Time integration of unsteady transonic flow to a steady state solution by the finite element method.

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TIME INTEGRATION OF UNSTEADY TRANSONIC FLOW TO A STEADY STATE SOLUTION BY THE FINITE ELEMENT METHOD

by

Raymond John Nichols Jr.

March 1977

Thesis Advisor: D. J. Collins

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Abstract:
A finite element method was applied to the unsteady transonic small disturbance equation and integrated until the solution converged to the steady state for a thin non-lifting airfoil. The method of weighted residuals was used to formulate the finite element equations and Houbolt's method of central differencing in time was used to integrate these equations.
A secondary investigation applied the steady transonic small disturbance equations to a converging-diverging nozzle.
Time Integration of Unsteady Transonic Flow to a Steady State Solution by the Finite Element Method

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ABSTRACT

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I. INTRODUCTION

Transonic inviscid flows past a smooth airfoil may be expressed in terms of the velocity potential $\phi$ satisfying the transonic small disturbance equation,

\[(1 - M^2_\infty - M^2_\infty (\gamma + 1)\phi_x)\phi_{xx} + \phi_{yy} = 0 \quad (1)\]

This equation presents two major difficulties, 1) it is non-linear and 2) it is of the mixed hyperbolic-elliptic type. Analytical solutions to non-linear equations are difficult to obtain. One must normally resort to numerical methods. When the coefficient $(1 - M^2_\infty - M^2_\infty (\gamma + 1)\phi_x)$ in equation 1 is negative, the flow is supersonic and the equation is called hyperbolic; otherwise the flow is subsonic and the equation is elliptic. The forms of the two solutions are fundamentally different. Hyperbolic equations admit both discontinuities, which propagate only in characteristic directions, and the presence of shock fronts. Elliptic equations, on the other hand, require that the dependent variables and their derivatives be continuous and that a change in any part of the flow field affects every other part. Many non-linear elliptic equations are solved by appropriate relaxation iteration techniques by casting the equation in Poisson's form with the non-linearity acting as the driving force. Solutions to hyperbolic equations are usually obtained by the method of characteristics or by
finite difference marching techniques which use an artificial viscosity to represent the average jump conditions across the shock wave. In mixed supersonic and subsonic flows, normal numerical procedures break down because the boundary between the two regions is not known a priori.

Finite element numerical techniques have evolved as a powerful tool in obtaining approximate solutions to a wide variety of engineering problems, particularly ones with Neumann-Dirichlet boundary conditions, i.e., elliptical problems. They offer several outstanding advantages. Some of these are:

1) Non-homogeneous problems may be treated with relative simplicity.
2) Complex geometries may be modeled with relative ease since the elements can be graded in size and shape to follow boundaries of arbitrary shape.
3) Once the finite element model has been established, a variety of problems can be solved by supplying the computer with the appropriate data.

Chan and Brashears [Ref. 5] developed a finite element computer program for steady transonic flow over a non-lifting airfoil. This program uses the least squares method of weighted residuals to approximate equation 1 by a system of algebraic equations, and assembles the equations in a special way to account for the hyperbolic region of flow. This technique prevents the influence of downwind nodes from propagating upstream in the supersonic region.

The purpose of this thesis is to investigate the possibility of speeding the convergence of a solution by transforming the steady transonic equation to the unsteady equation.
and integrating over time until the time dependent terms vanish and to extend the program of Ref. [5] to the transonic region of a converging-diverging nozzle.
II. DISCUSSION OF THE FINITE ELEMENT APPROACH

In a continuum problem of any dimension, the field variable, whether it is velocity potential, velocity, temperature, displacement or some other quantity, possesses infinitely many values because it is a function of each generic point in the solution region. Consequently, the problem is one of an infinite number of unknowns. The finite element approach subdivides the solution domain into a finite number of subdomains called elements and expresses the unknown field variable in terms of assumed approximating functions within each element. The approximating functions are sometimes called interpolating functions and are defined in terms of the values of the field variables at specified points called nodes or nodal points. Nodes usually lie on the element boundaries where adjacent elements are considered to be connected. In addition to boundary nodes, an element may also contain interior nodes. The nodal values of the field variable and the interpolating function for the elements completely define the behavior of the field variable within the elements. Once these unknowns are found, the interpolating functions define the field variable throughout the assemblage of the element.

Clearly, the nature of the solution and the degree of accuracy of the approximation depends not only on the number and size of the elements used but also on the interpolating
functions selected. Interpolating functions may not be chosen arbitrarily because certain compatibility conditions must be satisfied. Often such functions are selected so that the field variable or its derivatives are continuous across adjoining element boundaries. Once the problem is formulated in terms of individual elements, the contributions of each element may be assembled to define the entire solution domain. This means, for example, that if we are treating a problem in stress analysis we can find the force-displacement or stiffness characteristics of each element and then assemble the elements to determine the stiffness of the whole structure. Finite element solutions are not, of course, restricted to structures problems, but the matrix of equations defined by the interpolating functions and the nodal field variables is still referred to as the stiffness matrix regardless of the field variable in the problem.

Solutions to continuous problems by the finite element approach always follow a systematic step-by-step process. This process is completely general to the finite element method and it is outlined below. [Ref. 4]

1. Discretize the continuum.

The first step is to divide the solution domain into elements. A variety of element shapes may be used and one or more different element shapes may be used in the same region. The type and number of the elements used in a given problem are a matter of engineering judgement.
2. Select the interpolating functions.

The next step is to choose the type of interpolating function to represent the variation of the field variable over the element. The field variable may be a scalar, a vector, or a higher order tensor. Often polynomials are selected as interpolating functions for they are easy to integrate and differentiate. The degree of polynomial chosen depends on the number of nodes and the nature and number of the unknowns and the continuity requirements imposed at the nodes and the element boundaries. The unknown quantities at the nodes may be assigned to the field variable and their derivatives.

3. Find the element properties.

After the elements and their interpolating functions have been selected, the matrix of algebraic equations which express the properties of the individual elements must be determined. Several methods are available for this task. These are: the direct approach, the variational approach, the method of weighted residuals and the energy balance approach. Reference [4] is a good source of information on the various techniques.

4. Assemble the element properties to obtain the system equations.

To find the properties of the over-all system, the matrix equations expressing the behavior of each element must be
added to the matrix equation of all other elements. The basis for this assembly procedure stems from the fact that connecting elements have common nodes and the field variable must be the same for each element sharing that node.

At this point the boundary conditions for the system of equations must be accounted for and the system of equations must be modified before it is ready for solution.

5. Solve the system of equations.

The assembly process of step 4 produces a set of simultaneous equations which can be solved to obtain the unknown field variables. Linear equations have a number of standard solution techniques readily available, but solutions to non-linear equations are more difficult to obtain.

6. Make additional computations if desired.

Important parameters, such as pressure coefficient in aerodynamic problems, may now be calculated from the values of the field variables.
III. THEORY AND BASIC EQUATIONS

A. STEADY TRANSONIC FLOW

Chan et al. [Ref. 5] developed an algorithm to analyze steady transonic flow over non-lifting thin airfoils. Boundary layer effects were ignored and the imbedded shock wave was assumed to be weak. These assumptions are consistent with transonic small disturbance theory which can be expressed mathematically by the following expressions.

\[(1 - M'^2_\infty - M'^2_\infty(\gamma + 1)\phi_x)\phi_{xx} + \phi_{yy} = 0\]  \hspace{1cm} (1)

Boundary conditions -

\[\nabla \cdot \phi = 0 \hspace{1cm} \text{at infinity} \hspace{1cm} (2)\]
\[v = (1 + u)dg/dx \hspace{1cm} \text{on the airfoil} \hspace{1cm} (3)\]
\[u = 0 \hspace{1cm} \text{on the line of symmetry} \hspace{1cm} (4)\]

where \(g(x,y)\) defines the airfoil and \(dg/dx\) describes the airfoil slope.

The above expressions appear in their dimensionless form where \(\phi\) = perturbed velocity potential and the perturbed velocity components in the \(x\) and \(y\) directions are respectively defined as

\[u = \phi_x\]
\[v = \phi_y\]
\( M_\infty \) = freestream Mach number and \( \gamma \) = ratio of specific heats which for air is taken to be 1.4. The physical coordinates \( x' \) and \( y' \) and the velocity potential \( \phi' \) are related to the dimensionless quantities by

\[
x = x'/c, \quad y = y'/c, \quad \phi = \phi'/cU_\infty
\]

where \( c \) is the chordlength of the airfoil and \( U_\infty \) is the freestream velocity.

Once the flowfield solution is determined in terms of the perturbed velocities, the secondary unknowns are subsequently calculated. These include:

\[
a = [\frac{\gamma - 1}{2}(U_\infty^2 - V^2) + \frac{U_\infty^2}{M_\infty^2}] \frac{1}{2}
\]  
\[ M = \frac{V}{a} \]  
\[
\frac{p}{P_0} = \left[ 1 + \frac{\gamma - 1}{2}M^2 \right]^{\gamma/(\gamma + 1)}
\]  
\[
C_p = -\left[ \frac{2u}{U_\infty} + (1-M_\infty^2) \frac{u^2}{U_\infty^2} + \frac{v^2}{U_\infty^2} \right] \approx -\frac{2u}{U_\infty}
\]

In the above, \( U_\infty = 1 \) is the normalized freestream velocity, \( a \) = local sound speed, \( p \) = local static pressure, \( M \) = local Mach number, \( V \) = total velocity, \( P_0 \) = stagnation pressure and \( C_p \) = pressure coefficient.

**B. UNSTEADY TRANSONIC FLOW**

Unsteady transonic inviscid flow may be expressed in terms of the velocity potential \( \phi(x,y,t) \) to a first order approximation by
\begin{align*}
(1 - M_{\infty}^2 - M_{\infty}^2(\gamma + 1) \phi_x) \phi_{xx} + \phi_{yy} - 2M_{\infty}^2 \phi_t - M_{\infty}^2 \phi_{tt} &= 0 \tag{9}
\end{align*}

which has the same non-linear coefficient retained for steady transonic flow in Equation 1.

Boundary conditions require that the disturbances vanish far from the airfoil,

\begin{align*}
\phi_x &= 0 \quad \phi_y = 0 \text{ at infinity} \tag{10}
\end{align*}

and that the flow remain attached to the body. Let \( B(x,y,t) = 0 \) define the body at any instant. The surface tangency restraint may now be expressed by the substantial derivative \( DB/DT \) vanishing.

\begin{align*}
DB/DT &= B_t + (1 + \phi_x)B_x + \phi_y B_y \tag{11}
\end{align*}

If the body remains stationary \( B_t = 0 \), and the tangency condition becomes the same as in steady flow, namely

\begin{align*}
v &= (1 + u)dg/dx \tag{12}
\end{align*}

where \( dg/dx \) represents the airfoil slope.

