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Finite Area Method for Nonlinear Supersonic Conical Flows*

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Abstract

A fully conservative numerical method for the computation of steady inviscid supersonic flow about general conical bodies at incidence is described. The procedure utilizes the potential approximation and implements a body conforming mesh generator. The conical potential is assumed to have its best linear variation inside each mesh cell; a secondary interlocking cell system is used to establish the flux balance required to conserve mass. In the supersonic regions the scheme is desymmetrized by adding artificial viscosity in conservation form. The algorithm is nearly an order of a magnitude faster than present Euler methods and predicts known results accurately and qualitative features such as nodal point lift off correctly. Results are compared with those of other investigators.

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Introduction

Conical flows are one of the simplest type of inviscid flows that have the basic features of a three-dimensional flow. A flow field is classified as conical when all the physical properties, viz., the pressure, density, velocity, and entropy, remain constant along every straight line through a given point called the apex. Conical flows occur for example, around finite cones in supersonic flows because of the law of forbidden signals. The topological features of conical flows can be easily understood by studying the cross-flow streamlines; that is the traces of the conical stream surface's intersection with a sphere as sketched in Figure 1. The cross-flow streamlines will have critical points where the cross-flow velocities vanish. For a special class of critical points one can derive rules for the number of these points using Poincare indices. Thus, for example, irrotational conical flows must have an equal number of saddle points and nodes. At a nodal point the entropy, density and radial velocity are multivalued. At high angles of attack conical streamline patterns exhibit certain global changes such as the lift-off of the leeward node and, perhaps, the appearance of spiral nodes. In addition, the cross flow may become supersonic as it expands about the leading edge, leading to an embedded supersonic cross-flow region terminated by a shock wave (see Figure 1). It is interesting to note that the perturbation of shock free flows to see if neighboring solutions exist in the classical sense of Morawetz² remains to be studied for conical flows.

The isentropic assumption retains all of the topological features of these flows except spiral nodes and should provide an adequate approximation to the quantitative flow features if the Mach number normal to any shock is less than about 1.4. This approximation greatly

simplifies the computations because the governing equation is scalar and the possibility of multiple values at a nodal point (the vortical singularity) is eliminated.

First major success in computing nonlinear irrotational conical flows was reported by Grossman³, who devised a quasilinear finite difference method to this problem. An alternative approach is to extend Jameson's⁴ finite difference algorithm for transonic full potential equation in the euclidean three space as a marching scheme to treat supersonic potential flows. This extension has been developed by Shankar⁵ using Steger's⁶ density linearisation technique.

In this paper the theory of irrotational conical flows is described in a general coordinate system defined on a unit sphere. A finite area method is described that represents an extension of the conventional finite volume methods^{7,8} to vector fields defined on a curved surface. It is then used to compute various conical flow fields studied by other investigators^{3,9,10}. Similarity between the highest-order terms of the partial differential equation describing conical flows and that describing plane transonic flows has been exploited to devise a suitable artificial viscosity to implement the (mathematical) entropy condition¹¹ as well as to construct a stable iteration scheme.

Cross-flow velocity field

It is essential in the application of the finite area method to frame the equations in an invariant coordinate system. We have done this by first projecting the Euler equations for a general three-dimensional flow onto a sphere of radius r , and then scaling them to obtain the description on the unit sphere. We first note that the main stream velocity components, Q^i , and their projection on the sphere of radius r , V^α , are related by

$$\tilde{V}^\alpha = B_i^\alpha Q^i$$

where

$$B_\alpha^i = \frac{\partial X^i}{\partial \Xi^\alpha}, \quad \alpha = 1, 2 \text{ and } i = 1, 2, 3$$

are the projection factors¹² (or the tangents). Here the X^i are coordinates in Euclidian 3-space and the Ξ^α are parametric coordinates

on the surface of a sphere. We could also decompose the mainstream velocity as

$$Q^i = B_\alpha^i \tilde{V}^\alpha + Q_R N^i$$

where Q_R is the radial velocity and N^i the normal to the spherical surface.

Now, with the conical assumption in mind, we introduce a radial scaling to reduce the variables to those on a unit sphere, viz.,

$$V^\alpha = r \tilde{V}^\alpha, \quad V_\alpha = \frac{\tilde{V}_\alpha}{r}$$

such that the magnitude of the scaled cross-flow velocity $V^\alpha V_\alpha = \tilde{V}^\alpha \tilde{V}_\alpha = q_c^2$ is independent of r . The total velocity is thus

$$Q^i Q_i = Q^2 = q_c^2 + Q_R^2$$

Once the coordinates Ξ^α , the metric $g_{\alpha\beta}$, and the velocity vector V^α , are defined on a portion of the surface of the unit sphere, we may use elementary results from Riemann geometry to develop the governing equations. For potential flow we need to use only the continuity and the energy equations.

The continuity equation for the general three-dimensional inviscid flow is

$$\frac{\partial \rho / G}{\partial X^i} Q^i = 0$$

where \sqrt{g} is determinant of the metric tensor of the space X^i , and ρ the gas density. For conical flows this implies that on a unit sphere

$$\frac{\partial \rho \sqrt{g} V^\alpha}{\partial \Xi^\alpha} + 2 \rho \sqrt{g} Q_R = 0$$

Here \sqrt{g} is the determinant of the metric tensor of the parametric space Ξ^α on the surface of unit sphere.¹³ If the irrotational assumption is made, the velocity Q^i will have a potential $\phi(X^i)$ such that for conical flows

$$\phi(X^i) = r F(\Xi^\alpha)$$

where $F(\Xi^\alpha)$ may be called the conical velocity potential since

$$V_\alpha = \frac{\partial F}{\partial \Xi^\alpha}, \quad Q_R = F(\Xi^\alpha)$$

We also have the energy equation

$$\rho^{\gamma-1} = 1 + \frac{\gamma-1}{2} M_\infty^2 (1-Q^2), \quad (1)$$

where

$$Q^2 = V^\alpha V_\alpha + F^2$$

and M_∞ is the freestream Mach number. Thus, we must solve the equation

$$\frac{\partial \rho \sqrt{g} V^\alpha}{\partial \Xi^\alpha} + 2 \rho \sqrt{g} F = 0 \quad (2)$$

where

$$V^\alpha = g^{\alpha\beta} \frac{\partial F}{\partial \Xi^\beta} \quad (3)$$

and the density is given by the energy equation (1).

Substituting (1) and (3) into (2) and performing the differentiation, we find the quasilinear form of the governing partial differential equation:

$$\rho \sqrt{g} \left[\left(g^{\alpha\beta} - \frac{v^\alpha v^\beta}{a^2} \right) v_{\alpha||\beta} + \left(2 - \frac{q_c^2}{a^2} \right) F \right] = 0 \quad (4)$$

where "||" means surface covariant differentiation¹² and, a, the sound speed and is given by,

$$a^2 M_\infty^2 = \rho^{\gamma-1} \quad (5)$$

Equation (4) changes its type when

$$\left(g^{12} - \frac{uv}{a^2} \right)^2 - \left(g^{11} - \frac{u^2}{a^2} \right) \left(g^{22} - \frac{v^2}{a^2} \right) = 0$$

or, noting $g > 0$ always, when

$$\frac{1}{g} \left[\frac{q_c^2}{a^2} - 1 \right] = 0$$

Here we use the notation

$$v^\alpha = \begin{pmatrix} u \\ v \end{pmatrix}, \quad v_\alpha = \begin{pmatrix} u \\ v \end{pmatrix} \quad \text{and} \quad \Xi^\alpha = \begin{pmatrix} \xi \\ \eta \end{pmatrix}$$

Thus, the equation is hyperbolic, parabolic, or elliptic depending on whether the cross-flow Mach number M_c is the greater, equal, or less

than one. We could also derive this result by choosing a local coordinate system aligned with the cross-flow streamlines.

