Engineering Notes

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AIAA 82-0060R

Three-Dimensional Inviscid Analysis of the Scramjet Inlet Flowfield

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Introduction

A COMPREHENSIVE research program is underway at the NASA Langley Research Center to develop an airframe-integrated, hydrogen-fueled supersonic combustion ramjet (scramjet) engine for hypersonic propulsion.[1,2] The current scramjet concept uses a rectangular module approach which has a fixed-geometry inlet with swept, wedge-shaped sidewalls. The sweep of the sidewalls, in combination with a recess in the cowl, allows some flow to spill out ahead of the cowl, thus producing a variable-geometry-like behavior with a fixed-geometry inlet.[3] This provides the potential to operate over a range of Mach numbers even with the fixed-geometry inlet.

The flow in a scramjet inlet is highly three-dimensional and has complex shock-expansion wave interactions. It also involves strong shock/boundary-layer interactions which may result in separated regions. To analyze such flows, it is necessary to solve the full Navier-Stokes equations. An effort in this direction was started with the development of a two-dimensional Navier-Stokes code, described in Ref. 4. The present Note describes a three-dimensional inviscid code which solves the three-dimensional Euler equations in full conservation form to analyze the scramjet inlet flowfield. Detailed results are presented for a scramjet inlet configuration over a range of Mach numbers.

Governing Equations and Method of Solution

The inlet flowfield is described by the three-dimensional Euler equations in conservation form. The governing equations in physical plane are transformed to a regular computational domain by using an algebraic numerical coordinate transformation[5] which generates a set of boundary-fitted curvilinear coordinates. The governing equations are solved by a time-asymptotic, unsplit, two-step, finite-difference method developed by MacCormack.[6] This method is highly efficient on the CDC-CYBER-203 vector processing computer for which the current code is written. A typical solution can be obtained in from 10 to 15 min of computer time depending upon the number of time-steps required for convergence. More details are given in Ref. 7 about the governing equations, the method of solution, and the boundary conditions.

Presented as Paper 82-0060 at the AIAA 20th Aerospace Sciences Meeting, Orlando, Fla., Jan. 11-14, 1982; submitted Jan. 21, 1982; revision received May 14, 1982.

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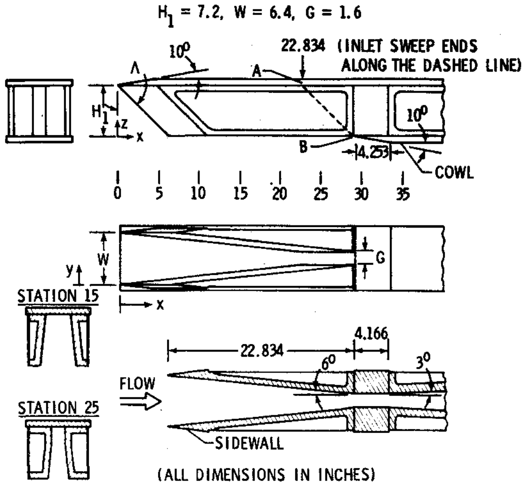

Fig. 1 Geometry of the scramjet inlet configuration.

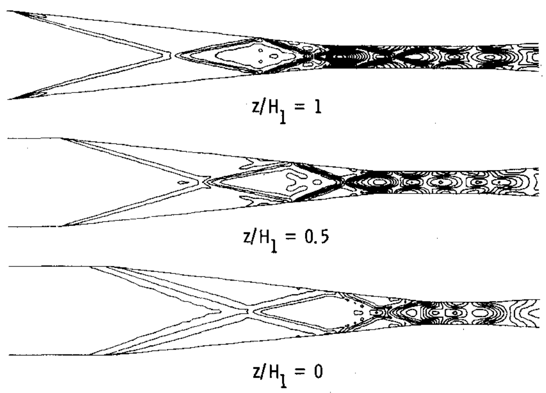

Fig. 2 Pressure contours in planes parallel to the plane of cowl ($M_I = 5.0$, $\Lambda = 45$ deg).

Results and Discussion

The code has been used to analyze the flowfield in a scramjet inlet configuration, shown in Fig. 1, which is also currently being used to study scramjet-related problems experimentally. In this configuration, most of the inlet compression is provided by the sidewalls which are swept, wedge-shaped surfaces. The sidewall sweep ends along line AB. In the experimental model, it is possible to vary the sidewall sweep, the cowl location, and the geometrical contraction ratio in order to be able to study the effects of various geometric parameters on the performance of the inlet over a range of Mach numbers. In the present numerical study, results are obtained for the sidewall sweep angles, Λ, of 30 and 45 deg over a Mach number range of from 3.4 to 6.0 at the face of the inlet. Various dimensions of the inlet are shown in Fig. 1.