The pressure coefficient for isentropic unsteady compressible flow is defined by

\[
C_p = \frac{2}{\gamma M_{\infty}^2} \left\{ \left[ 1 - \frac{Y-1}{2} M_{\infty}^2 (2 \phi_x + 2 \phi_t + \phi_x^2 + \phi_y^2) \right] \frac{Y}{(Y-1)} - 1 \right\} \tag{13}
\]

Expanding by the binomial expansion and retaining only the first order terms gives,

\[
C_p = -2\phi_x - 2\phi_t \tag{14}
\]
IV. **FINITE ELEMENT FORMULATION**

The method of weighted residuals is a technique for approximating solutions to linear or non-linear partial differential equations and it is the basis for the finite element formulation of the transonic small disturbance equation (Equation 1). This procedure involves assuming the general functional behavior of the field variable which would approximately satisfy the basic equation and boundary conditions. Substituting this approximation into the original differential equation results in some error called a residual. A system of algebraic equations results when a weighted average of the residual is forced to vanish as it is averaged over the entire domain.

A. STEADY FLOW

The approximate solution to equation 1 is assumed to be

\[ \hat{\phi} = N_i \phi_i \]  

(15)

where \( N_i \) are the interpolating functions which exhibits the behavior of equation 1 and \( \phi_i \) are the undetermined parameters at the nodal points.

When \( \hat{\phi} \) is substituted into equation 1, the resulting residual is

\[ R = \left[ 1 - M_\infty^2 - M_\infty^2(\gamma + 1)N_k,xx \phi_k \right] N_j,xx + N_j,yy \]  

(16)
The weighted average is determined by multiplying the residual \( R \) by \( m \) linearly independent weighting functions \( W_i \) and integrating over the elemental domain. Forcing this residual to vanish yields,

\[
\int W_i R \, dA = 0 \quad i = 1 \text{ to } m
\]

Chan et al. [Ref. 5] found that when the weighting function \( W_i \) for equation 1 is chosen to be \( \frac{\partial R}{\partial \phi_i} \) the resulting matrix is positive definite and well conditioned. This choice of weighting functions is referred to as the method of least squares because it is equivalent to minimizing the square of the residuals summed over the domain with respect to the undetermined parameters. That is,

\[
\chi = \int R^2 \, dA
\]

\[
\frac{\partial \chi}{\partial \phi_i} = \int \frac{\partial R}{\partial \phi_i} R \, dA = 0
\]

Integrating over the domain produces the system of algebraic equations

\[
S_{ij} \phi_j = 0 \quad (18)
\]

where the elemental matrix \( S_{ij} \) is defined as

\[
S_{ij} = \int Q_j P_i \, dA \quad (19)
\]

With \( Q_j \) and \( P_i \) equal to

\[
Q_j = [1 - M_{\infty}^2 - M_{\infty}^2 (\gamma + 1) N_k, x \phi_k] \ N_j, xx + N_j, yy
\]

\[
P_i = Q_i - M_{\infty}^2 (1 + \gamma) N_k, xx \phi_k N_i, x
\]
B. UNSTEADY FLOW

Development of the unsteady flow finite element equations is similar to the procedure used to formulate the finite element equations for steady transonic flow. The least squares method of weighted residuals is again used but \( \phi \) is now a function of time as well as the spatial coordinates \( x \) and \( y \).

The approximate solution has the form,

\[
\hat{\phi} = N_i(x,y)\phi_i(t)
\]  

(20)

Substituting \( \hat{\phi} \) in the unsteady transonic small disturbance equation, the weighted residual becomes,

\[
\chi = \iint(R_1 + R_2 + R_3)^2 dA
\]

(21)

where

\[
R_1 = \{[1 - M^2 - M^2(\gamma + 1)\phi_k^N_k,x]N_j,xx + N_j,yy\}\phi_j
\]

\[
R_2 = -2M^2N_j,x\phi_j
\]

\[
R_3 = -M^2N_j\phi_j
\]

Expanding equation 21 yields

\[
\chi = \iint[R_1^2 + R_2^2 + R_3^2 + 2R_1R_2 + 2R_2R_3]dA
\]

(22)

and minimizing with respect to the undetermined parameters \( \phi_i \) the following system of algebraic equations result,

\[
\phi_j = 0 = 2\iint\partial R_1/\partial \phi_j[R_1 + R_2 + R_3]dA
\]

\[
\partial R_1/\partial \phi_j = P_i
\]
where $P_i$ has been previously defined in the steady finite element formulation

The above equation may be rewritten in the form

$$S_{ij} \dot{\phi}_j + SC_{ij} \ddot{\phi}_j + SM_{ij} \dddot{\phi}_j = 0 \quad (23)$$

The stiffness matrix $S_{ij}$ is the same as that developed for the steady transonic equation and the damping ($SC_{ij}$) and mass ($SM_{ij}$) matrices are defined below.

$$SC_{ij} = -\iint M_{\infty}^2 N_j \times P_i dA \quad (24)$$

$$SM_{ij} = -\iint M_{\infty}^2 N_j P_i dA \quad (25)$$
V. ELEMENT DESCRIPTION AND ASSEMBLY OF EQUATIONS

A. ELEMENT DESCRIPTION

The basic element used in the finite element program is the non-conforming cubic triangular element developed by Bazeley et al. [Ref. 2]. Also used in the program are the quadrilateral and trapezoidal elements constructed from these triangular elements. These three types of elements can be mixed and used freely in the entire flow region except that only trapezoids should be used to cover the supersonic and mixed region in order to enact the special assembly procedures required by the hyperbolic equation which describes the flow in that region.

The basic triangular element is shown in Fig. 1, which at each vertex has the velocity potential and the velocity components as the undetermined parameters. This type of element was chosen because both Dirichlet and Neumann boundary conditions can be imposed with equal convenience. In addition, because velocity components are used as primary unknowns secondary parameters, such as Mach number and pressure coefficient can be calculated directly without resorting to numerical differentiation, which would produce additional errors.

In the element, the approximate solution is assumed as

\[ \hat{\phi} = N_i \phi_i \quad (i = 1 \text{ to } 9) \]
Figure 1 - Triangular Element
In which $\phi_i$'s are the nine undetermined parameters of $\phi$ and $N_i$ are the interpolation functions which are expressed in terms of the area coordinates.

The shape or interpolating functions and their first and second derivatives are defined below.

Letting,

\[ a_i = x_j y_k - x_k y_j \]
\[ b_i = y_j - y_k \]
\[ c_i = x_k - x_j \]
\[ \Delta = \text{area of triangle 1-2-3} = (b_j c_k - b_k c_j)/2 \]
\[ \alpha = 0.5 (c_k - c_j) \]
\[ \beta = 0.5 (b_j - b_k) \]
\[ H = \zeta_k \zeta_j \zeta_k \]
\[ H_x = b_i \zeta_j \zeta_k + b_j \zeta_k \zeta_i + b_k \zeta_i \zeta_j \]
\[ H_y = c_i \zeta_j \zeta_k + c_j \zeta_k \zeta_i + c_k \zeta_i \zeta_j \]
\[ H_{xx} = 2(\zeta_k b_j b_k + \zeta_j b_k b_k + \zeta_k b_i b_j) \]
\[ H_{yy} = 2(\zeta_i c_j c_k + \zeta_j c_k c_i + \zeta_k c_i c_j) \]

with $i = (1,2,3), k = (3,1,2)$ then one has for $l = (1,4,7)$, $i = (1,2,3)$

\[ N_1 = \zeta_i^2 (3 - 2\zeta_i) + 2H \]
\[ N_{1,x} = [6b_i \zeta_i (1 - \zeta_i) + 2H_x]/2\Delta \]
\[ N_{1,y} = [6c_i \zeta_i (1 - \zeta_i) + 2H_y]/2\Delta \]
\[ N_{1,xx} = \left[ 6b_i^2 \left( 1 - 2\zeta_i \right) + 2H_{xx} \right] / (2\Delta)^2 \]
\[ N_{1,yy} = \left[ 6c_i^2 \left( 1 - 2\zeta_i \right) + 2H_{yy} \right] / (2\Delta)^2 \]

for \( l = (2,5,8), \ l = (1,2,3) \)

\[ N_1 = \zeta_i^2 \left( c_k \xi_j - c_j \xi_k \right) + \alpha H \]
\[ N_{1,x} = \left[ 2b_i \zeta_i \left( c_k \xi_j - c_j \xi_k \right) + 2\zeta_i^2 + \alpha H_x \right] / 2\Delta \]
\[ N_{1,y} = \left[ 2c_i \zeta_i \left( c_k \xi_j - c_j \xi_k \right) + \alpha H_y \right] / 2\Delta \]
\[ N_{1,xx} = \left[ 2b_i^2 \left( c_k \xi_j - c_j \xi_k \right) + 4b_i (2\Delta) \zeta_i + \alpha H_{xx} \right] / (2\Delta)^2 \]
\[ N_{1,yy} = \left[ 2c_i^2 \left( c_k \xi_j - c_j \xi_k \right) + \alpha H_{yy} \right] / (2\Delta)^2 \]

for \( l = (3,6,9), \ l = (1,2,3) \)

\[ N_1 = \zeta_i^2 \left( b_j \xi_k - b_k \xi_j \right) + \beta H \]
\[ N_{1,x} = \left[ 2b_i \zeta_i \left( b_j \xi_k - b_k \xi_j \right) + \beta H_x \right] / 2\Delta \]
\[ N_{1,y} = \left[ 2c_i \zeta_i \left( b_j \xi_k - b_k \xi_j \right) + 2\zeta_i^2 + \beta H_y \right] / 2\Delta \]
\[ N_{1,xx} = \left[ 2b_i^2 \left( b_j \xi_k - b_k \xi_j \right) + \beta H_{xx} \right] / (2\Delta)^2 \]
\[ N_{1,yy} = \left[ 2c_i^2 \left( b_j \xi_k - b_k \xi_j \right) + 4c_i (2\Delta) \zeta_i + \beta H_{yy} \right] / (2\Delta)^2 . \]
Quadrilateral and trapezoidal elements as shown in Fig. 2 are also used in the present program, the former is used in the subsonic region and the latter in the mixed and supersonic region. The element matrix for the quadrilateral element is obtained by combining appropriately the matrices for two triangles, while the matrix for trapezoidal element is obtained by averaging contributions from two left-running and two right-running triangles. The averaging process is designed to remove the bias effects inherent in the quadrilaterals used.

