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Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

High Angle-of-Attack Inviscid Shuttle Orbiter Computation

William L. Kleb* and K. James Weilmuenster†
NASA Langley Research Center,
Hampton, Virginia 23665

Introduction

AN accurate description of the aerothermal environment is required to minimize the weight of the thermal protection system required on the leeside of winged re-entry vehicles. The inability of ground-test facilities to reproduce the high-enthalpy separated flow present during re-entry flight conditions, coupled with the prohibitive expense of flight tests, leads to the use of an analytical method—namely computational fluid dynamics (CFD)—to describe the flow.

Although the ultimate goal of this work is to accurately predict the leeside flow and its associated thermal environment, an essential and reasonable first step toward that goal is a comparison of pressure predictions by a code with wind-tunnel data. Until such CFD pressure predictions agree with wind-tunnel test cases, there is little hope of accurately predicting the thermal environment at flight conditions. Thus, the objective of this study is to compare the pressure distributions predicted by inviscid, perfect gas CFD to Shuttle Orbiter wind-tunnel data and to address any significant issues encountered during the computation.

Although flight data is available for the Shuttle Orbiter, a wind-tunnel case is chosen for this study to allow a tractable problem for preliminary investigation. A wind-tunnel case allows the perfect-gas assumption for the flow chemistry. This provides a significant computational savings over a several species finite-rate chemistry model which would be necessary if high-temperature effects present at flight conditions were to be included. In addition, by concentrating on the surface pressures, the analysis need only consider inviscid flow for general evaluation of the code capability. This further reduces the computational expense due to the absence of viscous terms and the associated decrease in the number of points required for the computational grid.

Previous computational efforts (such as STEIN[1] and HALIS[2]) have been directed toward the windward surface quantities, primarily due to restrictions in treating either the winged geometry or its associated subsonic regions at high angle of attack. The code used for this study, the LAURA (Langley Aerothermodynamic Upwind Relaxation Algorithm) code of Gnoffo,[3] represents a state-of-the-art code for computing the flow over complex configurations at hypersonic speeds. In the study, the LAURA code is applied to a wind-tunnel condition to initiate the assessment of the code's ability to predict the flow over a relatively complex hypersonic vehicle at high angles of attack. This presentation is used to highlight the pertinent results of a more detailed investigation[4] of the inviscid calculation over the Shuttle Orbiter with the LAURA code.

Numerical Method

The LAURA code is a point-implicit, finite volume solver based on the upwind-biased flux difference splitting of Roe. The code is capable of modeling any of three air chemistry assumptions: perfect gas, equilibrium, or thermochemical nonequilibrium. For this study, the code uses the perfect-gas, inviscid flow model. For a detailed description of the numerical algorithm in the LAURA code, see Ref. 3. Description of the physical flow models can be found in Ref. 5.

Geometry and Computational Mesh

The Shuttle Orbiter vehicle represents a very complex geometric modeling problem, especially the aft portion. Since this study is focused on the leeside flow over the vehicle forward of the elevon hinge line, simplifications are made to the aft section of the vehicle to greatly reduce the analytical geometry modeling and grid-generation effort. These simplifications are justifiable since the flow in the aft region of the vehicle is predominately supersonic. Thus, the modeling of the geometry aft of the elevon hinge line has negligible upstream influence. The geometrical simplifications consist of omission of the tail surface, body flap, and a continuation of the wing's trailing-edge thickness as a solid surface extending to the outflow plane. Note, however, that the entire forward portion of the vehicle is accurately modeled.

The volume grid, which contains just over one million grid points, is shown in Fig. 1. The grid has 120 points along the body, 140 circumferential, and 60 points from the body to just outside the bow shock.

Results and Observations

Computational results are obtained for flow about the Shuttle Orbiter at $M_\infty = 7.4$ and 40-deg angle of attack. Freestream conditions and measured surface pressures are taken from the wind-tunnel results reported by Dye and Polek[6] for which the Reynolds number per foot is 6.5×10^6.

During the computation, an inherent instability of the LAURA algorithm was encountered in the near-vacuum re-

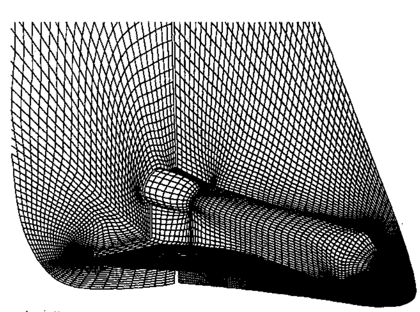

Fig. 1 Depiction of the volume grid (only every other grid line shown).

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*Research Engineer, Aerothermodynamics Branch, Space Systems Division.

†Senior Research Engineer, Aerothermodynamics Branch, Space Systems Division. Senior Member AIAA.

gion just below the wing-tip vortex on the leeside of the wing. The inviscid wall-boundary conditions had to be modified to maintain positive definite energies by specifying freestream total enthalpy at the surface. Note, however, that for a viscous calculation, this fix would no longer be available. Recently, a more rigorous fix for this problem was given by Einfeldt et al.[7]

Figure 2 shows a comparison of computed and measured pressure coefficient (C_p) distributions along the windward and leeward centerlines of the Shuttle Orbiter. A pressure distribution calculated by the HALIS code for the windward portion of a simplified Shuttle Orbiter is also included. As discussed earlier, the aft portion of the vehicle is not modeled accurately past 93% of the body length ($X/L = 0.93$). This is clearly evident in the windward surface pressures.