If we define streamwise and normal coordinates s, n such that

$$V_{\alpha} \frac{\partial \Xi^{\alpha}}{\partial n} = 0 \text{ and } \epsilon_{\alpha\beta} V^{\alpha} \frac{\partial \Xi^{\beta}}{\partial s} = 0,$$

with

$$g_{\alpha\beta} \frac{\partial \Xi^{\alpha}}{\partial s} \frac{\partial \Xi^{\beta}}{\partial s} = g_{\alpha\beta} \frac{\partial \Xi^{\alpha}}{\partial n} \frac{\partial \Xi^{\beta}}{\partial n} = 1$$

Here $\epsilon_{\alpha\beta}$ is the surface permutation symbol¹². Then we find

$$\frac{\partial \Xi^{\alpha}}{\partial s} = \frac{V^{\alpha}}{q_c}, \quad \frac{\partial \Xi}{\partial n} = -\frac{1}{\sqrt{g}} \frac{v}{q_c} \text{ and } \frac{\partial \eta}{\partial n} = \frac{1}{\sqrt{g}} \frac{u}{q_c}$$

Note also that in these coordinates

$$\frac{\partial F}{\partial s} = \frac{\partial F}{\partial \Xi^{\alpha}} \frac{\partial \Xi^{\alpha}}{\partial s} = q_c = \frac{V^{\alpha} V^{\alpha}}{q_c}$$

and

$$\frac{\partial F}{\partial n} = \frac{\partial F}{\partial \Xi} \left(-\frac{1}{\sqrt{g}} \frac{v}{q_c} \right) + \frac{\partial F}{\partial \eta} \left(\frac{1}{\sqrt{g}} \frac{u}{q_c} \right) = 0$$

Similarly, we also obtain the relations

$$\frac{\partial^2 F}{\partial s^2} = \frac{V^{\alpha} V^{\beta}}{q_c^2} \frac{\partial^2 F}{\partial \Xi^{\alpha} \partial \Xi^{\beta}} + \dots$$

and

$$\frac{\partial^2 F}{\partial n^2} = \left(g^{\alpha\beta} - \frac{V^{\alpha} V^{\beta}}{q_c^2} \right) \frac{\partial^2 F}{\partial \Xi^{\alpha} \partial \Xi^{\beta}} + \dots$$

Using these relations we may write the governing partial differential equation as

$$- \frac{\rho \sqrt{g}}{a^2} \left[(q_c^2 - a^2) \frac{\partial^2 F}{\partial s^2} - a^2 \frac{\partial^2 F}{\partial n^2} \right] + \dots = 0$$

We also note the following structure of these equation: Replacing the expression for $\partial^2 F / \partial s^2$ we obtain

$$- \frac{\rho \sqrt{g}}{a^2} \left[\mu V^\alpha V^\beta \frac{\partial^2 F}{\partial \xi^\alpha \partial \xi^\beta} - a^2 \frac{\partial^2 F}{\partial n^2} \right] + \dots = 0$$

where

$$\mu = \left(1 - \frac{a^2}{q_c^2} \right)$$

Now if we define two functions \tilde{P} , \tilde{Q} such that

$$\tilde{P} = \mu \rho \frac{\sqrt{g}}{a^2} \left(U^2 \frac{\partial^2 F}{\partial \xi^2} + UV \frac{\partial^2 F}{\partial \xi \partial \eta} \right)$$

and

$$\tilde{Q} = \mu \rho \frac{\sqrt{g}}{a^2} \left(UV \frac{\partial^2 F}{\partial \xi \partial \eta} + V^2 \frac{\partial^2 F}{\partial \eta^2} \right)$$

then the partial differential equation becomes

$$-(\tilde{P} + \tilde{Q}) + \rho \sqrt{g} \frac{\partial^2 F}{\partial n^2} + \dots = 0$$

This form is useful for explaining the introduction of a conservative artificial viscosity.

Finally, we note that the governing equation is of quasilinear type and hence, that it admits shock jumps. The jump condition that conserves mass follows immediately from the Eq. (2):

$$\left(\frac{d\eta}{d\xi}\right)_{\text{shock}} = \frac{\|\rho V\|}{\|\rho U\|}$$

This is obviously the jump condition that would be desired from the mainstream continuity equation with the conical assumption.

Finite area method

Jameson's finite volume method for the potential equation⁸ may be extended to a vector field defined on a non-Euclidian space as long as we have a similar partial differential equation. In this section we develop the finite area method on the unit sphere. It should be emphasized that the derivation would be the same for a vector field on a general curved surface. We assume that on this curved surface a smooth grid is provided, as sketched in Figure 2, with the surface coordinates (latitude θ , longitude ψ) provided for each nodal point:

$$\theta^\alpha = \begin{pmatrix} \theta \\ \psi \end{pmatrix}$$

We call these primary cells. In order to implement the finite area method the primary cells are mapped to a unit square using a local bilinear transformation in the parametric space such that

$$\theta = \sum_{i=1}^4 S^i_\theta \theta^i \quad \text{and} \quad \psi = \sum_{i=1}^4 S^i_\psi \theta^i$$

Here i denotes the nodal values and

$$S^i = 4\left(\frac{1}{4} + \xi^i \xi\right)\left(\frac{1}{4} + \eta^i \eta\right)$$

The geometrical quantities are calculated in the following manner. The first fundamental form in the spherical coordinate system θ^α is $ds^2 = \sin^2\psi d\theta^2 + d\psi^2$, or

$$\bar{g}_{\alpha\beta} = \begin{bmatrix} \sin^2\psi & 0 \\ 0 & 1 \end{bmatrix} \quad (6)$$

and

$$\sqrt{\bar{g}} = \sin \psi \quad (7)$$

In a mapped coordinate system Ξ^α , with $ds^2 = g_{\alpha\beta} d\Xi^\alpha d\Xi^\beta$, then

$$g_{\alpha\beta} = \bar{g}_{\lambda\mu} \frac{\partial\theta^\lambda}{\partial\Xi^\alpha} \frac{\partial\theta^\mu}{\partial\Xi^\beta} \quad (8)$$

and

$$\sqrt{g} = \sqrt{\bar{g}} J$$

Here J is the Jacobian of the parametric transformation $\theta^\alpha (\Xi^\beta)$, that is

$$\sqrt{g} = \sin \psi (\theta_{\xi} \psi_{\eta} - \theta_{\eta} \psi_{\xi}) \quad (9)$$

We always calculate the geometric quantities at the center of the cells and therefore the bilinear transformation and its best linear substitute have the same role¹⁴. Thus we take

$$S^i = S_b^i = \frac{1}{4} + \xi^i \xi + \eta^i \eta$$

and thus

$$\theta_\xi = \sum_{i=1}^4 \theta_\xi^i, \text{ etc.}$$

and at the center of the cell

$$\theta = \frac{1}{4} \sum_{i=1}^4 \theta^i, \text{ etc.} \quad (10)$$

Equations (6) - (10) define geometric quantities at the center of primary cells. The flow quantities are also defined at the center of the cells. The potential is of course defined only at the nodal points. The flow quantities may be calculated as follows: Let f be the disturbance to the freestream potential f_∞ due to the body, i.e., $F = f_\infty + f$. Then we assume the disturbed potential also to have the bilinear form

$$f = \sum_{i=1}^4 S^i f^i$$

Because lumping is not used in the present formulation (it was not found to be necessary), we may replace S^i by S_b^i .

Thus,

$$f = \sum_{i=1}^4 S_b^i f^i$$

and
$$f_{\xi} = \sum_{i=1}^4 \xi^i f^i, \text{ etc.}$$

The total velocity is computed from

$$v^{\alpha} = g^{\alpha\beta} \left[\frac{\partial f_{\infty}}{\partial \Xi^{\beta}} + \frac{\partial f}{\partial \Xi^{\beta}} \right]$$

and

$$f_{\infty} = \cos \hat{\alpha} \cos \phi + \sin \theta \sin \phi \sin \hat{\alpha},$$

where $\hat{\alpha}$ is the angle of attack.

We are now ready to implement the finite area method. We first introduce a secondary interlocking cell structure as shown in Figure 3 in order to integrate the mass continuity equations. We now integrate the weak conservation law over the domain Ω so that

$$\int_{\Omega} \frac{1}{\sqrt{g}} \frac{\partial \rho \sqrt{g} v^{\alpha}}{\partial \Xi^{\alpha}} \sqrt{g} d\xi d\eta + \int_{\Omega} 2\rho F \sqrt{g} d\xi d\eta = 0$$

Applying the surface divergence theorem to the first term, we find

$$\int_c \rho \sqrt{g} v^{\alpha} n_{\alpha} dS + \int_{\Omega} 2\rho F \sqrt{g} d\xi d\eta = 0$$

Here n_{α} is tangent to the surface and normal to the curve c . This relation is valid for any arbitrary Ω and therefore also valid locally for a flux cell. Since the flux cell faces are parallel to coordinate lines in the mapped plane, and using one point evaluation for each integral, we obtain

$$\delta[\rho U \sqrt{g}] + \delta[\rho V \sqrt{g}] + (2\rho F \sqrt{g})_0 = 0$$

for each cell, where $\delta[\dots]$ denotes the net flux change across the cell and $(\dots)_0$ the average over the cell. We also need to define the flux quantities at points A,B,C and D of the flux cell faces. In this formulation we simply use a box scheme to evaluate these terms. Thus we obtain the approximation to Equation (2) as

$$\mu_\eta \delta_\xi (\rho \sqrt{gU}) + \mu_\xi \delta_\eta (\rho \sqrt{gV}) + \mu_\xi \mu_\eta (2\rho \sqrt{gF}) = 0.$$

where μ and δ are respectively the averaging and central difference operations.