B. ASSEMBLY OF EQUATIONS

Straightforward application of the finite element assembly technique to transonic flows would fail (the solution diverges) because this would allow disturbances to propagate upwind in the supersonic region of flow where the governing equation is hyperbolic. Hyperbolic equations have a time-like dependency in that the solution at the downwind station is affected by the upwind station but not vice-versa. Assembly techniques for a transonic flow finite element program must take into account this time-like dependency. If the x-axis is taken as a time-like direction in the supersonic region, the element matrix may be assembled in a way similar to a backward finite difference operator, which has been successful in solving hyperbolic equations.

Consider the rectangular element sketched below with the upwind station I and the downwind station II, each having two nodal points with the element type chosen. The element matrices can be constructed in the usual manner.
a. Quadrilateral Element

b. Trapezoidal Element

Figure 2 - Quadrilateral and Trapezoidal Elements
However, before assembling the element matrix into the system matrix the non-linear coefficient of equation 1 is evaluated.

\[ C = 1 - M_{\infty}^2 - M_{\infty}^2 (\gamma + 1) u \]

The sign of the coefficient being positive, zero, or negative defines the equation as elliptic, parabolic, or hyperbolic. If \( C \) is non-positive for all nodes in the element, the rows representing the improper downwind influence on the solution at an upwind station are ignored during assembly. This feature is automatically applied in the program requiring only a little care in arrangement of the nodes of the element. In the anticipated supersonic region, element node points should be arranged in the order as indicated in figure 3, starting with the upper left corner and proceeding in the counter-clockwise direction. In the elliptic region, i.e., where the coefficient is positive, no special assembly technique is invoked.

C. ITERATIVE PROCEDURES

With the equations assembled and the proper boundary conditions imposed, the system of non-linear algebraic equations is solved by iterative procedures in the form

\[ S_{ij}(\tilde{\phi})\phi_j^{(n)} = l_i \quad (23) \]

to solve for the solution in the \( n^{th} \) iteration. The function \( \tilde{\phi} \) is defined as

\[ \tilde{\phi} = \theta \phi^{(n-1)} + (1-\theta)\phi^{(n-1)} \]
Figure 3 - Nodal Arrangement for Supersonic Region
in which the under-relaxation factor $\theta$ is in the range $0 < \theta \leq 1$. For subsonic flow $\theta = 1$, which is simply a successive approximation, yields good results, but it is necessary to under-relax somewhat with $\theta$ approximately .5 for supercritical flow. Generally, a smaller relaxation factor will make the solution more stable but it will tend to slow down the rate of convergence.

Equation 23 is subject to the convergence criterion that the change in local Mach number between two successive iterations is less than a prescribed value $\varepsilon$ at all nodes in the flow field. That is,

$$\frac{M(n) - M(n-1)}{M(n)} \leq \varepsilon.$$
VI. INTEGRATION OF UNSTeady FInITE ELEMENT EQUATIONS

The unsteady transonic small disturbance equation (equation 9) when suitably reduced to a finite element approximation appears in the form,

\[ S_{ij} \phi_j + SC_{ij} \dot{\phi}_j + SM_{ij} \ddot{\phi}_j = R_j \]  (26)

This equation is analogous to a damped spring mass system, hence \( S_{ij} \), \( SC_{ij} \), and \( SM_{ij} \) are respectively referred to as the stiffness, damping, and mass matrices.

Mathematically, equation 26 represents a system of second order differential equations with constant coefficients, which can be solved by standard numerical procedures for differential equations, such as Runge-Kutta or Milne methods. However, this would be a very costly technique if the coefficient matrices are very large. In practical finite element analysis there are a few effective methods which take advantage of the banded matrices usually encountered in finite elements. One such method is the direct numerical integration method.

Direct integration involves a numerical step-by-step procedure aimed at satisfying equation 26 only at discrete time intervals \( \Delta t \) apart and not over all time \( t \). Conceptually, direct integration is a finite element method in space and a finite difference method in time. Examples of direct integration are the central difference method, Houbolt integration and the Wilson method. The first two schemes are finite
difference schemes whereas the latter is a linear acceleration method. Linear acceleration integration assumes a linear variation of acceleration from time $t$ to time $t + \Delta t$.

Central differencing can be very effective in the solution of many dynamic problems especially those that involve a large system of equations. However, this method is unstable for all time steps larger than a critical time step.

Houbolt integration is an implicit finite differencing method related to central differencing, only it has the advantage of being stable for all TIME STEPS.

The Houbolt method was used to integrate the unsteady finite element equations because of this stability.

Houbolt integration uses the following finite difference expansions:

$$
\phi_{i,t+\Delta t} = \frac{[2\phi_{i,t+\Delta t} - 5\phi_{i,t} + 4\phi_{i,t-\Delta t} - \phi_{i,t-2\Delta t}]}{\Delta t^2}
$$

$$
\phi_{i,t+\Delta t} = \frac{[11\phi_{i,t+\Delta t} - 18\phi_{i,t} + 9\phi_{i,t-\Delta t} - 2\phi_{i,t-2\Delta t}]}{6\Delta t}
$$

which are two backward-difference formulas with errors of order $(\Delta t)^2$.

The solution of $\phi_{i,t+\Delta t}$ must satisfy equation 26 and at time $t+\Delta t$ equation 26 becomes

$$
S_{ij}\dot{\phi}_{j,t+\Delta t} + SC_{ij}\phi_{j,t+\Delta t} + SM_{ij}\ddot{\phi}_{j,t+\Delta t} = 0
$$

Substituting the finite difference formulas for $\phi_{j,t+\Delta t}$ and rearranging all known vectors on the right hand side, the solution for $\phi_{j,t+\Delta t}$ is obtained, namely:
\[(a_0 SM_{ij} + a_1 SC_{ij} + S_{ij})^{\phi}_{j,t+\Delta t} = R_j,t+\Delta t \quad (27)\]

\[(a_2 SM_{ij} + a_3 SC_{ij})^{\phi}_{j,t} + (a_4 SM_{ij} + a_5 SC_{ij})^{\phi}_{j,t-2\Delta t}\]

Where the constant integration coefficients are:

- \(a_0 = \frac{2}{\Delta t^2}\)
- \(a_1 = \frac{11}{6\Delta t}\)
- \(a_2 = \frac{5}{\Delta t}\)
- \(a_3 = \frac{3}{\Delta t}\)
- \(a_4 = 2a_0\)
- \(a_5 = -a_5/2\)
- \(a_6 = a_0/2\)
- \(a_7 = a_3/9\)

Equation 27 may be written as

\[SE_{ij}^{\phi_j,t+\Delta t} = RE_j \quad (28)\]

where the effective stiffness matrix \(SE_{ij}\) and the effective load vector \(RE_j\) are defined as:

\[SE_{ij} = S_{ij} + a_0 SM_{ij} + a_1 SC_{ij}\]

\[RE_j = SM_{ij} (a_2^{\phi_j,t} + a_4^{\phi_j,t-\Delta t} + a_6^{\phi_j,t-2\Delta t}) + SC_{ij} (a_3^{\phi_j,t} + a_5^{\phi_j,t-\Delta t} + a_7^{\phi_j,t-2\Delta t})\]

Accurate knowledge of the vectors \(\phi_{j,t-\Delta t}\) and \(\phi_{j,t-2\Delta t}\) are required to yield an accurate solution for \(\phi_{j,t+\Delta t}\) and
normally the Houbolt integration scheme requires a special starting procedure to determine the initial two vectors \( \phi_j, \Delta t \) and \( \phi_j, 2\Delta t \). However, since the primary interest of this problem is to integrate the equations until they converge to a steady state solution, it is not necessary to obtain an accurate time history of the flow. Errors induced by the inaccurate starting vectors will vanish as time approaches infinity. Therefore, the starting vectors may be chosen somewhat arbitrarily.
VII. CONVERGING-DIVERGING NOZZLE

S. F. Shen [Ref. 10] demonstrated the feasibility of calculating compressible flows through a converging-diverging (Laval) nozzle by dividing the region of calculations into three patches, a subsonic region, a supersonic region and a transonic one, of course bounded by the other two regions. The locations of the boundaries for each region were chosen arbitrarily provided the sonic line is bracketed by the subsonic and supersonic boundaries.

Two different finite element formulations were used for the subsonic and supersonic regions, but Shen [10] resorted to analytical approximations to cover the transonic patch. This restricted the calculations to nozzles with small throat curvatures because no analytic solutions exist for nozzles with large throat curvatures. It is conceivable that STRANL-II could be adapted to provide a continuous solution throughout all three regions.

Outside the transonic region of flow the governing small disturbance equation is

\[(1 - M_\infty^2)\phi_{xx} + \phi_{yy} = 0\]  

(29)

This holds for both subsonic and supersonic flow. Comparing equation 29 with equation 1, the transonic small disturbance equation, we notice that only the non-linear coefficient \(M_\infty^2(\gamma + 1)u\) distinguishes the two equations from each other.
This coefficient becomes negligible when the Mach number becomes less than .8 or greater than 1.2. With this consideration in mind, it was assumed that equation 1 would adequately describe the flow through the nozzle and that the finite element formulation developed for the non-lifting airfoil would apply to the Laval nozzle.

A. BOUNDARY CONDITIONS

Two solutions are possible for a converging-diverging nozzle: 1) Symmetric flow, where the flow is subsonic through the domain, except for a small supersonic region near the wall in the throat, and 2) Asymmetric solution, where the flow accelerates to sonic velocity in the throat and then continues to accelerate to supersonic velocity in the diverging section. Different boundary conditions apply for the two solutions. For the symmetric case, both inlet and exit velocities must be specified. Inlet and exit velocities are equivalent in the subsonic solution. The supersonic solution requires that only the inlet velocities be specified. If the exit velocities are also applied, the problem is overspecified and the solution may not converge.

Velocities at the inlet and exit are not uniform in the \( y \) direction, therefore the disturbances cannot be set to zero as in the case of the non-lifting airfoil. Boundary velocities must be calculated by solving equation 29 analytically.

Equation 29 is a linear equation which can be mapped to Laplace's equation,

\[ \nabla^2 \phi = 0, \]
by letting $y' = \sqrt{1 - M^2} y$. Laplace's equation is easily solved for the case of the hyperbolic nozzle by transforming from cartesian coordinates to elliptic coordinates. This transformation simplifies the solution because the streamlines must be hyperbolas to follow the nozzle boundary and therefore follow the hyperbolic coordinate $v = \text{constant}$.

