE
   R1 = (ETNEW(KK)-ET(K3)).*(ETNEW(KK)-ET(KM1))
   ET(K) = ET(K) - (ETNEW(KK)-ET(K)).*(ET(K) - ET(KM1))
   R2 = (ETNEW(KK)-ET(K)).*(ETNEW(KK)-ET(K3))
   ET(K3) = ET(K3) - (ETNEW(KK)-ET(K)).*(ET(K) - ET(K3))
   R3 = (ETNEW(KK)-ET(K)).*(ETNEW(KK)-ET(K))
   ET(K3) = ET(K3) - (ETNEW(KK)-ET(K)).*(ET(K) - ET(K3))
   GO TO 65

100 CONTINUE
60 CONTINUE
K = L
IF (KK.EQ.NEWNL) K = NK
KK = L
RATIO = 0.
K3 = K
R1 = L.
R2 = 0.
R3 = 0.
65 CONTINUE
DG, L = L + NL
UNW(KK,L) = U(K,L)*R1 + U(KM,L)*R2 + U(K3,L)*R3
VNW(KK,L) = V(K,L)*R1 + V(KM,L)*R2 + V(K3,L)*R3
WNW(KK,L) = W(K,L)*R1 + W(KM,L)*R2 + W(K3,L)*R3
PNW(KK,L) = P(K,L)*R1 + P(KM,L)*R2 + P(K3,L)*R3
HUNW(KK,L) = H(K,L)*R1 + H(KM,L)*R2 + H(K3,L)*R3
IZNW(KK,L) = ZI(K,L)*R1 + ZI(KM,L)*R2 + ZI(K3,L)*R3
75 CONTINUE
100 CONTINUE
C INTERPOLATE IN PHI.
DO 660 LL = 1, NEWNL
IF (LL.EQ.1 .OR. LL.EQ.NEWNL .OR. NL.EQ.1) GC TC 560
L = L - 1
550 L = L + 1
IF (L.GT.NL) GO TO 3000
IF (FINW(LL).GT.FI(L)) GO TO 550
L1 = L - 1
L2 = L - 2
IF (L.EQ.2 .OR. L.EQ.NL) GO TO 555
IF (FINW(LL).GT.FI(L1)).GT. FI(L+1).GT.FINW(LL)) L3 = L + 1
GO TO 557
555 CONTINUE
IF (L.EQ.2) L3 = 3
557 CONTINUE
R1 = (FINW(LL).GT.FI(L3)).GT. (FINW(LL).GT.FI(L1))
& IF (FI(L1).GT.FI(L3)) FI(L) = FI(L1)
R2 = (FINW(LL).GT.FI(L3)).GT. (FINW(LL).GT.FI(L3))
& IF (FI(L1).GT.FI(L3)) FI(L1) = FI(L1)
R3 = (FINW(LL).GT.FI(L3)).GT. (FINW(LL).GT.FI(L3))
& IF (FI(L3).GT.FI(L3)) FI(L3) = FI(L3)
GO TO 555
560 CONTINUE
L = 1
IF (LL.EQ.NEWNL) L = NL
17170
17180
17190
17200
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17500
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17560
17570
17580
17590
17600
LMI = L
RATJU = 0
L3 = L
R1 = T
R2 = C
K3 = C
565 CONTINUE
DO 575 K = 1, NEWNK
VNEWF(K,L) = VNEWE(K,L)*R1 + VNEWF(K,L)*R2 + VNEWE(K,L)*R3
575 CONTINUE
IF ( IV12.EQ.1 ) GO TO 600
DO 580 J = 1, NJ
VNEWW(J,L) = VBI(J,L)*R1 + VBI(J,L)*R2 + VBI(J,L)*R3
580 CONTINUE
600 CONTINUE
IF ( IV12 .EQ.1 ) RETURN
DO 1200 K = 1, NEWNK
ETK = ETNEW(K)
1200 CONTINUE
DO 1300 L = 1, NEWNL
F1(L) = FINEWL
1300 CONTINUE
RETURN
2000 CONTINUE
WRITE (6,6010)
6010 FORMAT (* THE NEW Y DISTRIBUTION IS NOT WITHIN THE RANGE OF THE
& OLD DISTRIBUTION*)
STOP
3000 CONTINUE
WRITE (6,6020)
6020 FORMAT (* THE NEW PHI DISTRIBUTION IS NOT WITHIN THE RANGE OF THE
& OLD DISTRIBUTION*)
WRITE (6,6030) FI, FINEW
6030 FORMAT (6E15.5)
STOP
END
SUBROUTINE OUTPUT (NK, NL, XET, F1, U, V, W, P, ZI)
REAL MU, ME
REAL MINF

C THIS SUBROUTINE OUTPUTS THE SOLUTION AT THE ETA-PHI C
GRID OF POINTS FOR A SPECIFIC VALUE OF X.

