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Axisymmetric Nonconical Supersonic Potential Flow with Embedded Subsonic Regions

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Introduction

FREESTREAM conditions in the 1.2-1.6 Mach number range can generate locally subsonic radial and total Mach numbers in the vicinity of fuselage-canopy and wing leading-edge regions. In this low supersonic range traditional transonic methods should be applicable. Unfortunately, transonic meshes are not well suited to attached bow shock computations and if the flowfield is predominately supersonic the transonic iterative technique is inefficient for the treatment of flows in this Mach number range. Hence, an intermediate method that marches in the supersonic zones and iterates in a localized region of subsonic flow would be an efficient technique for this problem. This type of procedure was first suggested privately to the author by South.[1] Recently, this type of technique was adopted by Shankar et al.[2]

Results of an Axisymmetric Study

The fully implicit marching method of Refs. 3 and 4 is used to solve the axisymmetric nonconservative full potential equation in a spherical coordinate system. For strong bow shocks, inaccuracies develop due to the nonconservative capture and smearing of these shocks. Hence, the bow shock is fit isentropically as a boundary (e.g., Ref. 5 or 6). The occurrence of a subsonic total Mach number region precludes the use of a marching scheme and an iterative technique must be used in the radial marching direction, Z. As a preliminary study, the conical solution was computed and held fixed at the apex or $r=0$, and the entire flowfield over the forebody shape was then computed by iteratively sweeping downstream using body-to-bow shock line relaxation. The Z derivatives must be modified to accommodate the iterative procedure. The radial Z second derivatives of the potential were computed using second-order accurate central difference formulas in subsonic zones. First derivatives were always central differenced. The details of the numerical scheme are presented in Ref. 6.

In general, the remainder of the body could be computed using the marching scheme. No attempts were made in this preliminary study to a priori define the zone of subsonic radial and total Mach number.

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Figure 1 shows computed results for a 25-deg cone at $M_\infty = 1.401$ with an expanding afterbody initiated at $Z=0.2$ and terminating in a cylinder at $Z=0.3$. This solution was generated on a 60×45 (Y,Z) grid and took less than 1 min of CPU time on an IBM 3033. Figure 1a shows a Mach number contour plot. A significant portion of the conical flow at the apex contains subsonic flow. The conical transonic flow solution at the apex $(Z=0)$ is used as the upstream starting condition. The interesting aspect of this solution is that little upstream influence occurs due to the presence of subsonic flow (Fig. 1). In fact, the sonic line attaches to the body at the point where the body slope first deflects. Figure 1b shows the surface pressure coefficient solution indicating that about five points upstream of the shoulder differ noticeably from the initial cone pressure. Reference 7 contains some Mach contour experimental data for cone cylinders under the same conditions but for a shoulder region of zero radius of curvature. The data also indicate that the upstream influence is very small. The present technique did not permit the calculation of transonic flow over cone cylinders with discontinuous curvature. It should be mentioned that the transonic cone solution was used as the starting potential for the forebody and is far from ideal as an initial guess. It initially violates the hyperbolic downstream condition but very quickly becomes supersonic downstream of the shoulder.

Figure 2 shows a series of fine mesh (60×97) solutions at $M_\infty = 1.55$ for a 20-deg supersonic cone (at the apex) with a gradual compression initiated at $Z=0.01$ and terminating at a specified deflection at $Z=0.25$. The compression surface is followed by an expanding afterbody which terminates in a cylinder at $Z=1.00$. These fine grid solutions were determined using a single mesh refinement. Some instabilities arose in the fine mesh solution in the vicinity of the downstream sonic line due to the abrupt finite difference switching at $M=1$. These

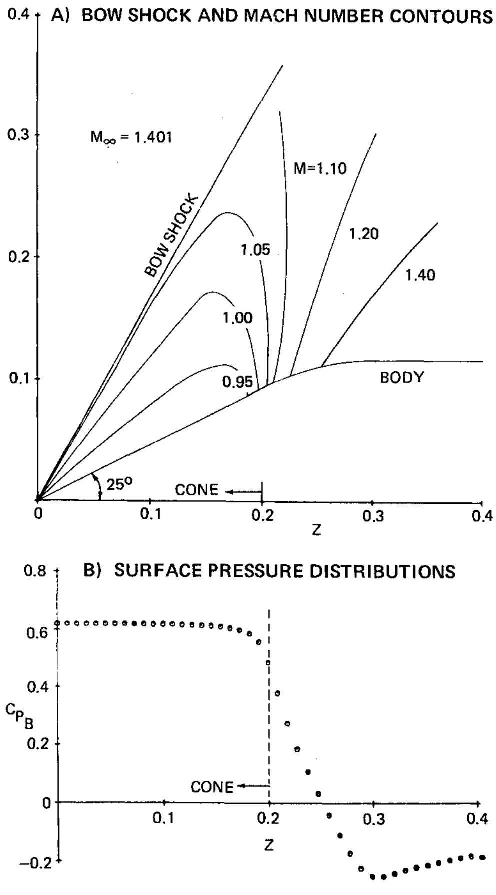

Fig. 1 Axisymmetric solution for a transonic 25-deg cone with an expanding afterbody at $M_\infty = 1.401$.