If the elliptic coordinates $\mu$ and $v$ are chosen such that the curves $\mu = \text{constant}$ are ellipses and the $v$ curves are hyperbolas, then the velocity potential which satisfies Laplace's equation for a hyperbolic nozzle is simply

$$\phi = A\mu$$

where $A$ is a constant of integration. The stream function is

$$\psi = A v$$

The transformation $w = \mu + i v = \cosh^{-1}(2z/a)$ gives rise to the elliptic coordinates

$$y = 1/2 \ a \ \cosh \mu \ \cos \ v, \ x = 1/2 \ a \ \sinh \mu \ \sin \ v$$

$$r = 1/2 \ a \ [\cosh^2 \mu - \sin^2 v]$$

$$r_1 = \sqrt{(y + a/2)^2 + x^2}$$

$$r_2 = \sqrt{(y - a/2)^2 + x^2}$$

Solving for $\mu$ and $v$ produces

$$\mu = \cosh^{-1} [(r_1 + r_2)/a]$$

$$v = \cos^{-1} [(r_1 + r_2)/a]$$

The nozzle boundary is defined by $v_0 = \text{constant}$, which along with the equation for the nozzle wall in cartesian
coordinates, \( y' = f(x) \), implicitly defines the constant \( a \). Substituting for \( \mu \) in the velocity potential produces,

\[
\frac{\partial r_1}{\partial \rho} = \frac{A}{\sqrt{(r_1 + r_2/2)^2 + x^2}}
\]

from which the velocities may be determined.

\[
u = \phi_y = \frac{A}{\sqrt{r_1 + r_2}}
\]

\[
u = \phi_y = \frac{A}{\sqrt{r_1 + r_2}}
\]

\[
u = \phi_y = \frac{A}{r_1 + r_2}
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u = \phi_y = \frac{A}{r_1 + r_2}
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\[
u = \phi_y = \frac{A}{r_1 + r_2}
\]

\[
u = \phi_y = \frac{A}{r_1 + r_2}
\]

The constant of integration \( A \) may be determined by specifying the flow rate through the nozzle, but when the inlet velocities are normalized with respect to the freestream velocity \( (U_\infty) \) \( A \) is factored out of the problem.

Velocities for compressible flow can be solved by mapping back to the physical coordinate system \((x,y)\) plane.

Other boundary conditions are universal to both problems. These are:

\[
u = 0 \quad \text{on the line of symmetry}
\]

\[
u = (1 + u)df/dx \quad \text{at the nozzle wall}
\]
F(x) defines the nozzle boundary in terms of a ratio of the throat semi-height as a function of x. The throat semi-height is taken to be 1 for convenience.

Pressure ratio, sound speed, and Mach number are calculated as before by equations 5 through 8.
VIII. DISCUSSION OF RESULTS

A. TIME INTEGRATION TO A STEADY STATE SOLUTION

As stated before, the Houbolt method of integration is stable for all time steps. Results of the test cases bear this out with the larger time steps providing the most rapid convergence to a steady state solution. Time steps were tried from $t = 0.1$ to $t = 100$. Time steps larger than $t = 100$ were not attempted because as $t$ becomes too large the influence that the damping and mass matrices have on the effective stiffness matrix becomes negligible compared to the stiffness matrix. That is:

$$SE_{ij} = S_{ij} + 2SC_{ij}/\Delta t^2 + 6SM_{ij}/\Delta t$$

as $\Delta t \to \infty$

$$SE_{ij} = S_{ij}$$

The starting solutions were chosen somewhat arbitrarily. $\phi_{j,2\Delta t}$ was chosen to satisfy the first iteration of the steady solution

$$S_{ij}\phi_{j,2\Delta t} = 0$$

when the non-linear term ($u$) in the coefficient

$$1 - M_\infty^2 - M_\infty^2(\gamma + 1)u$$

was set to zero. $\phi_{j,\Delta t}$ and $\phi_{j,0}$ were chosen as multiples of $\phi_{j,2\Delta t}$ and respectively they were
\[ \phi_j, \Delta t = 0.5 \phi_j, 2\Delta t \]
\[ \phi_j, 0 = 0 \]

This starting procedure proved to be superior to choosing the first three vectors closer to the converged solution. If \( \phi_j, 2\Delta t \), \( \phi_j, \Delta t \), and \( \phi_j, 0 \) were chosen to be the last three time steps of the previous case, the solution oscillated and converged much slower than with the starting solutions chosen as above.

The stiffness, mass, and damping matrices were recalculated after each time step, using the under-relaxation technique described above. This was necessary to utilize the special assembly procedures invoked by STRANL-II to prevent the inadmissible influence of downwind nodes from propagating upstream in the supersonic region.

For barely critical flow \( (M_\infty = .861) \) and subsonic flow, an under-relaxation factor \( \theta = 1 \) (successive approximation) resulted in convergence to a steady state solution after only three time steps. Eleven time steps were required for the supercritical solution to converge using the same relaxation factor. Reducing \( \theta \) to .5 increased the rate of convergence and the solution achieved steady state after six time steps. Figure 4 compares the steady state solution for a 6% thick circular arc airfoil at \( M_\infty = .909 \), using the same integration method, with the results obtained in Ref. [5]. Chan's results converged in 10 iterations after using the results from the barely critical flow as an initial guess to the
supercritical solution. Figure 4 is a plot of local Mach numbers at boundary nodes on the airfoil.

B. CONVERGING-DIVERGING NOZZLE

The nozzle chosen for the test cases was the two-dimensional Oswatitsch nozzle with the boundary defined as

\[ y = 1 + \sqrt{2(x - 2.5)^2} \]

where the throat at \( x = 2.5 \) has a semi-height of 1. The inlet was taken to be \( x = 0 \) and the exit was at \( x = 5 \). \( M_\infty = 0.44 \), the inlet Mach number on the nozzle center-line was chosen to yield sonic conditions in the throat.

Two solutions were possible for this inlet condition, the symmetric solution and the asymmetric solution; but neither solution was achieved by the finite element method. Although the solution converged for the subsonic case in three iterations, center-line Mach numbers deviated significantly from both one-dimensional theory and from Oswatitsch's approximation [Fig. 5]. When the local Mach number \( M \) exceeded the inlet Mach number by approximately 0.2 (\( M > 0.64 \)) the solution was invalid. Differences at the center part of the nozzle are due to an essentially incorrect free stream Mach number. Patching the solution at \( x \approx 1.5 \) would improve the solution.

A second test case was run for the supersonic section of the nozzle with the inlet boundary on the sonic line. The exit boundary was left free to float. Here the solution was unstable and no meaningful results were obtained.
Figure 4 - Comparison of Time Integration Results with Steady State Results.
Figure 5 - Nozzle Center-Line, Inlet Mach Number 0.4300.
IX. PROGRAM MODIFICATION

The finite element computer program for non-lifting air-
voils, as developed in Ref. [5], is separated into two parts.
These have been designated STRANL-I and STRANL-II by Lockheed
Corporation. STRANL-I generates a finite element mesh to be
used as inputs to STRANL-II, which assembles the finite ele-
ment equations, applies the boundary conditions, and solves
the non-linear system of equations. Detailed descriptions
and instructions for the use of the two programs can be found
in Ref. [5]. Only the modifications to the above programs
will be discussed in this section.

A. UNSTEADY EQUATIONS

Modifications to STRANL-II to form and solve the unsteady
finite element equations were three-fold:

1) The new elemental matrices $SC_{ij}$ and $SM_{ij}$ were calculated
   and assembled.

2) All the matrices were stored on an external magnetic
disk to be accessed and reassembled later because of
the amount of space required to store three large
matrices, in core memory.

3) The effective stiffness matrix $SE_{ij}$ and the effective
   load vector $RE_{ij}$ were assembled, and the system of
   equations solved.

    Several existing subroutines in the original STRANL-II
program were modified to assemble the damping and mass matrices.
These include subroutines NEWK, EMTC, DERV, and EMQT. Two new
subroutines were added to perform the other tasks.
B. MODIFICATIONS TO CALCULATE THE MASS AND DAMPING MATRICES

EMTC in the STRANL-II program calculated the elemental stiffness matrix by numerically integrating the equation,

\[ S_{ij} = \int_0^1 Q_i P_j \, dA \]

Equations were added to EMTC to perform the additional numerical integrations for the mass and damping matrices. All three matrices were calculated at the same time. EMQT assembled the elemental stiffness matrices for a quadrilateral and trapezoidal element from the contributions of the triangular elements. Mass and damping matrices were calculated in the same fashion.

Subroutine NEWK, an original subroutine in STRANL-II, which assembled the finite element equations for steady flow, was modified to assemble \( SC_{ij} \) and \( SM_{ij} \). A new calling argument, NMAT was passed to NEWK, which assembled contributions from the triangular, quadrilateral and trapezoidal element matrices into the global matrices \( S_{ij} \), \( SC_{ij} \), and \( SM_{ij} \), depending on NMAT being 1, 2 or 3.

1. Subroutine STORE

Given a non-symmetric matrix stored in a banded node, plus the right hand side vector, subroutine STORE separates this system into two matrices and stores them on a magnetic disk. Figures 6 and 7 show the decomposition of a banded matrix into banded storage, and the further decomposition of this banded stored matrix to two smaller matrices by subroutine STORE. In these figures, D, L, and U represent the
Figure 6 - Decomposition of a Banded Matrix Plus Right Hand Side
Figure 7 - Separation of a Banded Stored Matrix by Store
diagonal matrix, the lower triangular matrix, and the upper triangular matrix respectively. HBW is the half bandwidth and R is the right hand side vector.

STORE requires an additional work area one-half the size of the originally dimensioned matrix which is to be stored.

2. Subroutine TIME

Subroutine TIME integrates the system

\[ S_{ij} \dot{\phi}_j + SC_{ij} \ddot{\phi}_j + SM_{ij} \dddot{\phi}_j = R_j \]

by Houbolt integration.

TIME reassembles the three matrices which were stored on the magnetic disk to form the effective stiffness matrix and the effective load vector. Once this system of equations is assembled, a banded equation solver is called to yield the solution for \( \phi_j, t+\Delta t \). Figure 8 is a schematic flow chart of TIME. In Fig. 8 when \( L = 1 \), the lower triangular matrix and the diagonal of the effective stiffness matrix are formed by adding the appropriate contributions from the stiffness, mass and damping matrices. When \( L = 2 \), the upper triangular matrix is formed in like fashion.