Boundary conditions

We consider the computational domain in Figure 4. The outer boundary C_0 is taken well outside the bow shock wave. Boundaries C_1 and C_2 are symmetry planes and C_b is the cone body where the normal velocity vanishes.

Outerboundary

At the outer boundary all the disturbance vanish, i.e., f , f_ξ , f_η are all zero. This is implemented in the following way, if N_2 grids are the rings, then

$$f(I, N_2) = f(I, N_2 + 2) \quad \text{and} \quad f(I, N_2 + 1) = 0$$

Symmetry plane

At the symmetry plane we introduce an additional grid line and explicitly set the reduced potential to be the same on both grid lines. Thus, if N_1 grids are in the circumferential direction, then

$$f(1, J) = f(3, J) \quad \text{and} \quad f(N_1 - 1, J) = f(N_1 + 1, J)$$

Cone surface

On the body surface the normal velocity should be zero. If $\mathcal{B}(\Xi^\alpha)$ is the cone surface, then $U^i \partial \mathcal{B} / \partial X^i = 0$ implies $V^\alpha \partial \mathcal{B} / \partial \Xi^\alpha = 0$ since the body is a cone. If the body coincides with a coordinate surface, ξ for example, then $\mathcal{B}(\Xi^\alpha) = \eta = 0$ and the boundary condition implies $V = 0$, i.e., the contravariant cross-flow component that does not lie on the body must vanish. This is implemented by considering a half flux cell about the cone and using flux reflection.

Artificial viscosity

In order to stabilize the scheme in the supersonic regions we desymmetrize the scheme by upwind differencing the contribution for the F_{ss} term. Also, since the higher-order terms of the partial differential equation for conical flows are similar to that of plane transonic flows, if we do the upwind differencing with first-order accuracy (at least near the shocks), then the resulting truncation errors will look like the viscous term for plane flows and therefore may be expected to capture any shock waves and insure the entropy condition. The viscosity should be introduced in the conservation form and this can be accomplished in the following manner. Let us consider the case when $V^\alpha > 0$. We noticed earlier that the terms contributing the F_{ss} term have a structure containing $-(\tilde{P} + \tilde{Q})$ and therefore will effectively be evaluated as $-\tilde{P}_{i,j} - \tilde{Q}_{i,j}$ in the finite area scheme. To upwind we need to replace

them by $-\tilde{p}_{i-1,j} - \tilde{Q}_{i,j-1}$ and this means we need to add a viscosity term τ_{ij} , such that $\tau_{ij} = (\tilde{p}_{i,j} - \tilde{p}_{i-1,j}) + (\tilde{Q}_{i,j} - \tilde{Q}_{i,j-1})$, to the residual R_{ij} . We use the switching function

$$\mu = \begin{cases} (1 - \frac{a^2}{q_c^2}) & \text{in the supersonic zones} \\ 0 & \text{in the subsonic zones} \end{cases}$$

The method has to be appropriately modified for the other directions of contravariant velocity.

Iteration scheme

The nonlinear algebraic equations resulting from the finite area method are solved using a "constructed" line relaxation scheme. This means that we assume that the problem is being solved by Jameson's rotated difference scheme in the quasilinear form along with Jameson's special relaxation method⁹. Here we assume that the iteration process is equivalent to a problem of evolution in an artificial time and choose the explicit time dependent terms such that the problem is well posed. We do have certain restrictions on the direction of the sweep. We should not sweep against the flow inside the supersonic zone. At high angle of attack this condition is difficult to maintain with a ring relaxation inward from the bow shock wave. Thus the suitable line relaxations are either a circumferential sweep or a combination of the two (see Figure 4). One should note that the restrictions on the sweep direction can be easily removed by devising an approximate factorization scheme¹⁶. We use line relaxation mainly to test the finite area formulation. It was found that a circumferential relaxation from windward to leeward is the best in most of the cases and is this scheme described here. Assume that $V^\alpha > 0$ and consider the line relaxation scheme.

scheme

$$\begin{aligned} A_1 C_{ij} + A_2 (C_{ij} - C_{i-1,j}) + A_3 (C_{ij} - C_{i,j-1}) + A_4 (C_{ij} - C_{i,j+1}) \\ = R_{ij} + T_{ij} + A_5 (C_{i-1,j-1} - C_{i-1,j+1}) \end{aligned}$$

If we now consider that $R_{ij} + T_{ij}$ are equivalent to their quasilinear finite difference equivalent multiplied by ρ/g , then, construction of the Jameson iterative scheme will give the following values for

A_1, \dots, A_5 :

$$A_1 = \begin{array}{ll} \rho/g(g^{11} - \frac{U^2}{a^2})(\frac{2}{\omega} - 1) & \text{subsonic} \\ 0 & \text{supersonic} \end{array}$$

where ω is the over-relaxation factor,

$$A_2 = \rho/g(g^{11} - \frac{U^2}{a^2} + 3\mu \frac{U^2}{a^2} + 2\mu \frac{UV}{a^2})$$

$$A_3 = \rho/g(g^{22} - \frac{V^2}{a^2} + 3\mu \frac{V^2}{a^2} + 2\mu \frac{UV}{a^2})$$

$$A_4 = \rho/g(g^{22} - \frac{V^2}{a^2} + \mu \frac{V^2}{a^2})$$

and

$$A_5 = \frac{1}{2} \rho/g(g^{12} - \frac{UV}{a^2} + \mu \frac{UV}{a^2})$$

where μ is the switching function. We note here that in subsonic flow, provided $\omega < 2$, all the coefficients A_1, \dots, A_4 are positive. Thus the scheme is linearly stable. We obtain further insight by looking at its equivalent time dependent form for each flow type:

Subsonic zone

$$\Delta t \left[(g^{11} - \frac{U^2}{a^2}) (\frac{2}{\omega} - 1) F_t - \frac{v}{\sqrt{g} q_c} F_{nt} + \frac{U}{q_c} (1 - M_c^2) F_{st} \right] = (1 - M_c^2) F_{ss} + F_{nn} + \dots$$

Supersonic zone

$$\Delta t \left[- \frac{v}{\sqrt{g} q_c} F_{nt} - \frac{2(U + V)}{q_c} (1 - M_c^2) F_{st} \right] = (1 - M_c^2) F_{ss} + F_{nn} + \dots$$

In the supersonic zone we apply the condition,

$$\left[\frac{U + V}{q_c} (M_c^2 - 1) \right]^2 > \left[\frac{1}{2} \frac{v}{\sqrt{g} q_c} \right]^2 (M_c^2 - 1)$$

to ensure that s is time-like in the unsteady problem as well. This means that

$$4 \left(\frac{U + V}{v} \right)^2 g (M_c^2 - 1) > 1$$

To ensure that the above condition is always satisfied, especially near the sonic line, we further augment the first term by adding $\epsilon (U + V) F_{st} / q_c$ where ϵ is as small as possible and yet sufficient to ensure stability. The term F_{st} has to be represented by an upwind difference, we write this as

$$\epsilon \left(\frac{U + V}{q_c} \right) \left[\frac{U}{q_c} (C_{ij} - C_{i-1,j}) + \frac{V}{q_c} (C_{ij} - C_{i,j-1}) \right]$$

This scheme must be appropriately modified when V changes sign.

Grid generation on a curved surface

Suppose we are interested in generating grids for a simply-connected region on a curved surface. We could use the following simple method: First we note that the first fundamental form is in the θ^α coordinate system is

$$ds^2 = g_{\alpha\beta} d\theta^\alpha d\theta^\beta$$

We first transform to a new coordinate system ξ^α such that

$$ds^2 = \lambda^2 (d\zeta^2 + d\eta^2)$$

where $\lambda = \lambda(\zeta, \eta)$

This coordinate system is called the isothermal coordinate system¹⁷ and this transform maps the surface portion conformally to a plane. Then we define a complex variable z such that

$$z = \xi + i\eta$$

and apply further conformal transformations to obtain a simple domain where we may generate the desired grids. Alternately, one could derive a numerical grid generation method for the isothermal coordinates. In the present problem we used the grid generation procedure that is commonly used in supersonic computations, that is, we obtain the isothermal coordinates for a unit sphere using stereographic projection and then use a Joukowski transformation followed by a simple shearing to obtain a suitable grid network.

