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Improved Interaction Method for Exhaust Nozzle Boattail Flows

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Abstract

EXTENSIONS and improvements are described for computational methods for axisymmetric afterbody flowfields. Previous work has provided the capability to obtain flowfield solutions for the freestream Mach number range 0.5-0.95, provided separation, if present, is not shock induced. Also, exhaust jet entrainment was calculated using an approximate model of the inviscid core of the jet. The extensions described in the present paper include relaxation of the assumption that the effective outer boundary of the separated flow is conical, use of a method of characteristics exhaust jet inviscid core calculation, and the capability to treat shock-induced separation.

Contents

Improvements and extensions for the method of Ref. 1 are discussed in the present paper. Both the original and improved methods combine a finite-difference, inviscid flow method with integral methods for the boundary layer and exhaust plume mixing layer of flows over axisymmetric boattailed afterbodies. A displacement surface is calculated from the viscous layer, which forms an effective boundary for the inviscid flow and is compatible with the resulting inviscid pressure distribution. An integral method boundary-layer program, which can be applied in a direct (boundary-layer edge velocity, u_e prescribed) or an inverse (boundary-layer displacement thickness, δ^*prescribed) mode is used to solve the viscous flow. The inviscid flow method used is the South-Jameson[2] theory as implemented by Keller and South[3] with minor modifications to accommodate the iterative interaction procedure.

Previous Approach

In Ref. 1 the first step in calculating the viscous/inviscid interaction was to calculate the inviscid flow over the basic body. The resulting distribution of the velocity at the boundary was then prescribed in the second iteration step as the boundary-layer edge velocity u_e for the boundary-layer calculation in the direct mode up to the separation point. The boundary-layer calculation was then switched to the inverse mode and the solution was continued into the separated flow region using a prescribed distribution of the boundary-layer displacement thickness δ^*. The result of the inverse calculation was a solution for the boundary-layer edge velocity u_{e_v} which, in general, would not agree with the velocity u_{e_I} produced by the inviscid flow theory. The effective displacement surface between separation and a point downstream of reattachment or in the plume entrainment region was assumed to be conical and an iterative procedure was used to find the particular cone angle θ_s and the separation point location x_s for which u_{e_v} and u_{e_I} would agree within an acceptable tolerance. A stable iteration was produced for flows at subsonic or transonic Mach numbers provided separation was not shock induced. When shock waves of strength sufficient to separate the boundary layer were present, the iteration was unstable.

The inviscid jet core flow was calculated using an approximate method in which the jet flow was assumed uniform in each cross section and Prandtl-Meyer theory was employed to match the internal pressure to the external pressure at each boundary point.

Present Approach

In the improved interaction procedure, the separation point location x_s is assumed known. The new interaction procedure begins in the same manner as in Ref. 1. The first step is to calculate the inviscid flow over the basic body. The second step is to calculate a boundary-layer displacement thickness assuming a conical displacement surface in the separated region. The next step in the new interaction procedure is the computation of the new displacement thickness distribution in which the assumption of a conical surface is dropped and the new displacement thickness is deduced from the mismatch of the viscous and inviscid velocities by

$$\delta^*_{\text{new}} = \delta^*_{\text{old}} \left(u_{e_v} / u_{e_I} \right) \tag{1}$$

The displacement surface is prescribed in this manner for all subsequent iterations. Also, it is no longer necessary to operate the boundary-layer method in a direct mode up to the separation point, but the inverse method is used with the displacement surface prescribed over the entire afterbody flow region.

As for the method of Ref. 1 calculations using Eq. (1) were found to be unstable for flows containing shock waves of strength sufficient to separate the boundary layer. A new calculative technique was derived for such flows, which employs Prandtl-Meyer theory and the semiempirical approach of Mager.[4]

Another improvement over the method of Ref. 1 is a more accurate calculation of the exhaust jet plume. The effect of an exhaust jet plume on the flow on an afterbody has been found to consist of two separate effects. First is the effect of the shape of the plume. Second is the effect of the entrainment of external air into the plume boundary. The two effects oppose each other since the entrainment of low-speed external air by the high-speed jet tends to decrease the effective expansion of the jet boundary.

The shape of the jet plume is accounted for by the expansion of the inviscid jet core flow. The entrainment effect is determined by calculating a jet mixing displacement thickness and defining an effective body shape using that surface.

The basis of the new exhaust plume entrainment model is the technique developed by Peters et al.,[5] in which an integral method for the exhaust plume mixing layer is coupled with a method of characteristics inviscid jet calculation. The boundary of the jet is taken to be the midpoint of the mixing layer and the displacement thickness of the mixing layer is