C. CONVERGING-DIVERGING NOZZLE

1. Application of the Boundary Conditions

Regardless of the type of problem for which a set of system equations have been assembled, the equations will have the form

\[ K_{ij} x_i = R_i \]
Figure 8 - Flow Chart of Subroutine TIME
Figure 9 - Flow Chart of STANL-II Modification to Integrate Unsteady Equations
in which $K_{ij}$ is an $nxn$ matrix and $x_i$ and $R_i$ are vectors of length $n$. These equations do not take into account the known values of $x_i$ on the boundaries. However, for a unique solution of the above equation, at least one or more nodal variables must be specified and $K_{ij}$ must be modified to render it non-singular. For each equation $i$, either $x_i$ or $R_i$ must be specified but it is physically impossible to specify both $x_i$ and $R_i$. There are a number of ways to apply the boundary conditions to the equations and when they are applied the number of equations is reduced. However, it is convenient to leave the number of equations unchanged to avoid major restructuring of the computer storage. One such method is described below.

If $k$ is the subscript of the prescribed nodal variable, the $k^{th}$ row and the $k^{th}$ column of the original $K_{ij}$ matrix are set to zero, $K_{kk}$ is set to 1 and $R_k$ is replaced by the known value of $x_k$. Each of the $n-1$ remaining terms of $R_i$ is modified by subtracting from it the value $K_{ik}x_k$. This procedure is repeated for all the boundary values. Of course, when the matrix is stored in a banded mode, the algorithm will differ from that for the $nxn$ square matrix, but the procedure is similar.

Subroutine BNDRY applies the boundary conditions for the modified program. Setting the option parameter IOPT(4), in STRANL-II, equal to 1 will call BNDRY which will read the boundary velocities and apply them to a banded stored matrix by the method described above.
When the value of the $x_k$ is zero, as in the non-lifting airfoil problem, the algorithm becomes simpler than the above method because there is no need to either set the $k^{th}$ column to zero or subtract the value $K_{ik}x_k$ from the right hand vector.
X. TEST CASES

In computing the flow field for either the non-lifting airfoil or for the Laval nozzle, the following procedures were followed:

1) The desired mesh was sketched with each node assigned a number.

2) Appropriate input cards based on the sketch were prepared and supplied to STRANL-I to generate the data on punched cards for input to STRANL-II.

3) The above punched cards were supplied to STRANL-II with three additional cards as input parameters for each case, plus additional cards for the boundary velocities, if the nozzle solution is desired.

4) Results of the finite element calculations are printed after each iteration, and the converged solution is punched on cards for possible later use.

A. TIME INTEGRATION TO A STEADY STATE SOLUTION

Test cases for the integration of the unsteady transonic finite element equations were conducted to calculate the steady transonic flow over a 6% thick circular arc airfoil. These tests were made using the same airfoil, mesh, and free-stream Mach numbers as Chan et al. [Ref. 5] published. These conditions were chosen to provide a source for comparison of the results.

Freestream Mach numbers used in these calculations were:

\[ M_\infty = .806 \text{ (subcritical)} \]
\[ M_\infty = .861 \text{ (barely critical)} \]
\[ M_\infty = .909 \text{ (supercritical)} \]
Each case was treated individually with $\phi_j = 0$ used as the initial guess for each case, whereas Chan et al. [Ref. 5] used zero for the initial guess for $M_\infty = .806$ and then used the computed results as the initial guess for each subsequent case.

DELT, the value for the time step, is input by a parameter specified in columns 41-45 of the second card following the title card for each case when the unsteady option (IOPT(6) = 1) is selected.

1. **STRANL-I Program**
   a. **Input**

   Input cards used to generate the finite element mesh are listed on the next page. Cards were arranged in accordance with Ref. [5], in the following order:
   
   Title card
   Option card
   Element cards
   Card for the total number of nodes
   Node coordinate cards
   Card for the number of boundary nodes
   Card for the boundary nodes at infinity
   Card for the nodes on the line of symmetry
   Card for the nodes on the airfoil
   Cards for the slope of the airfoil.

   Input cards to STRANL-I for these tests are listed on the next three pages.

   b. **Output**

   Output from STRANL-I is in the form of printouts and punched cards. Printouts from STRANL-I are listed on the following eight pages.
## INPUT TO STRANL-I

**STEADY TRANSCOMIC FLOW--MESH 6--154 ELEMENTS, 170 NODES**

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OUTPUT FROM STRANL-1

TIME INTEGRATION SOLUTION--MESH 6--154 ELEMENTS, 170 NODES

ONO. OF ELEMENTS = 154  NO. OF NODES = 170  FULL BANDWIDTH = 84

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**Nodes at Farfield**

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61  66  71  76  81

**Nodes on Line of Symmetry**

2  3  4  5  82  83  84  85

**Nodes on the Airfoil**

66  85  93  98  104  111  118  125  132  139  146  153  159  164  168

**Slopes Along Nodes on the Airfoil**

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2. **STRANL-II Program**
   
a. **Input**
   
   Listed on the next three pages are the input cards to the STANL-II program.
   
b. **Output**
   
   The output from this program is in the form of printouts for each iteration and punched cards for the converged solution. Output from STRANL-II for $M_\infty = .909$ is listed on the following eight pages.
## INPUT TO STRANL-II

**TIME INTEGRATION SOLUTION -- CIRCULAR ARC -- 170 NODES -- M=0.909**

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**Note:** The table values are truncated for readability and may not reflect the full precision of the original data. The columns represent different values or quantities, but without a clearer context, the specific meaning is not immediately apparent. The values are likely to be related to a specific scientific or engineering computation, possibly involving numerical integration or solution of differential equations related to a circular arc. The .005, .909, and .500 suffixes suggest variations or initial conditions. The full data set would provide more context and precision for analysis.
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<td>149</td>
<td>60</td>
<td>0.26500E 00</td>
<td>0.35620E 00</td>
</tr>
<tr>
<td>150</td>
<td>59</td>
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<td>0.50830E 00</td>
</tr>
<tr>
<td>151</td>
<td>58</td>
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<td>0.67550E 00</td>
</tr>
<tr>
<td>152</td>
<td>57</td>
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<td>0.92000E 00</td>
</tr>
<tr>
<td>153</td>
<td>56</td>
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<td>0.19240E 00</td>
</tr>
<tr>
<td>154</td>
<td>55</td>
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<td>0.17400E 00</td>
</tr>
<tr>
<td>155</td>
<td>54</td>
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<td>0.21530E 00</td>
</tr>
<tr>
<td>156</td>
<td>53</td>
<td>0.26500E 00</td>
<td>0.56640E 00</td>
</tr>
<tr>
<td>157</td>
<td>52</td>
<td>0.26500E 00</td>
<td>0.75000E 00</td>
</tr>
<tr>
<td>158</td>
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<td>0.13190E 00</td>
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<tr>
<td>159</td>
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<td>0.21320E 00</td>
</tr>
<tr>
<td>160</td>
<td>49</td>
<td>0.26500E 00</td>
<td>0.33200E 00</td>
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<tr>
<td>161</td>
<td>48</td>
<td>0.26500E 00</td>
<td>0.39750E 00</td>
</tr>
<tr>
<td>162</td>
<td>47</td>
<td>0.26500E 00</td>
<td>0.55200E 00</td>
</tr>
<tr>
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<td>0.26500E 00</td>
<td>0.57200E 00</td>
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<td>0.21300E 00</td>
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<td>0.39600E 00</td>
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<tr>
<td>167</td>
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<td>0.26500E 00</td>
<td>0.10000E 00</td>
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<tr>
<td>168</td>
<td>41</td>
<td>0.26500E 00</td>
<td>0.22000E 00</td>
</tr>
<tr>
<td>169</td>
<td>40</td>
<td>0.26500E 00</td>
<td>0.22000E 00</td>
</tr>
<tr>
<td>170</td>
<td>39</td>
<td>0.26500E 00</td>
<td>0.22000E 00</td>
</tr>
<tr>
<td>NODES AT LAMINAR</td>
<td>6 11 16 21 26 31 32 36 39 42 45 48 51 55 60 61 66 71 76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>----------------------------------</td>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>NODES ON THE LINE OF SYMMETRY</td>
<td>2 3 4 5 82 83 84 85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NODES ON THE AIRfoil</td>
<td>66 89 93 58 104 111 118 125 132 139 146 153 159 164 168</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLOPE ALONG NODES ON AIRfoil</td>
<td>0.60220E+01 0.10820E+00 0.90040E-01 0.71930E-01 0.53890E-01 0.35090E-01 0.17940E-01 0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.17940E-01 -0.35090E-01 -0.53890E-01 -0.71930E-01 -0.90040E-01 -0.10820E+00 -0.60220E+01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
B. CONVERGING-DIVERGING NOZZLE

Two test cases were run for the converging-diverging nozzle. The first case was for symmetric flow designed to yield sonic conditions in the throat of the nozzle. The second case dealt with supersonic flow in the diverging section by starting with the sonic line as the boundary of the nozzle mesh. Oswatitsch's two-dimensional nozzle [Ref. 9], 

\[ y = 1 + \sqrt{2(x - 2.5)^2} \]

with a semi-throat height of 1 at \( x = 2.5 \) was used in both cases. Boundaries for the subsonic nozzle were at \( x = 0 \) and \( x = 5 \).

1. Symmetric Solution

This problem was analyzed using the mesh shown in Fig. 10, which consists of 126 elements and 152 nodes. In the second card (the option card) IOPT(4) = 1 indicates that non-zero boundary velocities at the inlet and the exit will be read and applied by subroutine BNDRY. This option requires that the number of inlet and exit boundary nodes be specified in columns 36-40 of the next card. Perturbation velocities at the boundary nodes follow on the subsequent four cards. Subroutine BNDRY reads \( u \) and \( v \) respectively for the first boundary node and then continues reading \( u \) and \( v \) for each inlet and then each exit node in the order specified on the appropriate card.