Results and discussion

Computations were made to demonstrate that the method predicts qualitative features of simple flows correctly and their quantitative aspects accurately. All the calculations were performed on three mesh levels starting with a 16×16 grid system. On this initial grid 150 iterations were performed and this was followed by 100 iterations at the 32×32 level and at the final level. Convergence for the last two grids is reliable after 25 to 50 iterations, depending principally on whether or not there is a body shock wave. Calculations were performed with uniform grids without any clustering; a typical grid is shown in Figure 5. The results for a circular cone of 10° half angle at 10° angle of attack in a freestream of Mach 2, are shown in Figures 6a and 6b. While the results shown are for a 64×64 grid, excellent agreement for the pressure coefficient on the body and the bow shock positions was obtained using the 16×16 grid and this required fewer than 70 iterations. This coarse grid only requires few seconds of CDC 7600 CPU time. The pressure distribution in the field is shown in Figure 7 for three circumferential angles. Excellent agreement with the Euler computations of D.J. Jones⁹ is again demonstrated. An example of lift off is given in Figure 8, where the streamline patterns for the 10° angle of attack case are compared with those for an angle of attack of 20° .

Results for two thin elliptic cones are shown in Figures 9 and 10. One ellipse has a major to minor axis ratio of approximately 6:1 and the other has a ratio 13:1. In the first case a comparison with the Euler equation calculations of Siclari¹⁰ is made. The agreement is generally excellent except for the extra leading edge suction which may be due in

part to the potential approximation, and except for the post shock pressure. We note here that the Euler result does not show the expected shock foot singularity* captured by our potential calculations. The second example compares the Euler equation results of Siclari, the non-conservative potential finite difference results of Grossman³ and our results. Here all three methods capture to some extent, the shock foot singularity. The finite area method agrees well with the Euler results. The difference in the shock position between the conservative and nonconservative method is to be noted. The total computation time for a case with body shock wave is about 40 seconds of CDC 7600 CPU time.

*The pressure gradient immediately behind the shock must be logarithmically infinite.

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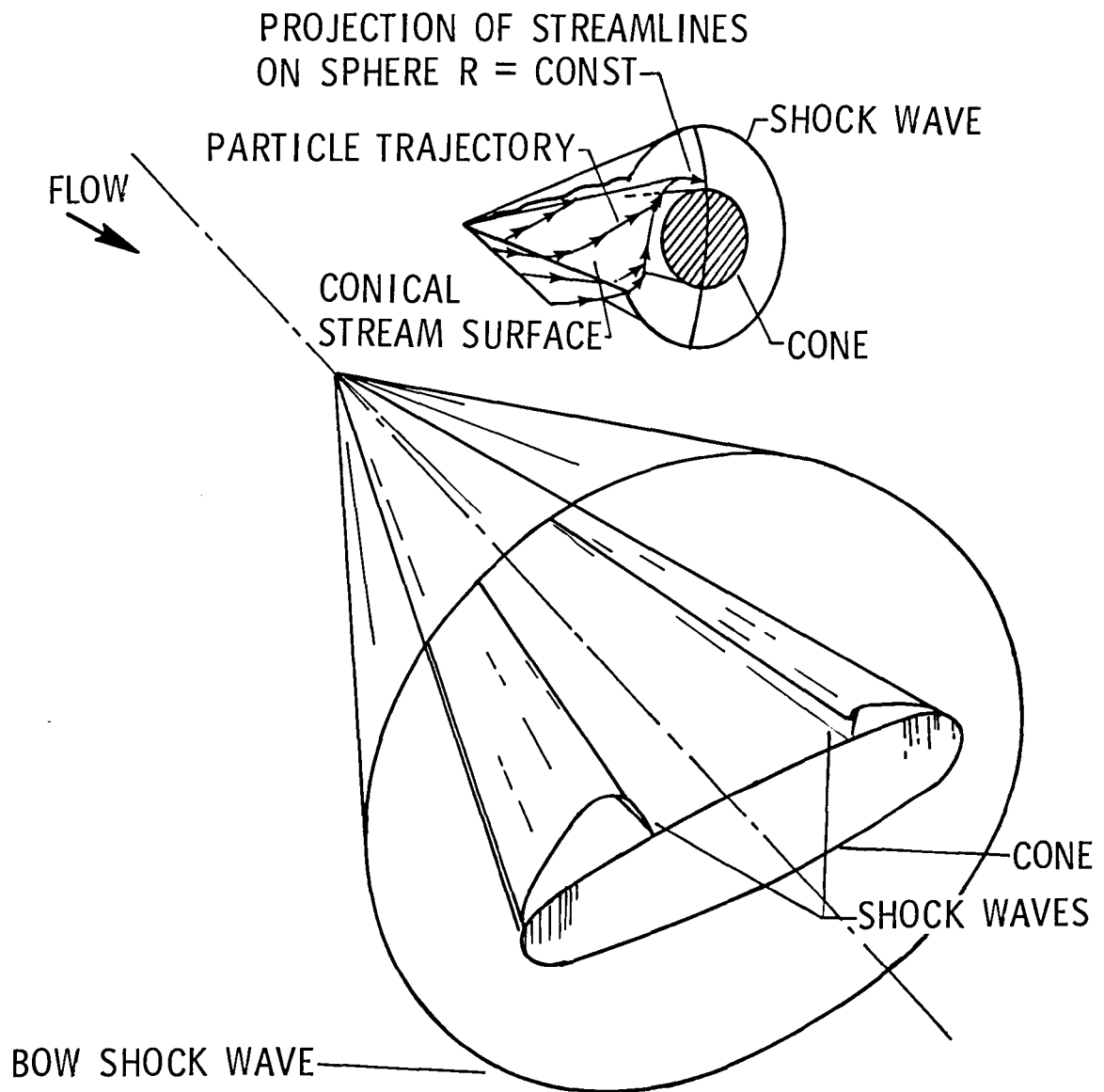


Figure 1. Conical flow particle trajectories and stream surface (from Ref. 1), and sketch of flow about an elliptic cone showing bow shock wave, cross-flow sonic surface and cross-flow shock waves.

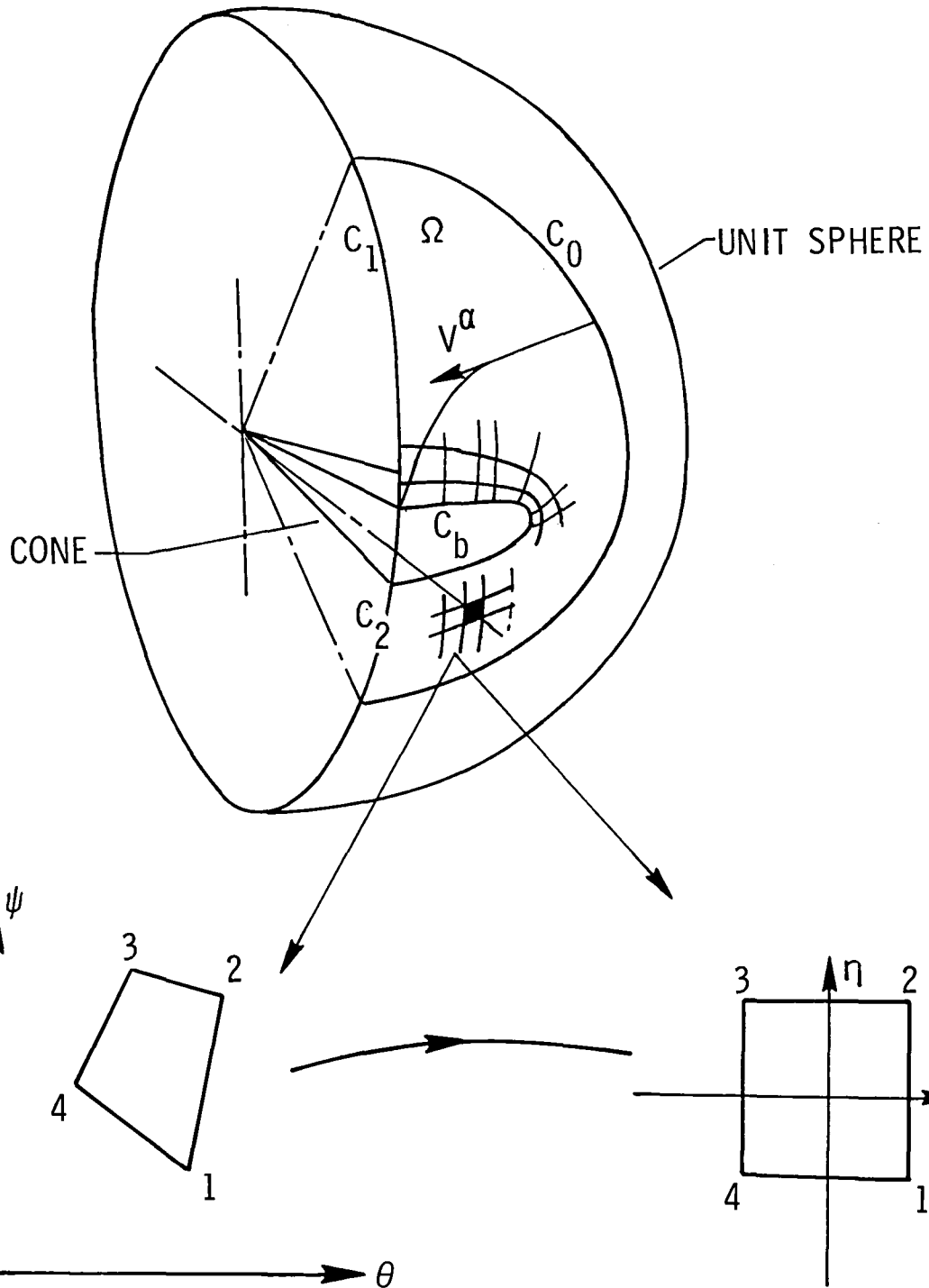


Figure 2. The computational domain and a sketch of the bilinear parametric transformation on a unit sphere.