C THE SOLUTION IS PRINTED, WRITTEN ON TAPE4, AND WRITTEN ON
TAPE2. TAPE2 CAN BE SET UP AS THE CARD PUNCH SINCE THE C
FORMAT THAT IS USED FOR TAPE2 IS COMPATIBLE WITH THE FORMAT C
OF TAPE1. SUBROUTINE BGC USES THE SOLUTION FROM CARDS.

C HOWEVER FOR RESTART PURPOSES IT IS ADVISABLE TO USE THE C
WRITE ON TAPE4 READ FROM TAPE3 COMBINATION.

LEVEL 2, U, V, W, P, H, ZI
DIMENSION ET(NK), F1(NL), U(NK, NL), V(NK, NL), W(NK, NL),
H(NK, NL), P(NK, NL), ZI(NK, NL)

COMMON /PUNCH/ TAPE
COMMON /CONST/COST, SINTC, REINF, PRINF, ME, REINF, RPRARE, PREME, GM2,
6 MINT, ALFA, SINLFA, CTC, SITC, CTSA, CTSS, CTSA, CTSC, PINS, KBAR, SPROP
COMMON /VARY/JXJ1, JXJ2, JXJ1P, DX, DXJ1, JXI, JXJI

COMMON YL)

C************THE DIMENSIONS OF UYPHZ MUST BE NUMK, NUL, 6 WHERE NUMK AND**
C************YML ARE EQUAL TO OR GREATER THAN NK AND NL BUT EQUAL TO OR**
C************LESS THAN MAXK AND MAXL (SEE THE MAIN PROGRAM). WHEN THE***
C************CDC7600 LEARNS HOW TO READ AND WRITE LARGE CORE ARRAYS UYPHZ
C************CAN BE ELIMINATED AND THE SOLUTION STORED IN LARGE CORE!***
C************CAN BE WRITTEN AND READ DIRECTLY.******************************

COMMON /OUTDEP/ UYPHZ(50, 20, 6)
DATA KTAPE/-1/
WRITE (6, 11CC) X
DO 200 L=1, NL
Q1=FIL*57.29577951
IF (Q1.LT.1. AND. Q1.LT.11. AND. L.NE. NL-1) GC TC 200
RZT = 0. / (Z11, 11, ET(2)-ET(1))
CALL PROPMC ( HL, L), PCL, RHC, DRH, UM, QZ1, CCM, Z2)
CINF = 2. * REINF* RZT* MUS*(U12, 1)-U11, 1)
STINF = 2. * RPRARE* CON* RZT* (H(2, 1)-H(1, 1))
WRITE (6, 1200) Q11, CINF, STINF, Z11, Z11

C CONVERT NORMAL COORDINATE TO DIMENSIONED QUANTITY.
Q11=Z11, 1
DO 100 K=1, NK
Y(K)=ET(K)*Q1

100 CONTINUE
DO 193 K=1, NK

C STATIONS TO BE PRINTED CAN BE CONTROLLED BY AN APPROPRIATE
C STATEMENT HERE.
IF (K.GT.2C .AND. L.EQ.NK .AND. L.NE.NL-1 .AND. J.GT.0) GC TO 193

IF (K.GT.2C .AND. L.EQ.NK .AND. L.NE.NL-1 .AND. J.GT.0) GC TO 193

HTUT = H(K,L) + .500*ME *(U(K,L)*U(K,L) +V(K,L)*V(K,L) +
W(K,L)*W(K,L))

WRITE (6,130C) Y(K),U(K,L),V(K,L),H(K,L),HTOT

193 CONTINUE
200 CONTINUE
220 CONTINUE
DO 230 L=1,NL
DO 210 K=1,NK
UVWPH(K,L,1) = U(K,L)
UVWPH(K,L,2) = V(K,L)
UVWPH(K,L,3) = W(K,L)
UVWPH(K,L,4) = P(K,L)
UVWPHZ(K,L,5) = H(K,L)
UVWPHZ(K,L,6) = ZI(K,L)

230 CONTINUE
WRITE (4) X,ET,FI,UVWPH
KTAPE=KTAPE+1
IF (ITAPE.EQ.0) GC TO 500
KI=KTAPE/ITAPE
IF (KTAPE.NE.KI*ITAPE.OR.KTAPE.EQ.0) GC TO 500
WRITE (12,11CC) X
DO 30C L=1,NL
QZ1=FI(L)*57.29577951
WRITE (2,21C0) QZ1,ZI(L,L)
QZ1=ZI(L,L)
DO 25C K=1,NK
QZ2=ET(K)*QZ1
QZ2=ET(K)*QZ1
WRITE (2,21C0) QZ2,U(K,L),V(K,L),H(K,L)