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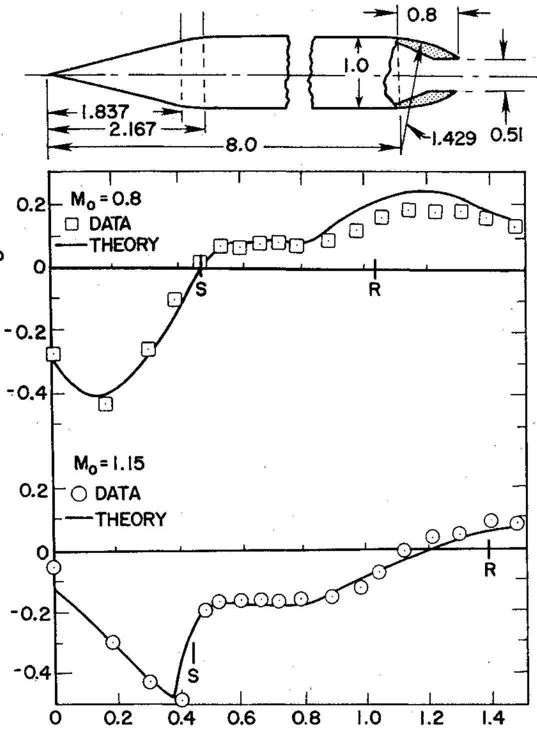

Fig. 1 Comparison of improved subsonic theory and data for a circular arc boattail with a cylindrical plume simulator.[6]

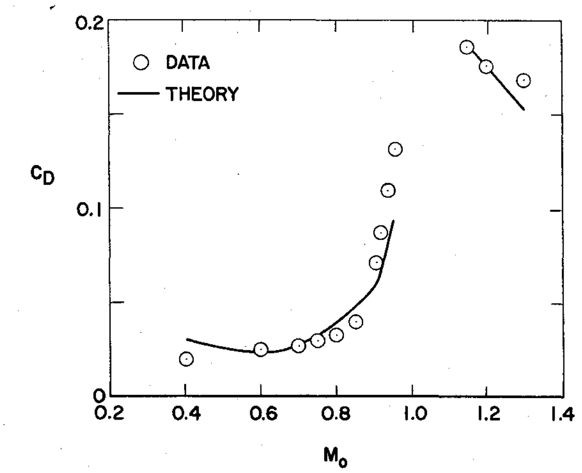

Fig. 2 Afterbody drag on a circular arc boattail with a cylindrical plume simulator.[6]

calculated in a manner analogous to that for a boundary layer. The entrainment of the boundary layer is thus accounted for to a first approximation by using the displacement surface of the jet as the effective boundary upon which to calculate a boundary layer. The boundary layer of the boattail is then simply extended onto this approximate surface as though the jet were a solid surface. Entrainment is accounted for by the fact that the displacement surface of the mixing layer velocity profile is a negative quantity relative to the jet boundary.

Results of the new interaction model for calculated pressure distributions on a model with a circular arc boattail and cylindrical plume simulator are shown in Fig. 1. Comparisons are shown between the present method and data from Ref. 6 for Mach numbers of 0.8 and 1.15. The comparison for the subsonic case at $M_\infty = 0.8$ is excellent.The results for shock-induced separation at a Mach number of 1.15 are very good

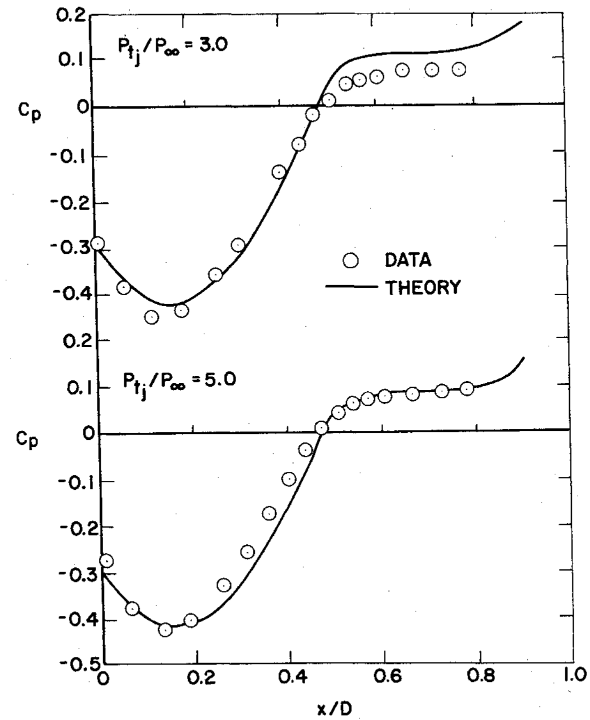

Fig. 3 Comparison between the theory and data[6] for a boattail with a high-pressure air jet, $M_0 = 0.8$.

with the predicted shock location and plateau pressure agreeing very closely with the data.

The afterbody drag on the model of Fig. 1 is shown in Fig. 2. The predicted drag is slightly high for low subsonic Mach numbers, but is well predicted for high subsonic Mach numbers and underpredicted for transonic Mach numbers. The prediction is excellent for the low supersonic Mach number of 1.15, but is slightly low at higher Mach numbers.

Two cases with real exhaust jets are shown in Fig. 3. The same afterbody as in the previous figures was used with a sonic nozzle and ratios of jet total pressure to freestream static pressure of 3.0 and 5.0. The data shown are for a freestream Mach number of 0.8. Good comparisons with the experimental data are calculated for both pressure ratios, although the comparison appears to improve with increasing nozzle pressure.

Acknowledgment

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