2. Supersonic Case--Diverging Section

The mesh used for this case is sketched in Fig. 11 and input cards to STRANL-II follow on the next page. For this
case the options in effect are I0PT(4) = 1 and I0PT(5) = 1 which cause non-zero boundary velocities to be applied to the sonic line only.
<table>
<thead>
<tr>
<th>113</th>
<th>114</th>
<th>115</th>
<th>116</th>
<th>117</th>
<th>118</th>
<th>119</th>
<th>120</th>
<th>121</th>
<th>122</th>
<th>123</th>
<th>124</th>
<th>125</th>
<th>126</th>
<th>127</th>
<th>128</th>
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</thead>
<tbody>
<tr>
<td>129</td>
<td>130</td>
<td>131</td>
<td>132</td>
<td>133</td>
<td>134</td>
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<td>139</td>
<td>140</td>
<td>141</td>
<td>142</td>
<td>143</td>
<td>144</td>
</tr>
</tbody>
</table>

**STEADY TRANSONIC FLOW—CONVERGING DIVERGING NOZZLE** $M = 0.4388$

<table>
<thead>
<tr>
<th>$1C$</th>
<th>$0.01$</th>
<th>$0.4388$</th>
<th>$1.0$</th>
<th>$16$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.0$</td>
<td>$0.00$</td>
<td>$-8.571E-04$</td>
<td>$3.995E-02$</td>
<td>$2.473E-02$</td>
</tr>
<tr>
<td>$1.458E-02$</td>
<td>$-1.611E-01$</td>
<td>$-3.356E-02$</td>
<td>$-2.021E-01$</td>
<td>$-3.525E-02$</td>
</tr>
<tr>
<td>$0.0$</td>
<td>$0.00$</td>
<td>$-8.571E-04$</td>
<td>$3.995E-02$</td>
<td>$2.473E-02$</td>
</tr>
</tbody>
</table>
Figure 10 - Finite Element Mesh for the Converging-Diverging Nozzle.
Figure 11 - Finite Element Mesh for the Supersonic Case
stead transonic flow analysis by finite element method

using least squares with triangular and quadrilateral elements

iopt(1)=1 use results of previous case as starting solution

while the other option is ignored

iopt(2)=1, read in non-zero initial guess

iopt(3)=1, apply linearized boundary condition on chordline

iopt(4)=1, read in non-zero boundary conditions

iopt(5)=1, sonic line velocities as inputs

the program as presently dimensioned allows these maxima

200 elements, 180 nodes, 50 nodes for each type of boundary condition

max full bandwidth = 84

developed and coded by stevens chan of lockheed-huntsville ala.

dimension title(18), iopt(20), nod(200,4), s(540,84), slp(540)

dimension work(540,42), ut(540,3), ndata(3)

cimension x(180), y(180), rm1(180), rmlp(180), ccf(180), njnt(180)

cimension nids(3), nid(3,50), vaf(50), ar(100)

cimension ub(50), ve(50)

logical lr(50)

equivalence(nids(1), nfaf), (nids(2), nwake), (nids(3), nbody)

equivalence (ndata(1), nsk), (ndata(2), nsm), (ndata(3), nsc)

cata ndata/9,13,14/

cata new,npm,ncm,na/200,180,84,50/

nrm=3*npm

nfcv=nrcn/2

cata pi/3.1415926, gamma/1.40/

ia=2*na

ccnst=0.5*(gamma-1.0)

exp=-gamma/(gamma-1.0)

read title, control keys and program parameters

cata nread,nwrite,npu/10,8,3/

100 read(nread,805, end=2000)(title(i),i=1,18)

1c1 continue

read(nread,820) (iopt(i),i=1,20)

read (nread,830) itgiv,ztest,rmac,f1,nfaf

write(nwrite,910) (title(i),i=1,18), ztest

write(nwrite,820) (iopt(i),i=1,20)

write(6,999) itgiv,ztest,rmac,f1,nfaf

995 format(110) (title(i),i=1,18), ztest

1'f1=',f8.4,5x,'nfaf=',15

ires=0

rft=1.0

scmac=rmac**2
IF (IOPT(4) .EQ. 1) READ(NREAD,840)(UB(I),VB(I),I=1,NFARF$)
IF (IOPT(4) .EQ. 1) CALL BCCND(UB,VB,IOPT(5),NFARF$)
IF (IOPT(1) .EQ. 1) GO TO 382

READ AND PRINT MESH DATA, BOUNDARY NODES, AND AIRFOIL SLOPE

READ (NREAD,825) NELS,NPS,NBW,(NICS(I),I=1,2)
READ (NREAD,825) ((NOD(I,J),J=1,4),I=1,NEL5)
READ (NREAD,840) (X(I),Y(I),I=1,NPS)
CC 110 I=1,3
NS=NIDS(I)
110 READ (NREAD,825) (NID(I,J),J=1,NS)
READ (NREAD,840) (VAF(I),I=1,NBODY)
120 READ (NREAD,825) (NJNT(I),I=1,NPS)

IF IOPT(3)=1, APPLY LINEARIZED BOUNDARY CONDITION ON CHORDLINE
OTHERWISE APPLY NONLINEAR BOUNDARY CONDITIONS ON AIRFOIL SURFACE

IF (IOPT(3) .NE. 1) GO TO 116
DO 115 J=1,NBODY
I=NID(3,J)
115 Y(I)=0.0
116 CONTINUE

WRITE (NWRITE,920) NELS,NPS,NBW
WRITE (NWRITE,930)
CC 220 N=1,NELS
WRITE (NWRITE,825) N,(NOD(N,J),J=1,4)
WRITE (NWRITE,935)
DO 230 I=1,NPS
WRITE (NWRITE,940) I, NJNT(I),X(I),Y(I)
WRITE (NWRITE,951) (NID(1,I),I=1,NFARF$)
WRITE (NWRITE,952) (NID(2,I),I=1,NWAKE)
WRITE (NWRITE,953) (NID(3,I),I=1,NBODY)
WRITE (NWRITE,955) (VAF(I),I=1,NBODY)

REDEFINE MESH DATA, ECT. USING NEW NODAL NUMBERING SYSTEM

CC 238 N=1,NELS
DO 238 I=1,4
IF (NOD(N,I) .EQ. 0) GO TO 238
KK=NOD(N,I)
NCD(N,I)=NJNT(KK)
238 CONTINUE
DO 239 I=1,3
IS=NID(4,I)
DO 239 J=1,IS
KK=NID(1,I)
NIC(I,J)=NJNT(KK)
239
CC 243 I=1,NPS
RMLP(I)=X(I)
243 RML(I)=Y(I)
DG 244 II=1,NPS
I=KJNT(II)
X(I)=RMLP(II)
244 Y(I)=RML(II)

C
HALF BANDWIDTH AND NUMBER OF EQUATIONS

C
NBW=NBW/2
NEQ=3*NPS

C
READ NONZERO INITIAL GUESS OR PROCEED WITH ZERO SOLUTION

C
IF (IOPT(2) .NE. 1) GO TO 250
READ (1,840) (S(I,NBW),I=1,NEQ)
GO TO 295
250 DG 260 I=1,NEQ
260 SLP(I)=0.0

C
ITERATIONS START HERE AND CHECKED IF ITGIV IS EXCEEDED. IF SO,
PRINT FAIL TO CONVERGE AND PROCEED TO NEXT CASE. OTHERWISE
CONTINUE TO ITERATE

C
265 IRES=IRES+1
1 CONTINUE
IF (IRES .GT. ITGIV) GO TO 600

C
FORMULATE SYSTEM OF ALGEBRAIC EQUATIONS

C
DG 266 I=1,NEQ
DG 266 J=1,NBW
266 S(I,J)=0.0
NMAT=1
CALL NEWK(SQMAC,NRM,NCM,NEQ,NBW,NEM,NELS,NOC,SLP,S,CCF,NPM,
1 X,Y,NMAT)

C
IMPOSE B.C. FOR FARFIELD, LINE OF SYMMETRY, AND ON AIRFOIL
IF (IOPT(4) .NE. 0) CALL BNDRY (S,UB,VB,VAF,NID,NFARF,NBODY,
1 NWAKE,NBW,NHBW,NEQ,IOPT,IRES)
IF (IOPT(4) .NE. 0) GO TO 276

DG 274 I=1,NFARF
IE=3*NID(1,1)-3
DG 272 II=1,3
IE=IE+1
DG 270 K=1,NBW
270 S(IE,K)=0.0
272 S(IE,NHBW)=1.0
274 CONTINUE
276 CONTINUE
DC 280 I=1,NWAKE
IE=3*NID(2,I)
DC 278 K=1,NBW
278 S(I,E,K)=0.0
28C S(I,E,NHBW)=1.0
DC 285 J=1,NBODY
IE=3*NID(3,J)
CC 282 K=1,NBW
282 S(I,E,K)=0.0
S(I,E,NHBW)=1.0
IF (IOTP(3) .NE. 1) S(I,E,NHBW-1)=VAF(J)
285 S(I,E,NBW)=VAF(J)
C
CALL BANDED SOLVER TO SOLVE THE SYSTEM OF EQUATIONS
C
STORE STIFFNESS MATRIX AND INITIALIZE STARTING TIME DEPENDENT UNKNOWNS
C
CALL STORE(S,WORK,NRM,NCM,NHCM,NFBW,NEQ,NSK)
IF (IRES .GT. 1 .OR. RMAC .GT. .91) GO TO 401
CALL BNDEQ(S,NRM,NCM,NEQ,NHBW)
DC 420 I=1,NRM
UT(I,3)=0.0
UT(I,2)=.5*S(I,NBW)
42C UT(I,1)=S(I,NBW)
GC TO 295
C
ASSEMBLE AND STORE THE DAMPING MATRIX
401 DO 400 I=1,NRM
DC 400 J=1,NCM
4C S(I,J)=0.0
AMAT=2
CALL NEWK(SQMAC,NRM,NCM,NEQ,NBW,NEM,NELS,SEC,SLP,S,CCF,NPM,
1 X,Y,NNAT)
C
ASSEMBLE AND STORE THE MASS MATRIX
CALL STORE(S,WORK,NRM,NCM,NHCM,NFBW,NEQ,NSC)
C
ASSEMBLE AND STORE THE DAMP M3A
41C S(I,J)=0.0
AMAT=3
CALL NEWK(SQMAC,NRM,NCM,NEQ,NBW,NEM,NELS,SEC,SLP,S,CCF,NPM,
1 X,Y,NNAT)
C
CALL STORE(S,WORK,NRM,NCM,NHCM,NFBW,NEQ,NSM)
C
CALL TIME(S,UT,WCRAK,NRM,NCM,NHCM,NFBW,NEQ)
C
PRINT COMPUTED RESULTS
C
255 WRITE (NWRITE,970) RMAC,RFT
WRITE (NWRITE,975) IRES
CC 305 I=1,NPS
TRA01440
TRA01450
TRA01460
TRA01470
TRA01480
TRA01490
TRA01500
TRA01510
TRA01520
TRA01530
TRA01540
TRA01550
TRA01560
TRA01570
TRA01580
TRA01590
TRA01600
TRA01610
TRA01620
TRA01630
TRA01640
TRA01650
TRA01660
TRA01670
TRA01680
TRA01690
TRA01700
TRA01710
TRA01720
TRA01730
TRA01740
TRA01750
TRA01760
TRA01770
TRA01780
TRA01790
TRA01800
TRA01810
TRA01820
TRA01830
TRA01840
TRA01850
TRA01860
TRA01870
TRA01880
TRA01890
TRA01900
TRA01910
TRA01920
WRITE (1,840) (S(I,NBW),I=1,NBQ)
GC TO 100
865 FORMAT (18A4)
870 FORMAT(40I2)
875 FORMAT(16I5)
880 FORMAT(I5,3F10.0,I5)
910 FORMAT(IH1,2X,18A4//' CONVERGENCE LIMIT=',F6.4//)
920 FORMAT(1HO,'NO. OF ELEMENTS=',I4,' NO. OF NODES=',I4,
1   ' FULL BANDWIDTH=',I4//)
930 FORMAT ('O.ELE. NO. OF ELEMENT NODES'/)
935 FORMAT ('OLD NODE', ' NEW NODE', 6X, 'X(I)', 'Y(I)'/)
940 FORMAT (I6,110,2E15.5)
950 FORMAT ('O.NODES AT FARFIELD'/2015)
955 FORMAT ('O.NODES ON THE LINE OF SYMMETRY'/2015)
960 FORMAT ('O.NODES ON THE AIRFOIL'/2015)
965 FORMAT ('O.SLOPE ALONG NODES ON AIRFOIL'/8E15.5)
970 FORMAT ('MACH NUMBER=',F6.3,'RELAX. FACTOR=',F6.4//)
975 FORMAT (1HO,'X', 'NO. OF ITERATIONS=',I4/
1   1HO,'X', 'NODE', 8X, 'PHI', 11X, 'UCM', 11X, 'VCCM',
980 FORMAT ('OFail to converge in specified no. of iterations'//)
985 FORMAT (IH1)
200 STOP
ENC
SUBROUTINE BCOND(U, V, IOPT, N)