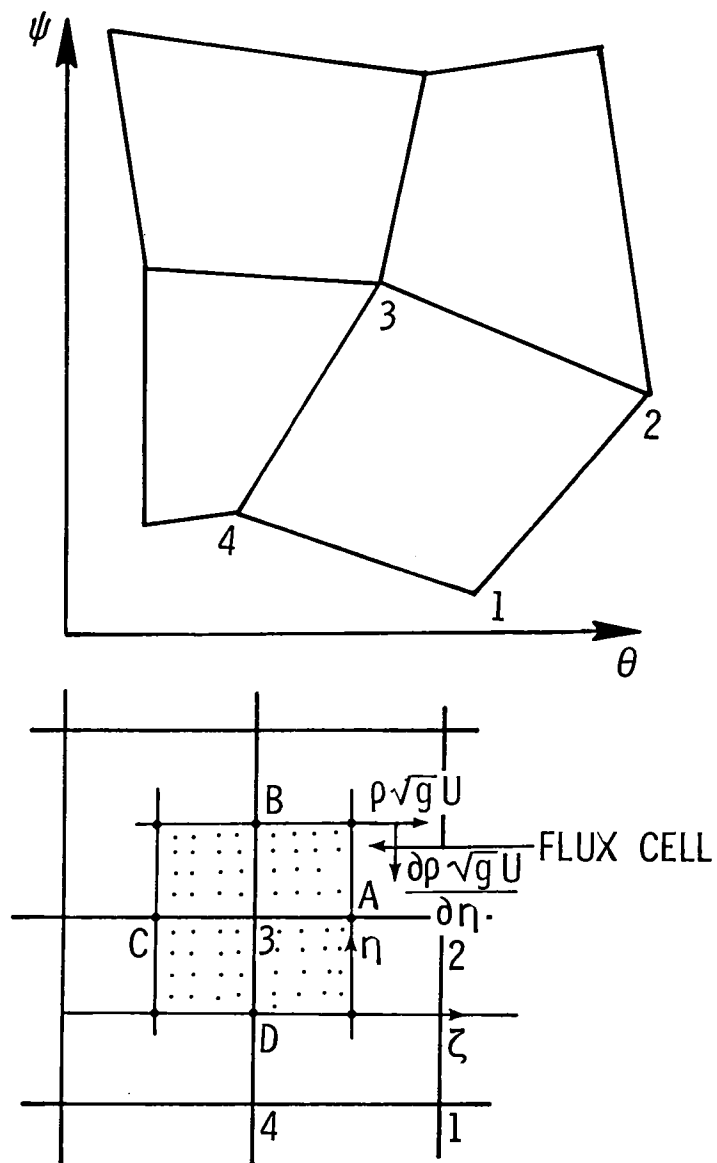


Figure 3. Sketch of primary cells and the flux cell.

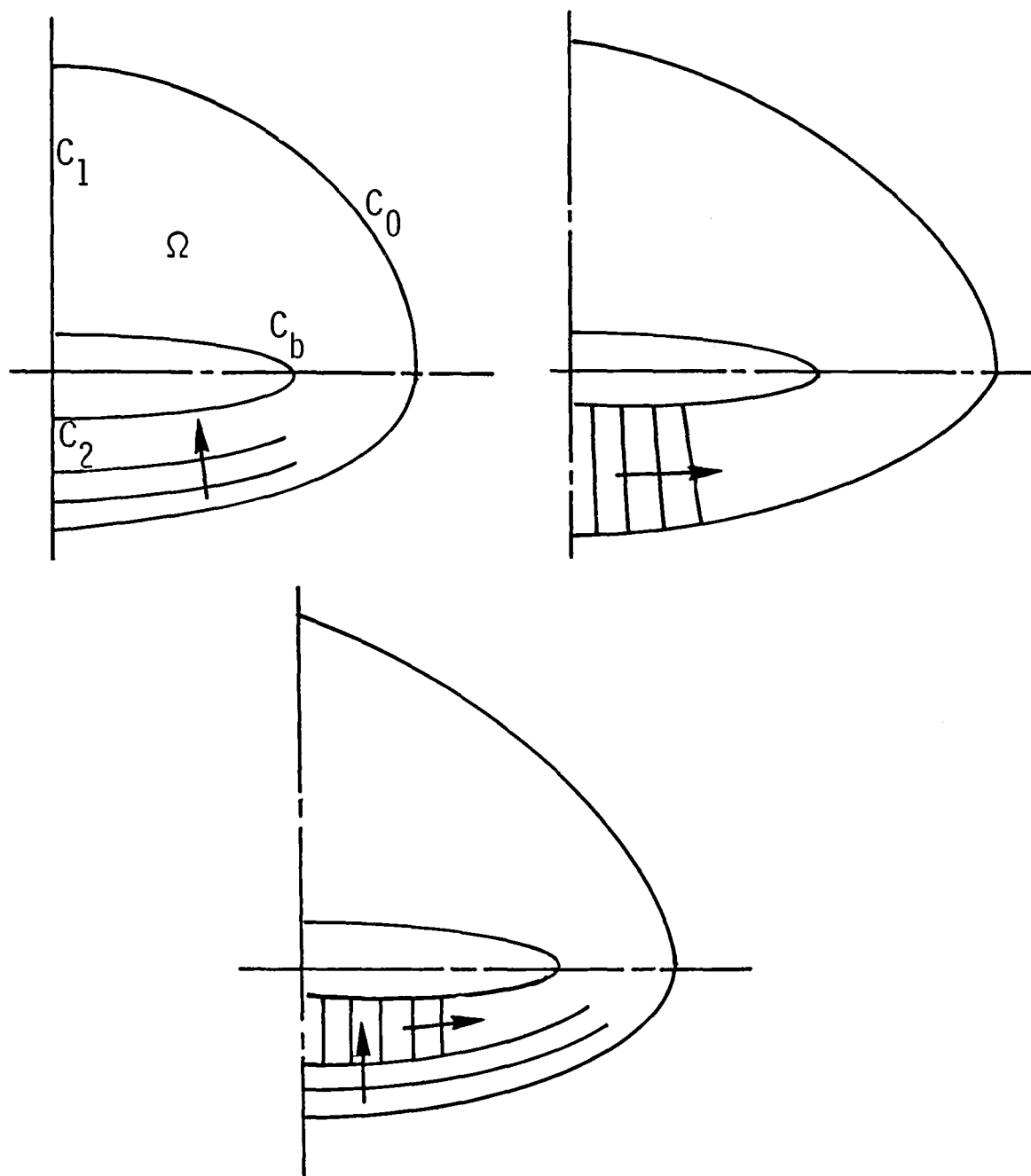


Figure 4. Computational boundaries and various possibilities for line relaxation.