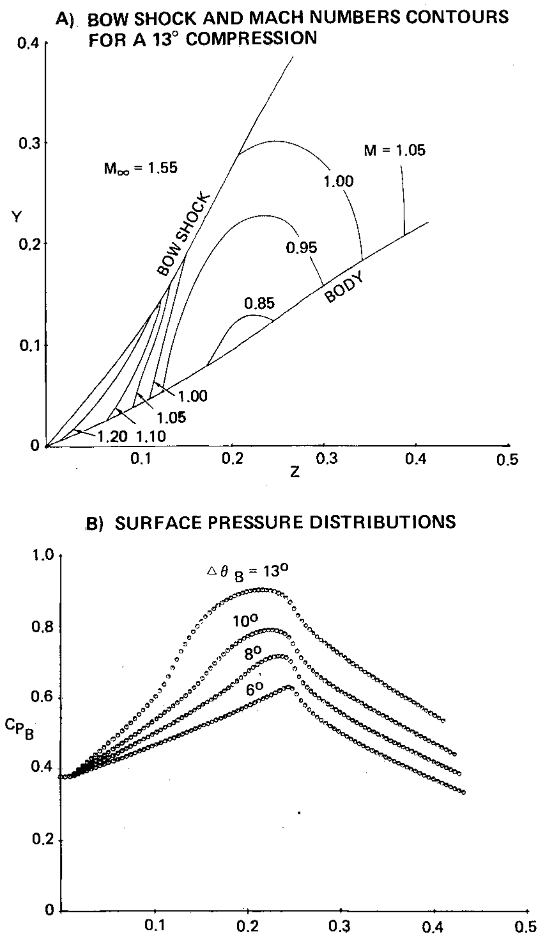

Fig. 2 Axisymmetric solution for a body with a 20-deg supersonic cone at the apex and a gradual compression followed by an expanding afterbody at $M_\infty = 1.55$.

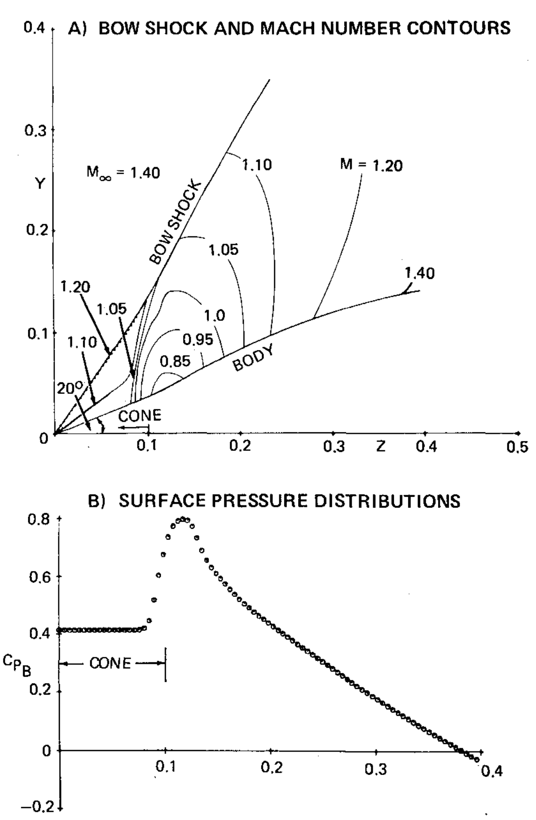

Fig. 3 Axisymmetric solution for a 20-deg supersonic cone with a steep compression of 8 deg followed by an expanding afterbody at $M_\infty = 1.40$.

instabilities were easily eliminated using a continuous switching of the residual with a bias toward the supersonic region. This continuous switching stabilized the downstream sonic line. Figure 2a shows the bow shock and Mach contours for the largest compression of 13 deg. This solution is most interesting because the sonic bubble has intersected the bow shock. The large deflection of the bow shock is already evident. Figure 2b shows the surface pressure distributions for several compression angles. At a compression angle of 6 deg the minimum surface total Mach number is just slightly supersonic. Evidently, the gradual nature of the body deflection leads to a shockless compression on the body surface for the larger compression angles.

Figure 3a shows another Mach contour solution at $M = 1.40$ initiated by a 20-deg supersonic cone at the apex, extending to $Z = 0.10$, at which point a steep 8-deg compression starts and terminates at $Z = 0.13$. An expanding afterbody starts at $Z = 0.13$ and terminates in a cylinder at $Z = 0.50$. Figure 3b shows the surface pressure distribution on a fine grid of 60×97. The interesting feature of this solution is that the subsonic flow creeps upstream into the supersonic cone region. A shock wave occurs upstream on the cone surface, as indicated by the upstream sonic line attachment position.

Conclusion

A new, efficient, and accurate procedure has been established for computing flows with attached bow shocks at low supersonic freestream Mach numbers that result in embedded subsonic flow regions. This procedure is mesh efficient in that the computation is bounded by a fitted bow shock and hyperbolic upstream and downstream conditions and an iterative procedure need be implemented only in a localized region of subsonic flow.

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Nikuradse's Experiment

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Introduction

THE values of the velocity loss term Δu_+ for Nikuradse's sand have been re-evaluated from the original measurements.[1] The wake term has been included in the

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