DIMENSION U(N), V(N), UP(50), VP(50)

CATA NWRITE/6/
CO 10 I=1,N
UP(I)=1+U(I)
VP(I)=V(I)
10 CONTINUE
IF (IOPT EQ. 1) GO TO 150
WRITE(NWRITE,100)
10C FORMAT (' UCOM AT INLET')
N2=N/2
N3=N2+1
WRITE (NWRITE,110) (UP(I), I=1,N2)
WRITE (NWRITE,120)
120 FORMAT (' VCOM AT INLET')
WRITE (NWRITE,110) (VP(I), I=1,N2)
WRITE (NWRITE,130)
130 FORMAT (' UCOM AT EXIT')
WRITE (NWRITE,110) (UP(I), I=N3,N)
WRITE (NWRITE,140)
140 FORMAT (' VCOM AT EXIT')
110 FORMAT (' H1.8(F10.7,5X)
WRITE (NWRITE,110) (VP(I), I=N3,N)
CC TO 160
150 WRITE(NWRITE,121)
WRITE(NWRITE,110) (UP(I), I=1,N)
WRITE (NWRITE,122)
160 WRITE(NWRITE,110) (VP(I), I=1,N)
121 FORMAT (' UCOM AT SONIC LINE')
122 FORMAT (' VCOM AT SONIC LINE')
160 RETURN
ENC
SUBROUTINE BNDEQ

C EQUATION SOLVER FOR BANDED NON-SYMMETRIC SYSTEM OF EQUATIONS
C SOLUTION STORED IN THE LAST COLUMN AT (I,2*ITERM)
C
C DIMENSION A(NRMAX,NCMAX)
C DATA NREAD,NWRITE,NPUNCH/4,8,3/
C CERO=1.E-6
C PARE=CERO**2
C NBND=2*ITERM
C NEM=NBND-1
C
C BEGINS ELIMINATION OF THE LOWER LEFT
C
C 1000 I=1,N
C IF(ABS(A(I,ITERM)) .LT. CERO) GO TO 410
C GO TO 420
C 410 IF(ABS(A(I,ITERM)) .LT. PARE) GO TO 1600
C WRITE (6,420) A(I,ITERM), I
C 420 FORMAT (' WARNING, ILL-CONDITIONED A-MATRIX. A=',E16.6,' I=',I4)
C 430 JLAST=MIN0(I+ITERM-1,N)
C L=ITERM+1
C 431 CONTINUE
C 500 J=I,JLAST
C L=L-1
C IF(ABS(A(J,L)) .LT. PARE) GO TO 500
C B=A(J,L)
C 450 K=L,NBND
C A(J,K)=A(J,K)/B
C 500 CONTINUE
C L=0
C JFIRST=I+1
C IF(JLAST .LE. I) GO TO 1000
C 900 J= JFIRST,JLAST
C L=L+1
C IF(ABS(A(J,ITERM-L)) .LT. PARE) GO TO 900
C 600 K=ITERM,NBM
C 600 A(J,K-L) = A(J-L,K) - A(J,K-L)
C A(J,NBND) = A(J-L,NBND) - A(J,NBND)
C IF(I .GE. N-ITERM+1) GO TO 900
C 800 K=1,L
C 800 A(J,NBND-K) = -A(J,NBND-K)
C 900 CONTINUE
C 1000 CONTINUE
C BACK-SUBSTITUTION
C
120C L=ITERM -1
DO 1500 I=2,N
DO 1500 J=1,L
IF (N+1-I+J .GT. N) GO TO 1500
ATEMP1=A(N+1-I, NBND)
ATEMP2=A(N+1-I+J, NBND)
ATEMP3=A(N+1-I, ITERM+J)
A(N+1-I, NBND)=A(N+1-I, NBND)-A(N+1-I+J, NBND)*A(N+1-I, ITERM+J)
1500 CONTINUE
RETURN
C PRINT THE ENTIRE MATRIX IF ZERO CN MAIN CIACCNAL
C
1600 WRITE (6,1601)
1601 FORMAT (' COMPUTATION STOPED IN BNEQ BECAUSE ZERC APPEARED ON
1 MAIN DIAGONAL. THE MATRIX FOLLOWS.')
1602 WRITE (NWRITE,1603) (A(I,J), J=1,NBND)
16C3 FORMAT (10E12.4)
STOP
END
SUBROUTINE BNDRY

SLBR]OUTINE BNDRY(S,UB,VB,VAF,NID,NFARF,NBODY,NWAKE,NBW)
1,NFW,NEQ,IOPT,RES)
DIMENSION S(456,60),UB(50),VB(50),VAF(50),NID(3,50),IOPT(40)

C)
IF (IOPT(5) .EQ. 1 .AND. IRES .GT. 1) NFARF=NFARF/2
DC 10 I=1,NFARF
IE=3*NID(1,1)-2
DC 10 J=1,2
IE =IE+1
NX=IE-NBW
BC=UB(I)
IF (J.EQ.2) BC=VB(I)
DO 41 L=1,NBW$
LX=NX+L
IF (LX.LE.0.OR.LX.GT. NEQ) GO TO 41

40 S(LX,NBW)=S(LX,NBW)-BC*S(LX,NBW-L)
S(LX,(NBW-L))=0.

41 CONTINUE
DC 30 K=1,NBW
31 S(IE,K)=0.0
3C CONTINUE
S(IE,NBW)=1.0
1C S(IE,NBW)=BC
DC 100 I=1,NBODY
IE=3*NID(3,1)
BC=VAF(I)
NX=IE-NBW
DC 410 L=1,NBW$
LX=NX+L
IF (LX.LE.0.OR.LX.GT. NEQ) GC TO 410

40C S(LX,NBW)=S(LX,NBW)-BC*S(LX,NBW-L)
S(LX,(NBW-L))=0.0

410 CONTINUE
DC 300 K=1,NBW
30C S(IE,K)=0.0
3C S(IE,NBW)=1.0
1C S(IE,NBW)=BC
DC 200 I=1,NWAKE
IE=3*NID(2,1)
DC 330 K=1,NBW
33C S(IE,K)=0.0
2C6 S(IE,NBW)=1.
IF (IOPT(5) .EQ. 1 .AND. IRES .GT. 1) NFARF=NFARF*2
RETURN
ENC
SUBROUTINE EMTC

SUBROUTINE EMTC(A,AT,ATT,XL,YL,PEL,SQMAC)

EVALUATE ELEMENT MATRIX FOR A TRIANGLE BY GAUSSIAN QUADRATURE
SUBROUTINE DERV CALLED TO EVALUATE SHAPE FUNCTION DERIVATIVES
AT THE GAUSSIAN POINTS

DIMENSION A(9,9),P(9),Q(9),NP(5),B(3),C(3),XL(3),YL(3),S(3),
1 DNX(9),DNXX(9),DNYY(9),PEL(5),
2 DN(9),AT(9,9),ATT(9,9)

DIMENSION EINT(3,7),WT(7)
DATA LMAX/7/,WT/0.225,3*0.13293415,3*12593518/
DATA EINT/3*0.33333333,0.05961587,3*0.4714206,0.05961587,
1 3*0.79742699,3*0.10128651,0.79742699/
2 0.4714206,0.05961587,0.79742699,3*0.10128651,0.79742699/
DATA NP/1,2,3,1,2,7,GAMMA/1.40/
DATA NREAD,NWRITE,NPUNCH/4,8,3/
CC 2 I=1,9
CC 2 J=1,9
AT(I,J)=0.
ATT(I,J)=0.
2 A(I,J)=0.0
CC 4 I=1,3
J=NP(I+1)
K=NP(I+2)
E(I)=YL(J)-YL(K)
4 C(I)=XL(K)-XL(J)
AREA=0.5*(B(2)*C(3)-B(3)*C(2))
CST1=1.0-SQMAC
CST2=SQMAC*(1.0+GAMMA)
DO 10 L=1,LMAX
DO 40 I=1,3
10 S(I)=EINT(I,L)
CALL DERV(AREA,B,C,S,DN,DNX,DNXX,CNYY)
U=0.0
UX=0.0
CC 30 I=1,9
U=U+DNX(I)*PEL(I)
3C UX=XL+DNX(I)*PEL(I)
ALPHA=CST1-CST2*U
DO 40 I=1,9
P(I)=ALPHA*DNXX(I)+DNYY(I)
4C Q(I)=P(I)-CST2*UX*DNX(I)
WEIGHT=WT(L)*AREA
CC 60 I=1,9
CST=WEIGHT*Q(I)
SUBROUTINE EMQT

SLEROUTINE EMQT(XQ,YQ,PMQ,SQMAC,ET,EQ,EQT,ETT,NTRS)

C
C GENERATE MATRIX FOR A QUADRILATERAL OR TRIANGLE
C SLEROUTINE EMTC CALLED TO GENERATE MATRIX FOR A BASIC TRIANGLE
C
DIMENSION EQ(12,12),ET(9,9),XQ(4),YQ(4),XT(3),YT(3),MP(3,4)