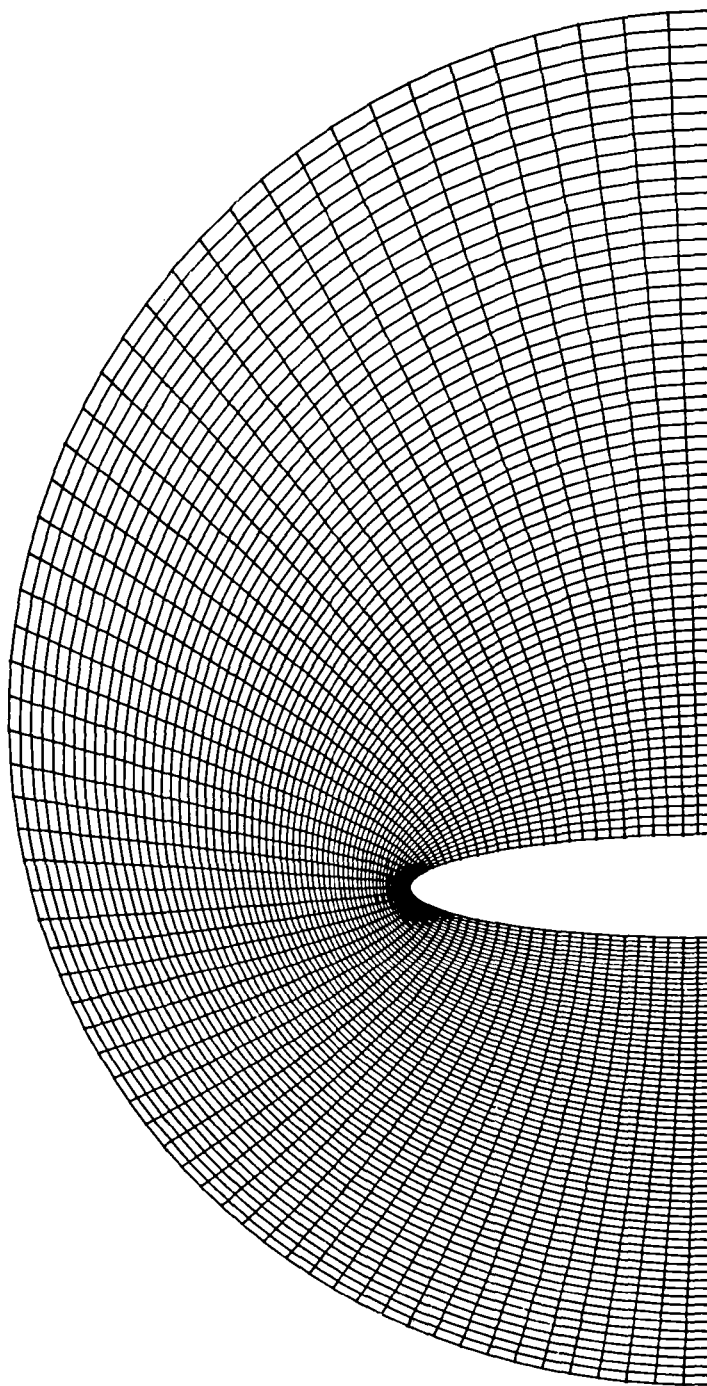


Figure 5. The 64 x 64 mesh for a 18.39^0 : 3.17^0 elliptic cone at 10^0 angle of attack.

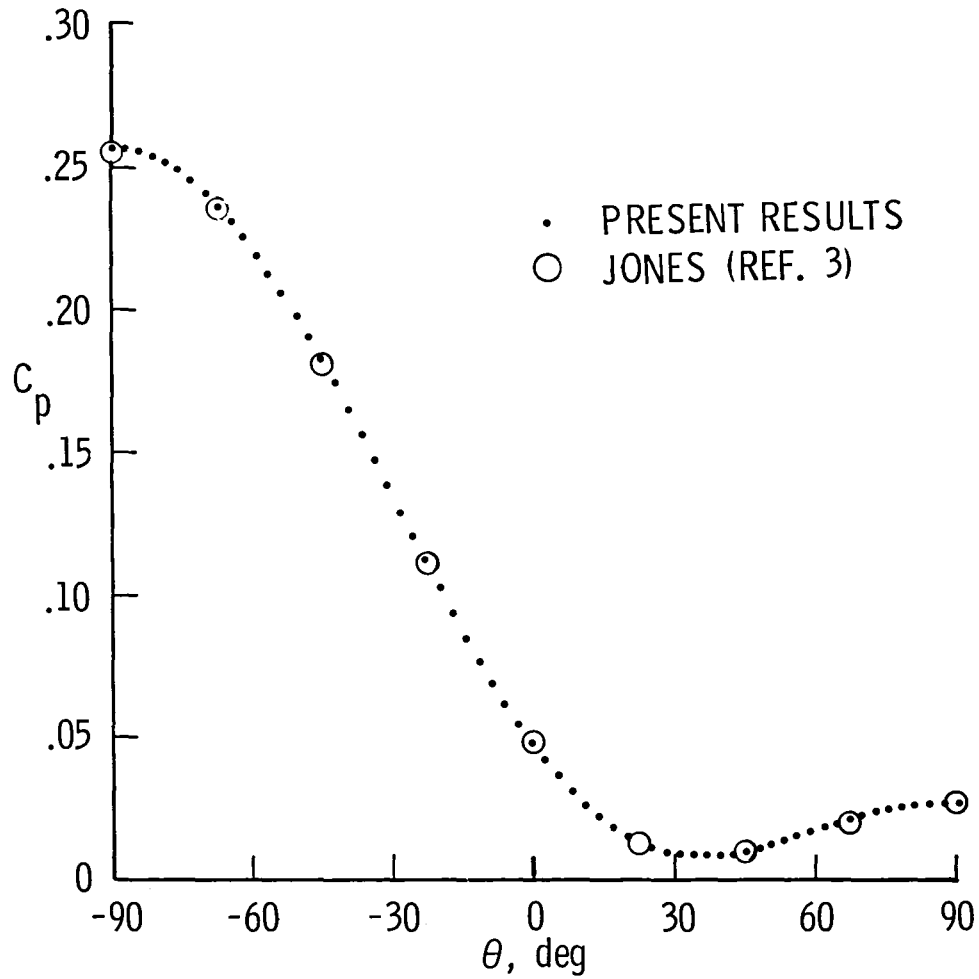


Figure 6a. Surface distribution for a circular cone at 10° angle of attack with $M_\infty = 2.0$; 64×64 grid. comparison is with the rotational calculations of Jones⁹.

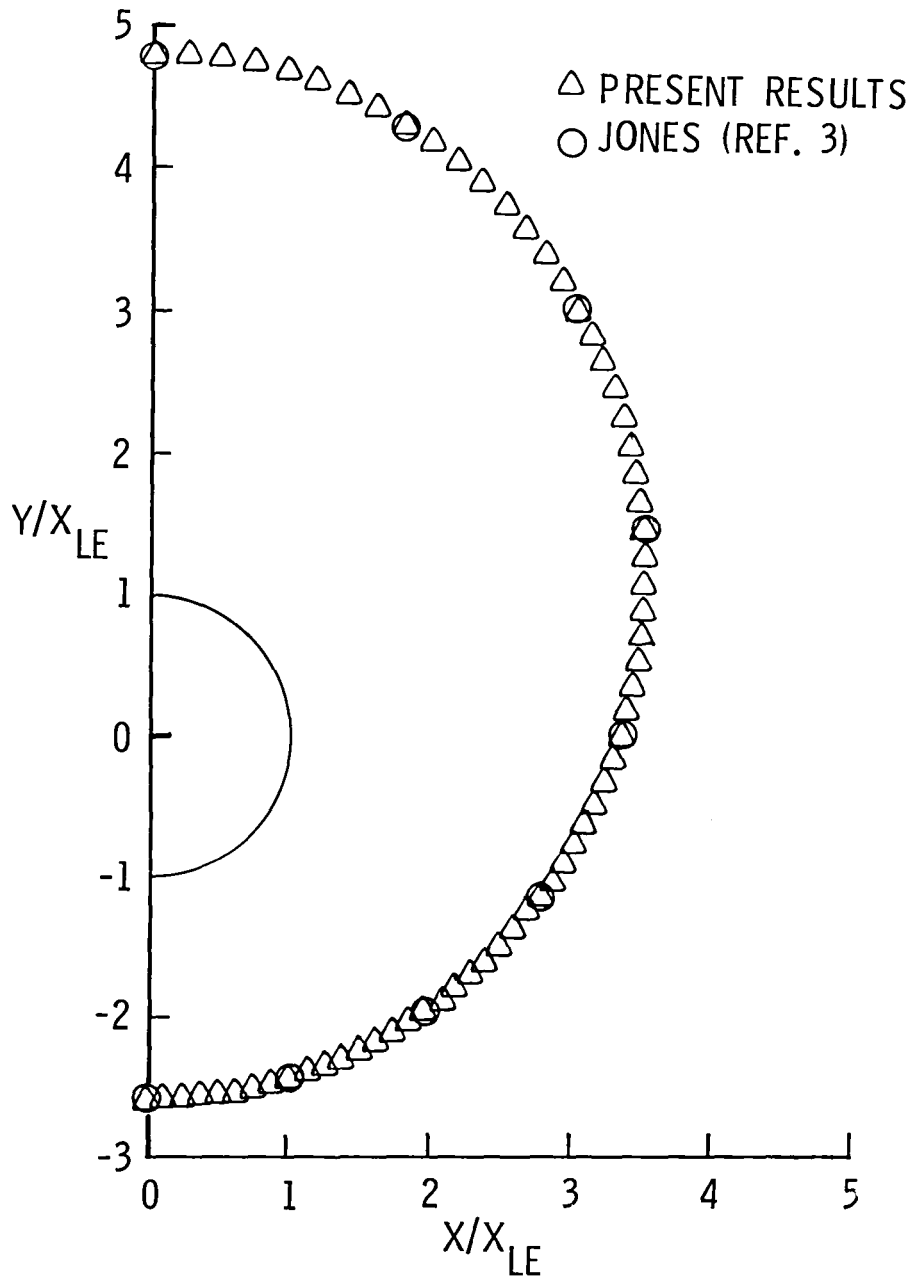


Figure 6b. Bow shock position for a circular cone of 10^0 half angle at 10^0 angle of attack. Calculated using a 64×64 grid. Comparison is with the rotational calculations of Jones⁹.

