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Final Technical Report
on
INTERACTIVE CALCULATION PROCEDURES FOR
MIXED COMPRESSION INLETS
(NASA Grant NAG 3-140)

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The proper design of engine nacelle installations for supersonic aircraft depends on a sophisticated understanding of the interactions between the boundary layers and the bounding external flows. The successful operation of mixed external-internal compression inlets depends significantly on the ability to closely control the operation of the internal compression portion of the inlet. This portion of the inlet is one where compression is achieved by multiple reflection of oblique shock waves and weak compression waves in a converging internal flow passage. However weak these shocks and waves may seem gas-dynamically, they are of sufficient strength to separate a laminar boundary layer and generally even strong enough for separation or incipient separation of the turbulent boundary layers.

Shock reflection without separation in inlets can however be obtained by bleeding off a portion of the mass flow near shock impingement regions. This is shown by Smeltzer and Sorenson (Ref. 1) describing on- and off-design performance of a mixed compression inlet for $M_\infty = 3.5$. They indicate that of the order of 20% of the capture mass flow must be bled to achieve maximum pressure recovery at the design Mach number. This is a very large fraction of the flow when one considers that the bleed flow is dumped giving negligible if any contribution to thrust. A NASA sponsored experimental study (Ref. 2) showed that satisfactory results can be obtained for smaller bleed flows.

An objective of the CWRU program was to develop sufficient understanding of the viscous-inviscid interactions and of the shock wave boundary layer interactions and reflections.

During the many years of the subject grant, the Principal Investigator has

participated with NASA-Lewis personnel in discussing their overall program in mixed compression inlets leading to specific identification of those portions to be carried out under the subject grant.

Interaction Procedure for Two-Dimensional and Axisymmetric Inlets

Dr. Yehuda Tassa developed an interaction calculation procedure using the finite difference techniques of Cebeci and Smith (Refs. 3,4) for compressible turbulent boundary layers together with a streamline-normal characteristics procedure due to Mr. B.H. Anderson of NASA-Lewis. Since much of the boundary layer flow is supersonic, it is desirable to trace Mach waves into the supersonic portion of the boundary layers so that the wave reflections are correctly located. Accordingly, the characteristics procedure was modified to include step by step entropy changes due to viscous shear and the matching between the characteristics region and the inner turbulent boundary layer takes place where the local Mach number is about 1.2, just outside the sonic line. This procedure is essentially as described by Ferri and Dash (Ref. 5) and by Miller (Ref. 6).

The procedure (Refs. 7-10) utilizes Anderson's characteristic procedure whose streamline-normal network is more readily compatible with the mesh for boundary calculations, and also a more sophisticated boundary layer program than used by the previous investigators. The Cebeci-Smith procedure was augmented to include the leading longitudinal and transverse curvature terms so that the procedure would be applicable for fairly thick boundary layers and sharp longitudinal curvatures as often encountered on boattails and sometimes on inlet centerbodies. The results show that although the interaction procedure

does work and can provide flow field information without resorting to the much more complicated and time-consuming Navier-Stokes calculation procedures. the quality of the results is very sensitively dependent on the care and local massaging exercised by the operator. These difficulties were made very apparent by the recent work of Ashpis (Ref. 11) completed under this grant. This procedure therefore shows little promise at this time of being adequate for use as a design code.

Shock Boundary-Layer Interactions

Since in a shock boundary layer interaction, there is a downstream condition that must be satisfied, a parabolic method cannot be adequate. The procedure must become elliptic thus requiring some kind of shooting technique to approach the correct downstream condition. In work completed under the grant, Goldberg (Ref. 12) has followed the suggestions of Wornom (Ref. 13) and Dwoyer (Ref. 14) in using the second derivative of the displacement thickness ($d^2\delta^*/dx^2$) as a branching parameter. He was able to proceed through the interaction zone to a converged solution even with zones of separation. He also showed the effect of suction on the character of shock-boundary-layer interactions. Goldberg's work provides the basis for the development of an oblique shock-boundary-layer interaction program to be incorporated into the PEPSIS procedure.

Three-Dimensional Flow Calculations

In order to properly start a three-dimensional flow calculation, say for an axis-symmetric centerbody at angle of attack, it is necessary to have an in-

teracted solution at the first station of a numerical program. The development of such a starting program was undertaken within the grant. The suggested technique substitutes a $3/4$ power law tip for the leading portion of the cone. For such a tip, the shock-wave and boundary-layer also have a $3/4$ power shape according to strong interaction theory (Ref. 15) and so the entire flow field is self-similar. The extension of the procedure to angle-of-attack follows Mirels and Thronton (Ref. 16). In an M.S. thesis by Mr. R. Srinivasan now nearing completion, it becomes apparent that the strong-interaction theory is valid only for hypersonic non-slender shapes ($M^2_{\infty} \gg 1$) and cannot be applied properly to inlet centerbodies at supersonic speeds.

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