To illustrate the complexity of the flow, Figs. 2 and 3 display the pressure contours in the inlet with $\Lambda = 45$ deg at Mach number, $M_I = 5.0$. In Fig. 2, the pressure contours are plotted in three planes parallel to the plane of the cowl, whereas in Fig. 3, the pressure contours are plotted in four planes perpendicular to the main flow direction. The contour

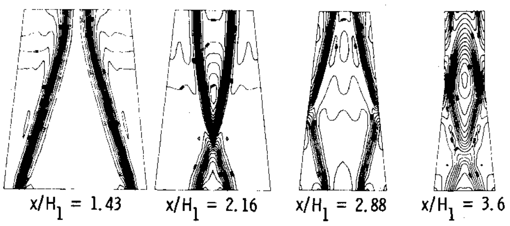

Fig. 3 Pressure contours at various axial locations ($M_I = 5.0$, $\Lambda = 45$ deg).

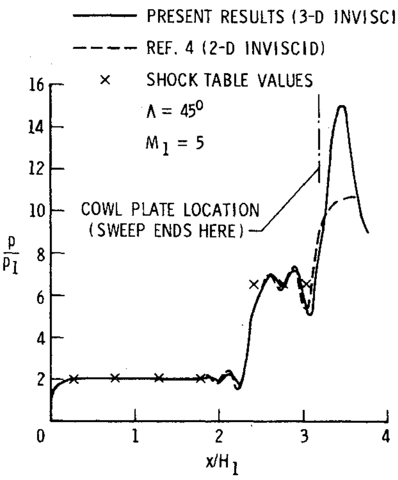

Fig. 4 Comparison of sidewall pressure distribution at $z/H_I = 0$.

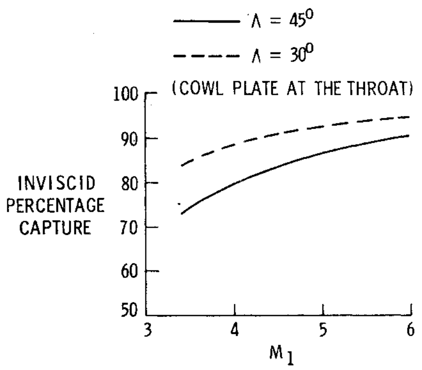

Fig. 5 Inviscid percentage capture as a function of Mach number.

plots clearly show the shock and expansion waves and their interactions with each other and with boundaries.

Figure 4 shows the sidewall pressure distribution at $M_I = 5.0$. The present results are compared with the pressure distribution obtained from the shock tables and with the two-dimensional analysis of Ref. 4. It is seen that the present distribution is in very good agreement with the other results up to the point of cowl closure. Beyond this point, the present analysis predicts much higher pressure due to the cowl shock which cannot be accounted for in two-dimensional analysis.

As mentioned earlier, the purpose of the sidewall sweep is to turn the flow downward, which results in some flow spilling out of the inlet ahead of the cowl plate. This provides the potential to operate over a range of Mach numbers even with a fixed-geometry inlet. The quantity of the flow captured by the inlet is a very important quantity in its performance calculations and needs to be estimated. Figure 5 shows the inviscid flow captured by the inlet as a function of Mach number for two sidewall sweep angles. These capture calculations are made with the cowl located at the minimum area section. The flow captured by the inlet with 45-deg sweep varies from 91% at $M_I = 6.0$ to 72.5% at $M_I = 3.4$. The capture with the 30-deg sweep is higher and varies from 94.5% at $M_I = 6.0$ to 84% and $M_I = 3.4$. In the calculations of the flow capture, the spillage due to the pressure differential between the inside and outside of the inlet has not been included. Of course, the viscous effects, which are not considered here, will also result in some decrease in the flow capture.

The preceding results are typical of the quantitative calculations that can be made with the present analysis. The numerical code can be very helpful in screening the inlet configurations by making similar calculations for other parametric variations of the basic geometry.

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AIAA 82-4243

Higher-Order Flow Angle Corrections for Three-Dimensional Wind Tunnel Wall Interference

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Nomenclature

c = chord
C_L = lift coefficient
l = semispan
L = spanwise lift distribution
M = Mach number
S = lifting surface
x = coordinate in the undisturbed flow direction
x_0 = $0.5\,(x_L + x_T)$
x_L = x coordinate of leading edge
x_T = x coordinate of trailing edge
y = coordinate normal to model plane of symmetry
z = vertical coordinate in the upward direction
Z = vertical coordinate of mean lifting surface
α = angle of attack
γ = lift distribution
τ = maximum height of parabolic arc

Superscripts and Subscripts

c = correction
ce = exact correction
F = free air corrected condition

Received March 15, 1982.

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