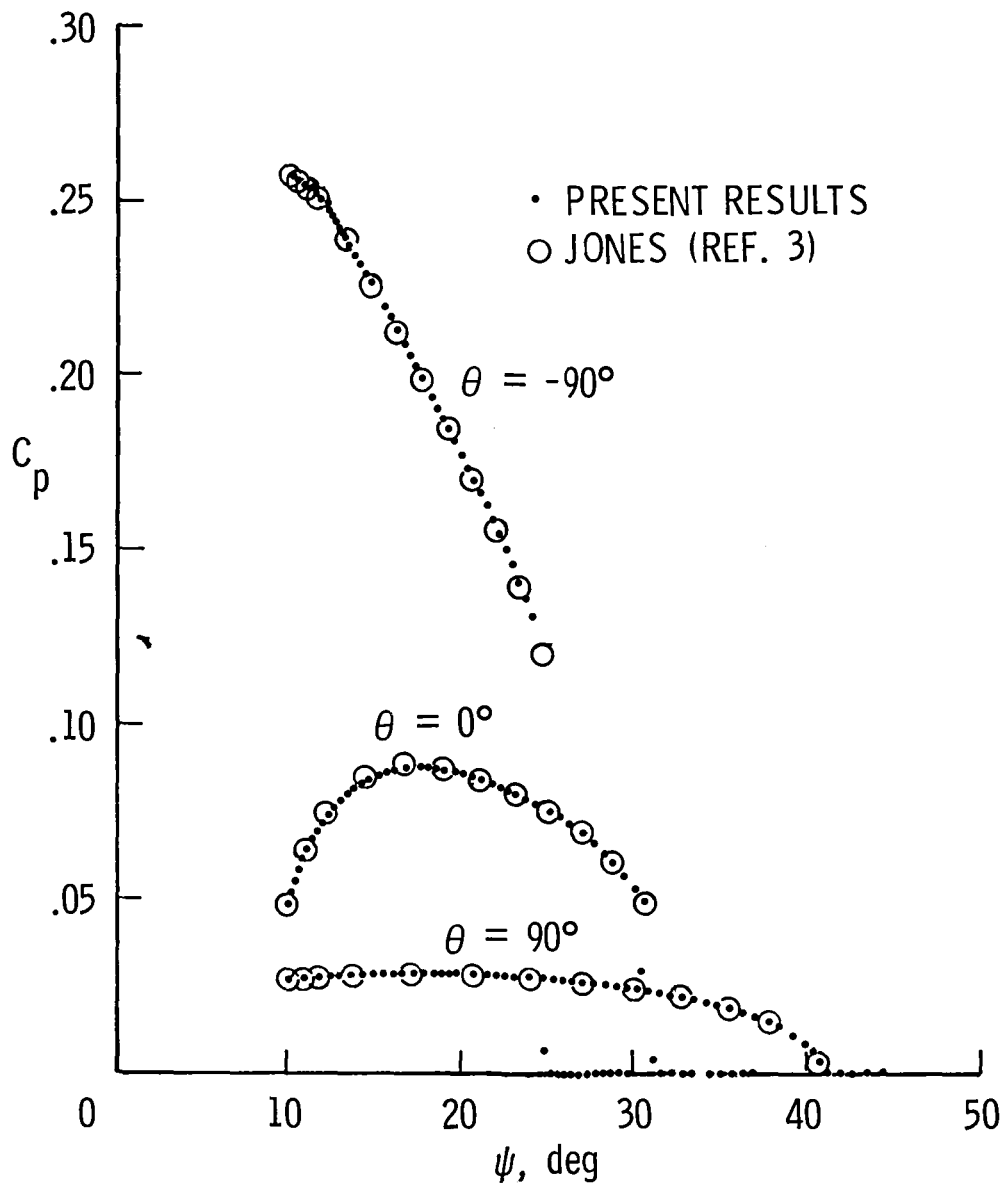


Figure 7. Pressure variation between the bow shock wave and the body for a circular cone of 10° half angle at 10° angle with $M_\infty = 2.0$. Comparison is with the rotational calculations of Jones⁹.

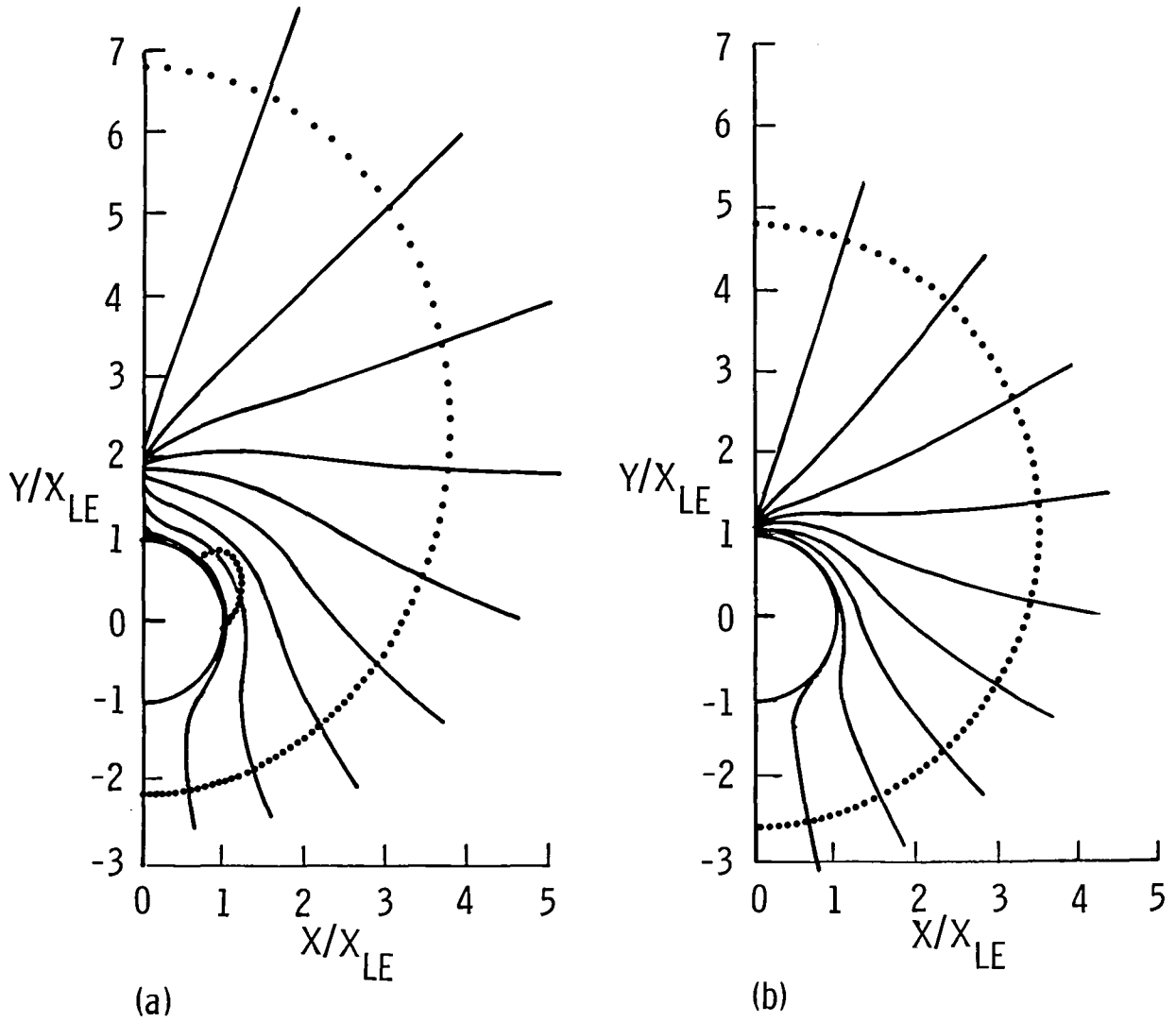


Figure 8. Comparisons of the streamline patterns on a circular cone at a) 20° and b) 10° angle of attack with $M_\infty = 2.0$. Note the lift-off of the leeward node as well as the formation of a supersonic zone in the cross flow.

