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Calculations of Hypersonic Flows Over a Series of Indented Nosetips

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Abstract

INVISCID hypersonic flows over a severely indented nosetip with small radius expansion corners and compression turn present serious difficulties in the numerical calculation. A series of four such nosetip shapes of practical interest has been examined in this paper. A special procedure of calculation has been developed in order to successfully apply the inviscid portion of the unsteady implicit numerical code of Kutler et al.[1] to these nosetips. Reasonable agreement between the inviscid solution and the experimental data for surface pressure and shock location is obtained when the separation bubble is relatively small. The calculated flowfields indicate that there is no strong embedded shock or slip surface within the shock layer for the cases investigated. The most serious aerodynamic problem for this series of nosetips is flow separation, which requires a solution to the Navier-Stokes equations.

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In Ref. 1, Kutler et al. developed a computer code for solving the unsteady Navier-Stokes equations with the thin-layer approximation for arbitrary nose shapes using the implicit factored numerical algorithm of Beam and Warming.[2] The steady solution is obtained asymptotically in time and both viscous and inviscid flowfields can be computed using the same computer program. However, when the inviscid portion of the computer code (mainly Kutler's contribution) was applied to a series of nosetip shapes reported in Refs. 3 and 4 difficulties were encountered during the course of computation because of the presence of small radius expansion corners and a concave compression turn in these nosetips. In order to represent the nosetip shape reasonably well, a sufficient number of grid points must be located in the areas where the body geometry changes rapidly. The code fails to carry out the computation with both the starting methods provided: 1) assuming a flowfield for sphere and deforming the sphere along each ray to the desired nosetip shape, or 2) specifying the locations for the initial body and shock. Only with a coarse grid, for example 12×19, can a solution be obtained with the body not well represented, particularly near the nosetip. The solution obtained then suffers an error of the total enthalpy in the flowfield as high as 20% for a severely indented nosetip and the surface pressure distribution also looks wrong to an experienced engineer. Such a solution is obviously unsatisfactory.

From experience, it was found that the divergence of solution stems from a too drastic change of flowfield from the initial one to the final one for severely indented nosetip shapes. To overcome such difficulty, the calculation should be proceeded gradually; that is a solution should be obtained initially with a coarse mesh and then additional grid points should be added successively in the areas of rapid geometry variation using the flowfield obtained previously as the starting solution. The calculation made for model 2 at $M_\infty = 6$ is used as an example to demonstrate the procedure. To begin with, a coarse mesh (typically 12×19) for sphere with equal angular increment rays (i.e., ξ = constant lines, the first two rays must straddle the axis) is used and a calculation is performed with the body being gradually deformed in time along each ray to the desired nosetip shape. The surface pressure obtained is plotted vs the arc length as shown in Fig. 1 by the broken line. The intersection point of the ray and the body surface is numbered along the body as shown in the sketch in Fig. 1. This solution is poor because the expansion corner is apparently missed and the maximum error in total enthalpy is 11.87%. An obvious cause is an insufficient number of grid points in the stagnation region and around the expansion corner. New rays are added which contain the same number of uniformly distributed grid points between the body and the shock. All of the original grid points are kept where they are. The flow variables at the new grid point are interpolated from the flowfield solution just obtained. Thus a new initial condition is obtained to continue the calculation.

As shown in Fig. 1, significant change in surface pressure distribution is found after adding three more rays (denoted by Nos. 20-22). The error in total enthalpy also reduces to 5.09%. The same procedure is repeated by adding ray Nos. 23 (the end point of the circular arc of the expansion corner) and 24. Now, the surface pressure looks like flow over a corner. In order to represent the corner better, the No. 25 ray is added in the middle of the circular arc. This addition is seen to catch the minimum surface pressure of the expansion corner. At this point, it is felt that the body geometry is well represented. A further attempt to add rays between No. 24 and No. 7 fails to obtain a solution. This part of the calculation is most

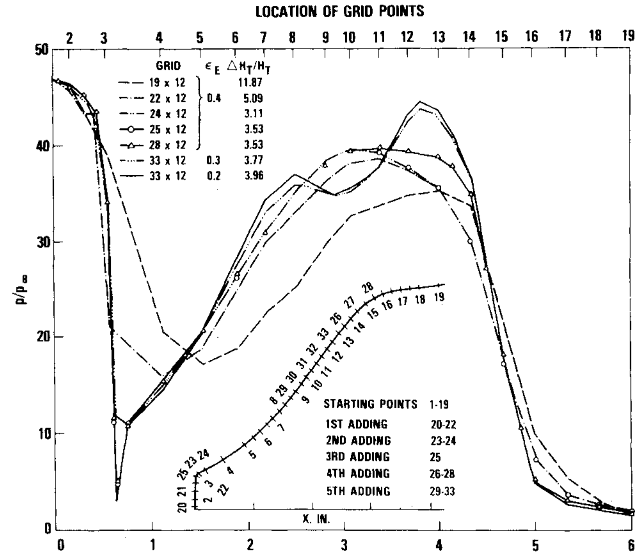

Fig. 1 Progress of surface pressure as a function of adding grid points, $M_\infty = 6$.