DIMENSION PMQ(12),PMT(9),EQT(12,12),ETT(12,12),ETT(9,9),

1

CATA MP/1,2,3,3,4,1,2,3,4,4,1,2/
CATA NREAD,NWRITE,NPUNCH/4,8,37
FTCR=1.0
IF (NTRS .EQ. 4) FTR=.5
DC 100 I=1,12
CC 100 J=1,12
ECT(I,J) = 0.0
ECT(1,J) = 0.0
10C
DO 150 I=1,NTRS
CC 105 I=1,3
NI=MP(I,II)
IT=3*(I-1)
IQ=3*(II-1)
CO 102 J=1,3
IT=IT+1
IQ=IQ+1
102 PMT(IT)=PMQ(IQ)
XT(I)=XQ(NI)
105 YT(I)=YQ(NI)
CALL EMTC(ET,ETT,ETT,XT,YT,PMT,SQMAC)
DC 130 K=1,3
NR=3*(MP(K,II)-1)
IE=3*(K-1)
DC 130 KK=1,3
NR=NR+1
IE=IE+1
DC 130 L=1,3
NC=3*(MP(L,II)-1)
JE=3*(L-1)
CO 130 LL=1,3
NC=NC+1
JE=JE+1
ECT(NR,NC)=EQT(NR,NC)+ETT(IE,JE)*FTR
ETT(NR,NC)=ETT(NR,NC)+ETT(IE,JE)*FTR
130 EQ(NR,NC)=EQ(NR,NC)+ET(IE,JE)*FTCR
150 CONTINUE
SUBROUTINE DERV

SLBROUTINE DERV(AREA,B,C,S,DN,DNX,DNX,NYY)

EVALUATE SHAPE FUNCTION DERIVATIVES AT GAUSSIAN PCINT

DIMENSION B(3),C(3),S(3),DN(9),DAX(9),DNYX(5),DNYY(9),NP(5)
CATA NREAD,WRITE,NPUNCE/4,8,3/ 
TWA=2.*AREA 
TWCAS=TWOA*2 
DC 200 I=1,3 
J=NP(I+1) 
K=NP(I+2) 
SI=S(I) 
SJ=S(J) 
SK=S(K) 
BI=B(I) 
BJ=B(J) 
BF=8(K) 
CI=C(I) 
CJ=C(J) 
CK=C(K) 
SISO=SI*SI 
BISO=BI*BI 
CISO=CI*CI 
ALFA=0.5*(CK-CJ) 
BETA=0.5*(BJ-BK) 
F=SI*SJ*SK 
FXX=2.*{SI*BK*SK+BI*SI+BK*SI*SK} 
FYY=2.*{SI*CJ*CK+SI*CK*BK*BI+SI*SK*BJ} 
CSS=6.*SI*(1.0-SI) 
CS=6.*(1.0-2.0*SI) 
L=3*I-2 
DN(L)=SI*SI*(3-2*SI)+2*H 
DNX(L)=BI*CSS+2.*HX 
DNYX(L)=BISO*CJ+2.*HXX 
DNYY(L)=CISO*CJ+2.*HYY 
CS=CK*SJ-CJ*SK 
L=L+1 
DN(L)=SISO*CJ+ALPHA*H 
DNX(L)=2.*BI*SI*CS+TWOA*SISO+ALFA*HX 
DNYX(L)=2.*BISO*CS+4.*BI*TWOA*SI+ALFA*HXX 
DNYY(L)=2.*CISO*CS+ALFA*HYY 
ES=BJ*SK-BK*SI 
L=L+1
DN(L) = SISQ*BS+BETA*H
CXX(L) = 2.*BI*SI*BS+BETA*HX
CXXX(L) = 2.*BISQ*BS+BETA*HXX
200 DNYY(L) = 2.*CISQ*BS+4.*C1*TWOA*SI+BETA*HYY
CC 300  I=1,9
CXX(I) = DNX(I)/TWOA
CXXX(I) = DNXX(I)/TWOASQ
30C DNYY(I) = DNYY(I)/TWOASQ
RETURN
END
SUBROUTINE NEWK

SUBROUTINE NEWK(SQMAC,NRM,NCM,NEQ,NBW,NEM,NELS,NOD,SLP,S,
1 COEF,NPM,X,Y,NMAT)

GENERATE SYSTEM MATRIX BY ASSEMBLING CONTRIBUTIONS FROM
ALL THE ELEMENTS
SUBROUTINE EMQ7 CALLED TO GENERATE ELEMENT MATRIX

DIMENSION COEF(NPM),X(NPM),Y(NPM),XQ(4),YQ(4),PM(12),BB(12,12)
DIMENSION BBC(12,12),BBM(12,12)
DIMENSION NOD(NEM,4),S(NRM,NCM),SLP(NRM)
DATA NREAD,NWRITE,NPUNCH/4,8,3/
NFWB=NBW/2
CC 480 N=1,NELS
II=1
IF (NOD(N,4)) 402,402,404

402 NPFL=3
NTRS=1
GO TO 410
404 NPFL=4
NTRS=4
II=0
CC 408 I=1,4
N=NOD(N,1)
C2 IF (COEF(NI) .GT. 1.00) II=I2+1
C3 IF(I2 .EQ. 0) NTRS=2
C4 IF(I2 .EQ. 4) II=3
C5 DO 425 I=1,NPEL
N=NOD(N,1)
XC(I)=X(NI)
YC(I)=Y(NI)
DC 425 J=1,3
IS=3*(NI-1)+J
IE=3*(I-1)+J
P1M(IE)=SLP(IS)
CALL EMQ7(XQ,YQ,PM,SQMAC,BB,BBC,BBM,NTR4)
DO 450 I=I1,NPEL
N=3*(NOD(N,1)-1)
I2=3*(I-1)
DC 450 II=I1,3
N=NR+1
IF=IE+1
DC 450 J=1,NPEL
NC=3*(NOD(N,J)-1)-NR+NHBW
JE=3*(J-1)
CC 450 JJ=1,3

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TRA000360
TRA000370
TRA000380
TRA000390
TRA000400
TRA000410
TRA000420
TRA000430
TRA000440
TRA000450
NC = NC + 1
JE = JE + 1
IF (NMAT = 2) 443, 442, 441
  S(NR, NC) = S(NR, NC) + BBM(IE, JE)
  GO TO 450
442  S(NR, NC) = S(NR, NC) + BBC(IE, JE)
  GO TO 450
443  S(NR, NC) = S(NR, NC) + BB(IE, JE)
450  CONTINUE
480  CONTINUE
RETURN
ENC
SUBROUTINE STORE

SUBROUTINE STORE (S, WCRK, NRM, NCM, NHC, NHBW, NEQ, NDATA)
DIMENSION S(NRM, NCM), WORK(NRM, NHC)

REWIND NDATA
CC 10 I = 1, NRM
CC 10 J = 1, NHC
10 WCRK(I, J) = 0.0
CC 20 I = 1, NEQ
CC 20 J = 1, NHBW
20 WCRK(I, J) = S(I, J)
WRITE (NDATA) WORK
CC 30 I = 1, NEQ
CC 30 J = 1, NHBW
JA = NHBW + J
30 WCRK(I, J) = S(I, JA)
WRITE (NDATA) WORK
REWIND NDATA
RETURN
END
SUBROUTINE TIME(S, U, WORK, NRM, NCM, N-FCM, NHBW, NEQ)
C HCBULT INTEGRATION FOR UNSTEADY PROBLEMS
C
DIMENSION S(NRM, NCM), WORK(NRM, NHBW), U(NRM, 3), NDATA(3)
CATA NDATA/9, 13, 14/
CATA DELT/100./
NHBW=2*NHBW
NHBW1=NHBW-1
AC=2./DELT**2
A1=11./(6*DELT)
A2=5./DELT**2
A3=3./DELT
A4=-2.*A0
A5=-A3/2.
A6=A0/2.
CC 100 I=1,NRM
DO 100 J=1, NCM
S(I,J)=0.0
C
FCRM LOWER TRIANGULAR PLUS DIAGONAL EFFECTIVE MATRIX
C
DO 25 K=1, 3
NDATA$=NDATA(K)
READ (NCATA$) WORK
IF (K-2)1, 2, 3
1 CCNST=1
GC TO 4
2 CCNST=A0
GC TO 4
3 CCNST=A1
4 DO 10 J=1, NHBW
CC 10 I=1, NEQ
S(I,J)=WORK(I,J)*CONST+S(I,J)
C
MULTIPLY CONTRIBUTING MATRICES BY THE TIME DEPENDENT
C VECTORS TO FORM RIGHT HAND SIDE
DO 20 J=1, NHBW
JM=NHBW+1-J
IM=0
CC 20 I=JM, NEQ
IN=IM+1
IF (K-2) 11, 12, 13
11 UN=0.
GC TO 20
12 UN=A2*U(IM, 1)+A4*U(IM, 2)+A6*U(IM, 3)
GC TO 20
13 UM=A3*U(IM,1)+A5*U(IM,2)+A7*U(IM,3)
20 S(IM,NBW)=S(IM,NBW)+WORK(I,J)*UM
25 CONTINUE

C FCMAT UPPER TRIANGULAR EFFECTIVE MATRIX
CG 45 K=1,3
NCATA$=NDATA(K)
READ(NCATA$) WORK
IF(K-2) 21,22,23
21 CCNST=1
GO TO 24
22 CCNST=AA
GO TO 24
23 CCNST=A1
24 DO 30 J=1,NHBW
DO 30 I=1,NEQ
JA=J+NHBW
30 S(I,JA)=S(I,JA)+WORK(I,J)*CONST
MAXJ=NHBW-1
CC 40 J=1,MAXJ
JA=NHBW+J
MAXI=NEQ-J
IM=J
DC 40 I=1,MAXI
IM=IM+1
IF (K-2) 31,32,33
31 UM=0
CC TO 40
32 UM=A2*U(IM,1)+A4*U(IM,2)+A6*U(IM,3)
CC TO 40
33 UM=A3*U(IM,1)+A5*U(IM,2)+A7*U(IM,3)
40 S(IM,NBW)=S(IM,NBW)+WORK(I,J)*UM
45 CONTINUE
843 FCMAT(1H ,4(F10.5,5X))
CALL BNDEQ(S,NRM,NCM,NEQ,NHBW)
CC 50 I=1,NRM
L(I,3)=U(I,2)
U(I,2)=U(I,1)
50 U(I,1)=S(I,NBW)
8CC FORMAT(1H ,6(F10.5,2X))
RETURN
END
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