In the figure, the discrepancies in the data and predictions between 7 and 20% of the body length may suggest the possibility of a geometric discrepancy between the wind-tunnel model and the analytic description of the geometry used for CFD. Since the wind-tunnel Reynolds number is high (6.5×10^6/ft), it can be argued that the viscous interaction cannot account entirely for this size of discrepancy. The HALIS solution also shows similar geometrical inconsistencies because its geometry is comprised of a sequence of conic sections that are not slope continuous at their junctures. It is interesting to note, however, that even though the geometric models used with LAURA and HALIS were developed independently and by different means, the solutions are in good agreement with one another.

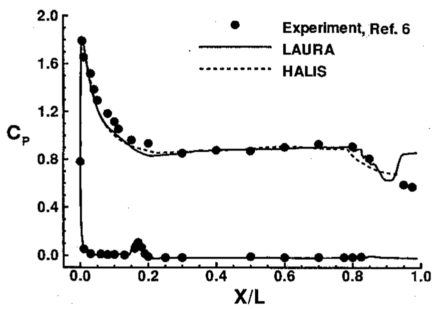
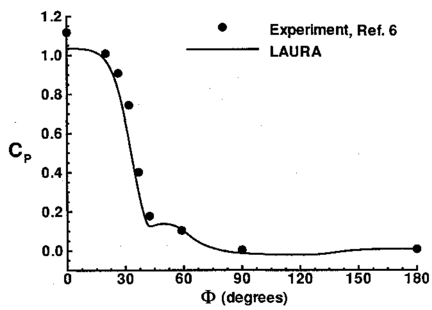
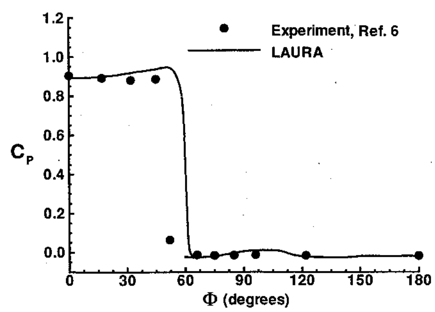


Fig. 2 Pressure coefficient along the windward and leeward centerlines for the Shuttle Orbiter at $M_\infty = 7.4$ and 40-deg angle of attack.

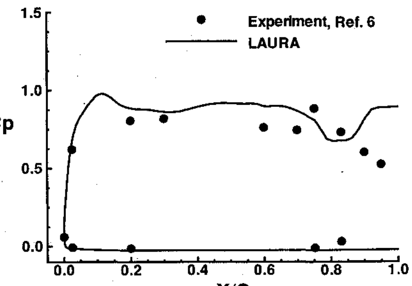


a) Fuselage station, X/L=0.1

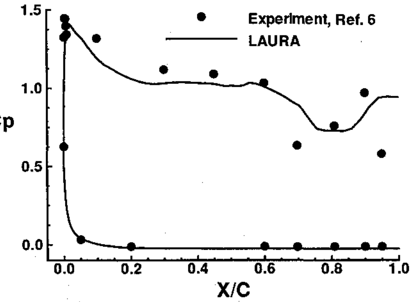


b) Fuselage station, X/L=0.6

Fig. 3 Pressure coefficient at two fuselage cross sections for the Shuttle Orbiter at $M_\infty = 7.4$ and 40-deg angle of attack.



a) Wing semi-span station, 2Y/B=0.4



b) Wing semi-span station, 2Y/B=0.6

Fig. 4 Pressure coefficient at two spanwise stations along the wing as a function of chord position for the Shuttle Orbiter at $M_\infty = 7.4$ and 40-deg angle of attack.

The windward surface pressure distribution predicted by LAURA around $X/L = 0.82$ is not smooth. This is due to irregularities in the surface geometry definition, and the discussion of Ref. 4 demonstrates that these surface irregularities are large enough to create compression waves.

Figure 3 presents the coefficient of pressure distribution as a function of the meridional angle Φ around the body at two cross-section stations. The angle Φ is measured from the windward centerline to the leeward centerline plane. The predictions and wind-tunnel data compare very well with the exception of the chine areas ($\Phi = 60$ deg) and the forward portion of the windward centerline ($\Phi = 0$ deg). As discussed, the centerline discrepancy for the $X/L = 0.1$ data is apparently due to a geometrical difference between the wind-tunnel model and the CFD model. The chine areas agree well until the last cross section ($X/L = 0.6$). At this station, the location of the pressure decrease around the wing is not predicted by the CFD solution. Since the first several stations agree well,[4] this could be attributed to slight geometric discrepancies between the wind-tunnel model and the CFD model at the leading edge of the wing. Additional possibilities for this discrepancy include inadequate grid resolution and/or accuracy of the measured pressures due to the extremely small magnitude of the leeside pressures.

Figure 4 shows the coefficient of pressure distribution at two spanwise stations along the wing ($2Y/B = 0.4$ and $2Y/B = 0.6$) as a function of the nondimensionalized chord position (X/C). (An additional outboard station is presented in Ref. 4). Again, due to geometrical simplifications in the CFD model of the vehicle aft region, the solution beyond the elevon hinge line is not applicable. The computed pressures are within 5% of the wind-tunnel data except at $X/C = 0.6$ and 0.7 on the windward surface of the inboard semispan station ($2Y/B = 0.4$).

Concluding Remarks

An inviscid solution for the Shuttle Orbiter was computed for a wind tunnel case. The pressures compare well with the wind tunnel data for both the windward and leeward sides. This implies that at least the salient inviscid flow features are being properly modeled. It was also found that a modified boundary condition was necessary to alleviate the inherent instability of Roe's flux difference splitting in the near-vacuum regions of the Shuttle Orbiter's wing-tip vortex. Also, for this inviscid computation, it was shown that slight surface imperfections of the windward surface of the Shuttle Orbiter noticeably contaminated the solution.

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Ernest V. Zoby
Associate Editor