250 CONTINUE
300 CONTINUE
500 CONTINUE
RETURN
1100 FORMAT (*1*,1CX,*SOLUTION AT X = *,E15.5)
1200 FORMAT (///,* AT FI = *,F2.2, 5X,*CFINF = *,E13.5, 5X,
*STINF = *,E13.5, 5X,*SHGCX DISTANCE = *,E13.5, 5X,
*///8X,*Y*,14X,*U*,14X,*V*,14X,*W*,14X,*P*,14X,*H*,12X,
*H TOTAL/*)//
1300 FORMAT (7E15.5)
2100 FORMAT (16F12.5)
END
SUBROUTINE PROP (H,P,RHO,DRP,DRH,DU,DMH,CCN,DCH)
C THIS SUBROUTINE OBTAINS THE FLUID PROPERTIES.
REAL MU,ME
REAL M0N
LEVEL 2*H*P
COMMON /CONST/COSC, SINTC, REINF, PRINF, ME, RREINF, RPRPE, PREME, GM2, 
C MINF, ALFA, SINB, CTCA, STSA, STCA, CTSA, PINF, BAR, SPROP 

D=GM2/H
RHO=DMP/P
DCH=-RHO/H

C PROPME IS AN ENTRY POINT USED TO OBTAIN MU AND CCA.
ENTRY PROPMC
MU=SQR((1.0+SPROP/1.0+SPROP/H)
D=4*(H+3.0+SPROP/12.0*(H+SPROP))
CON=mu
DCH=DMH
RETURN

C PROPRC IS AN ENTRY POINT USED TO OBTAIN RHC
ENTRY PROPRC
RHO=GM2*P/H
RETURN
END

SUBROUTINE SOLVEQ (NP, NPML, NPML6, N, A, B, C, F, DELU, DELV, CELW, 
C DELH, DELP, DELZI, DEL, RTSIDE, WCRK1, WORK2, 
C WORK3, WORK4)

C THIS SUBROUTINE USES A CLOCK TRIDIGONAL ALGORITHM TO SOLVE 
C THE SYSTEM OF LINEAR EQUATIONS. SEE ANALYSIS OF NUMERICAL 
C METHODS BY ISAACSON AND KELLER (1966) PF. 58, 59, 60.
LEVEL 2*A, B, C, F, DELU, DELV, DELP, DELH, DELZI, 
C WORK1, WORK2, 
C DIMENSION A(N, N), B(N, N), C(N, N), F(N, N), 
C DELU(N, N), DELV(N, N), DELP(N, N), DELH(N, N), 
C DELZI(N, N), 
C DIMENSION WORK1, WORK2, WORK3, WORK4
C COMMON /BIGMAT/ COEFF(I)
C DIMENSION BBM(N, N), G(N, N), FFNM
M=N*4-1

C FACTOR THE MATRIX
DO 10 J=1, N

103 CONTINUE
PROM = A(11,1,IN)*CC(11,12)
DO 107 I3=2,6
PROM = PROM + A(11,13,IN)*CC(13,12)
107 CONTINUE
R(11,12,IN) = B(11,12,IN) - PROM
108 CONTINUE
DO 109 I1=1,6
DO 109 I2=1,6
R(11,12) = B(11,12,IN)
CC(11,12) = CC(11,12)
109 CONTINUE
CALL LEO (PB,CC,6,6,6,6,DET)
DO 110 I1=1,6
DO 110 I2=1,6
C(11,12,IN) = CC(11,12)
110 CONTINUE
115 CONTINUE
C
FURWARD PASS
DO 203 I1=1,6
FF(I1) = 0.
203 CONTINUE
DO 215 I4=7,NP
DO 208 I1=1,6
PROM = A(11,1,IN)*FF(I1)
DO 207 I3=2,6
PROM = PROM + A(11,13,IN)*FF(I3)
207 CONTINUE
F(I1,IN) = F(I1,IN) - PROM
208 CONTINUE
DO 209 I1=1,6
FF(I1) = F(I1,IN)
DO 209 I2=1,6
B(11,12) = B(11,12,IN)
209 CONTINUE
CALL LEO (BB,FF,6,6,6,6,DET)
DO 210 I1=1,6
F(I1,IN) = FF(I1)
210 CONTINUE
215 CONTINUE
C
BACKWARD PASS
DO 303 I1=1,6
DELT(NP-2)*6+I1) = F(I1,NP)
303 CONTINUE
DO 315 IN=3,NP
NI = NP + 2 - IN
DO 303 I1 = 1, 6
    PROD = C(I1, 1, NI) * DEL((NI - 1) * 6 + 1)
DO 307 I3 = 2, 6
    PROD = PROD + C(I1, I3, NI) * DEL((NI - 1) * 6 + 1)
307 CONTINUE
    DEL((NI - 2) * 6 + 1) = F(NI, NI) - PROD
308 CONTINUE
315 CONTINUE
    DO 400 I1 = LIM, NP
        I2 = (I1 - LIM) * N + N - 6
        DELU(I1) = DEL(I2 + 2)
        DELV(I1) = DEL(I2 + 3)
        DELW(I1) = DEL(I2 + 4)
        DELP(I1) = DEL(I2 + 5)
        DELH(I1) = DEL(I2 + 6)
400 CONTINUE
    IF (N.EQ.5) RETURN
    DO 500 I1 = LIM, NP
        I2 = (I1 - LIM) * 6
        DELZ(I1) = DEL(I2 + 1)
500 CONTINUE
RETURN
END