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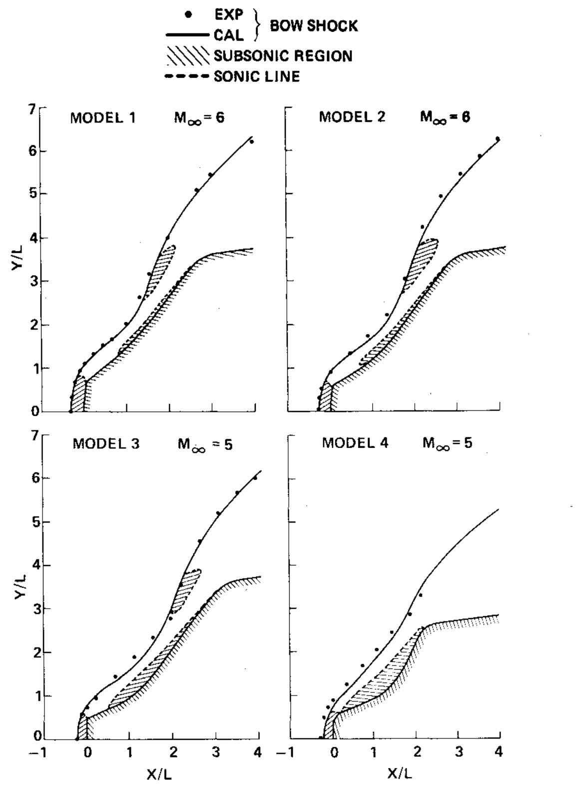

Fig. 2 Comparisons of shock location between inviscid solutions and experiments.

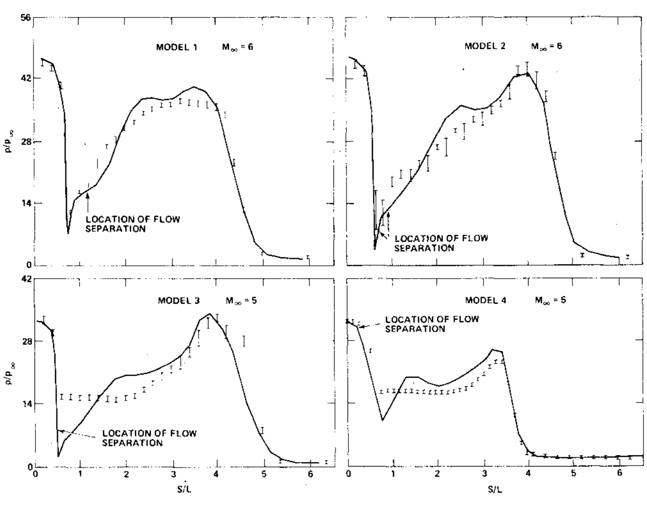

Fig. 3 Comparisons of surface pressure between inviscid solutions and experiments. Calculation: —; range of experimental data: I.

difficult and time consuming. Each addition of grid points requires about 600-1200 time steps to guarantee that the solution will converge. Should the solution diverge after the addition of grids, a change of locations for the new grids must be tried. To automatically carry out the trial and error procedure as described here is difficult but is under investigation.

At first, it seems that the solution obtained with 12×25 mesh is sufficiently accurate as shown in Fig. 1. Surprisingly enough, when three more rays (Nos. 26-28) are added at the expansion shoulder, the surface pressure there changes. Further addition of rays downstream of No. 28 does not have a large effect on surface pressure. Yet the addition of rays in front of No. 26, i.e., Nos. 29-33, are seen to catch the details of a process of recompression and expansion and recompression again. A further increase in the number of rays between No. 29 and No. 28 will change the surface pressure locally, but the general trend of the curve remains the same. The addition of rays between the compression turn and the expansion shoulder does not present any difficulty in obtaining a converged solution.

Next, the effect of explicit dissipation used in the code is examined. This is done by reducing the value of ϵ_E. As shown in Fig 1, the minimum value of ϵ_E required to obtain a converged solution is 0.2 (or $\epsilon_E/\Delta t \sim 25$) and the difference in surface pressure between $\epsilon_E = 0.2$ and 0.3 is small.

In summary, the procedures used to carry out indented nosetip calculation are as follows: 1) Use a coarse mesh for a sphere to start the calculation and deform the sphere along each ray to the desired nosetip shape. 2) Add new rays (a few rays at a time) to the critical areas featuring rapid variation in geometry and obtain a new converged solution. 3) Reduce the value of the explicit dissipation coefficient to the minimum value producing a converged solution. This entire calculation sequence requires a net CPU time of about 15-25 min on a CDC 7600 computer. Following these steps, the inviscid solutions for the nosetips under investigation are obtained and the results for shock location and surface pressure are shown in Figs. 2 and 3. It is noted that when the separation bubble is small, such as in model 1, the agreement is good. As the separation bubble becomes larger, as in models 2-4, the agreement deteriorates.

A calculation for model 4 at $M_\infty = 14$ has also been obtained. With all the results obtained as shown, it seems that the method can work for quite a large range of body and flow conditions.

Detailed flowfield descriptions can be found in Ref. 5. It should be pointed out that there is no strong embedded shock or slip surface within the shock layer as given by the solutions (or by the corresponding experiments) for the cases investigated. The most serious aerodynamic problem for this series of nosetips is flow separation, which requires a solution to the Navier-Stokes equations. A calculation of viscous hypersonic flows over smooth nosetips has been conducted as given in Ref. 6.

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