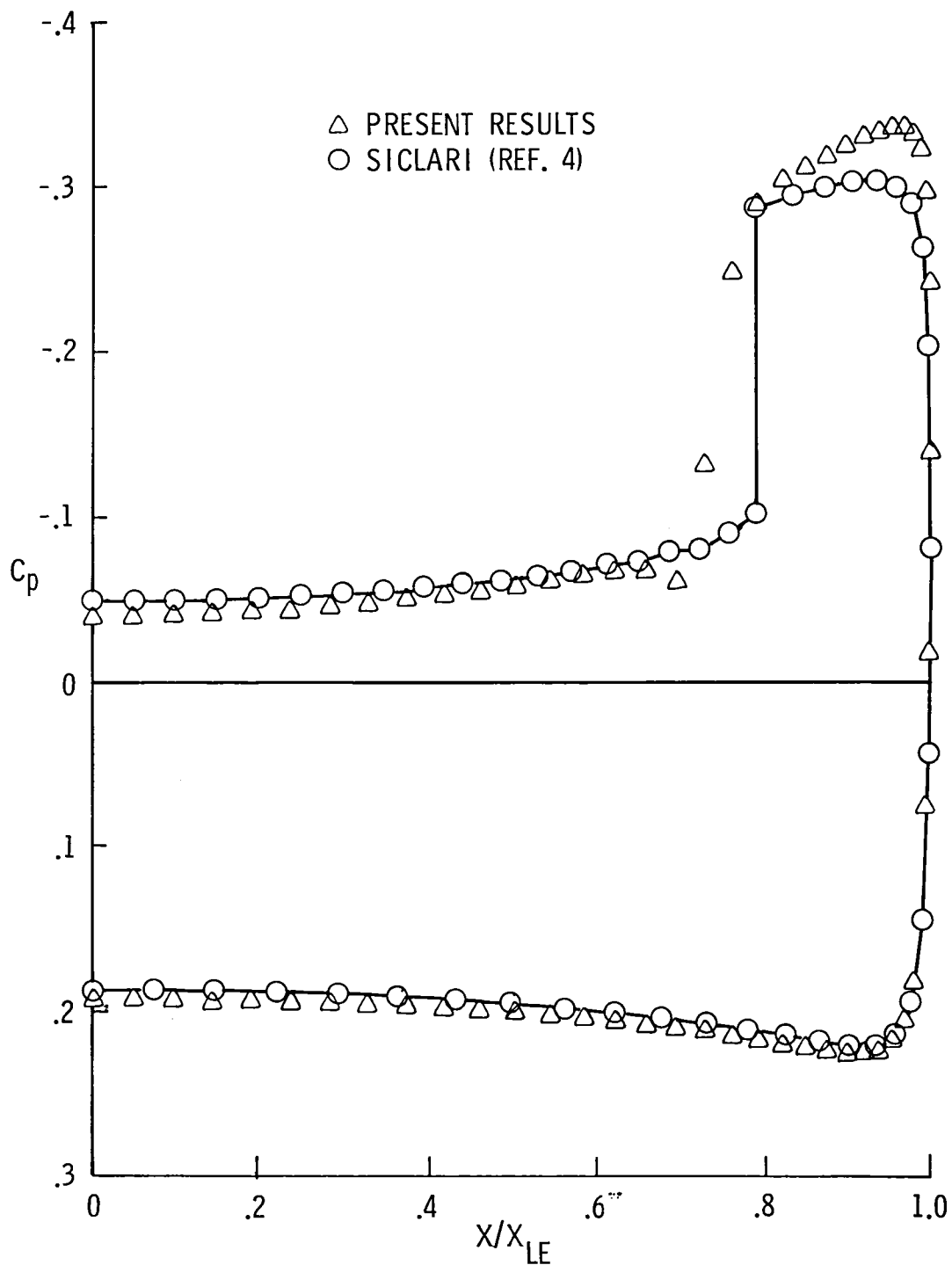


Figure 9. Comparison of the results using the Euler equations due to Siclari¹⁰ with the present results for a 18.39°: 3.17° elliptic cone at 10° angle of attack with $M_\infty = 1.97$.

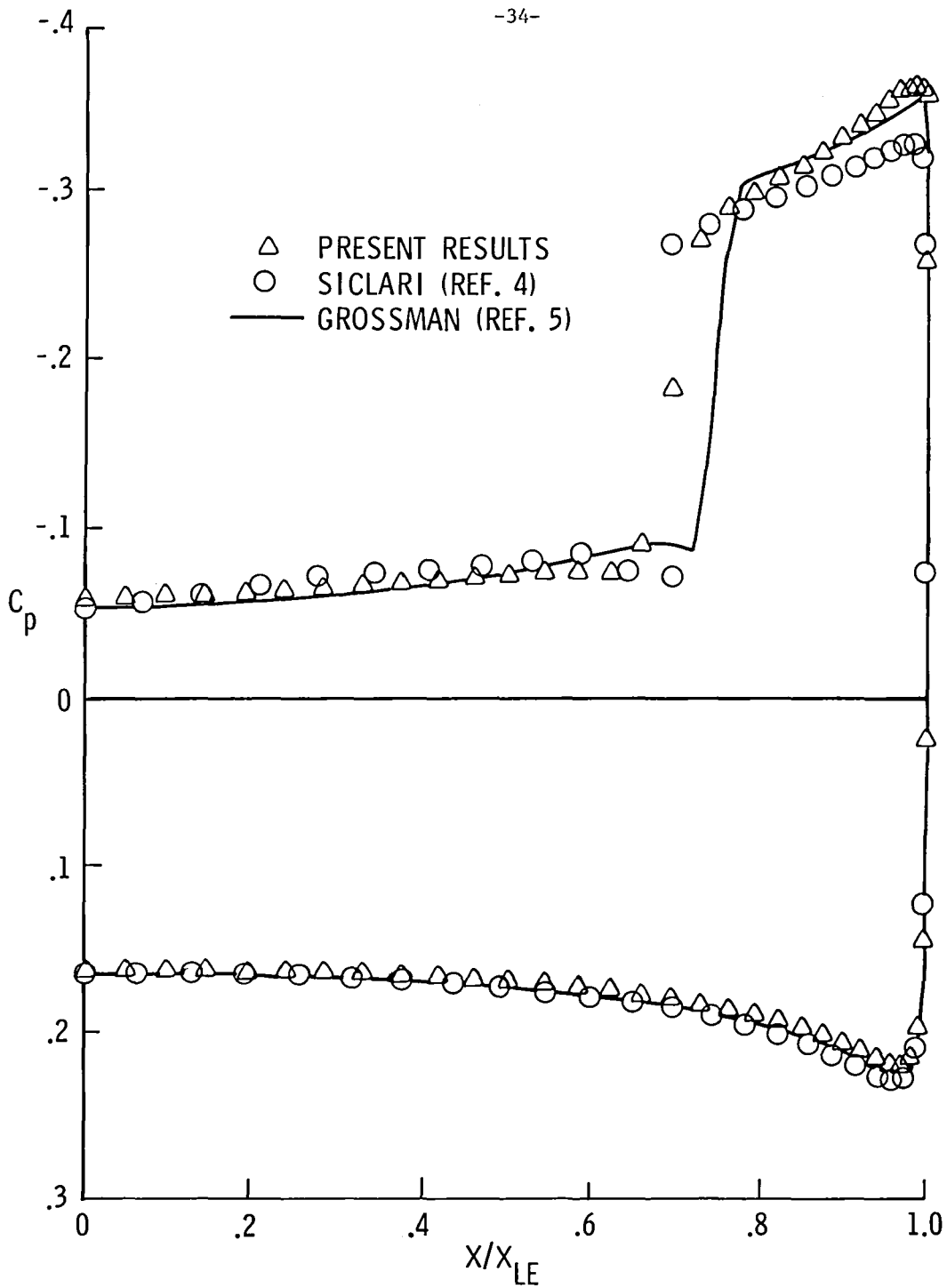


Figure 10. Comparison of the results using the Euler equations due to Siclari¹⁰, and a quasilinear formulation of the potential equation due to Grossman³, with the present result for a 20⁰: 1.5⁰ elliptical cone at 10⁰ angle of attack with $M_{\infty} = 2.0$.

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16. Abstract A fully conservative numerical method for the computation of steady inviscid supersonic flow about general conical bodies at incidence is described. The procedure utilizes the potential approximation and implements a body conforming mesh generator. The conical potential is assumed to have its best linear variation inside each mesh cell; a secondary interlocking cell system is used to establish the flux balance required to conserve mass. In the supersonic regions the scheme is esymmetrized by adding artificial viscosity in conservation form. The algorithm is nearly an order of a magnitude faster than present Euler methods and predicts known results accurately and qualitative features such as nodal point lift off correctly. Results are compared with those of other investigators.					
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