JOURNAL OF AIRCRAFT
Vol. 42, No. 5, September–October 2005

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following 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).

Shock-Based Waverider Design with Pressure Gradient Corrections and Computational Simulations

Mark J. Lewis* and Marie-Laure Chauffour†
University of Maryland, College Park, Maryland 20742

I. Introduction

WAVERIDER geometries are of special interest for hypersonic applications because they offer the promise of higher lift over drag, L/D, than generic hypersonic bodies.[1–6] Any supersonic geometry with its bow shock attached to the leading edge may be thought of as a waverider. A particularly flexible waverider generation approach is the so-called "osculating-cone" waverider design method proposed by Sobieczky et al.[7] in 1990. This technique is a shock-based solution that defines the flowfield directly from a specified shockwave and allows the direct selection of inlet flowfield while providing good volumetrics and packaging. In doing so, it eliminates the need to select an initial generating body, with the associated uncertainty of choosing the "best" generator, and also allows more direct fitting of waverider aerodynamics to basic generic forms.

The osculating-cone method is not exact, but rather approximates a three-dimensional flowfield as a series of two-dimensional planes neglecting effects of crossflow. Several studies have already been performed to validate computationally and experimentally various osculating-cone waverider designs. Takashima performed numerical simulations on osculating-cone waverider shapes to integrate those as the forebody of a hypersonic vehicle.[8] The computational results at the design Mach number and attitude agreed with the general map of the analytically predicted flowfield, though shock resolution was inadequate to assess the match to desired accuracy.

Miller and Argrow tested two aluminum models of Mach 4 and Mach 6 osculating-cone geometries[9] in the Mach 4 unitary plan wind tunnel and the Mach 6 blow-down tunnel of the NASA Langley Research Center, respectively. At the design Mach number and attitude the experimental results confirmed the predicted location of the shock wave. The measured surface-pressure distributions generally agreed with the analytical predictions. That study also confirmed that the osculating-cone waveriders provided the high promised hypersonic L/D values. The particular shapes chosen in that study had small crossflow pressure gradients, and so the effects of neglecting those gradients should not have been significant. This may not be true in all cases.

Unlike the original waverider solutions of Nonweiler,[10] osculating-cone waverider designs will not exactly preserve the original design flowfield, and this has raised some questions about the validity of the derived configurations. Previous osculating-cone waverider work has assumed that the azimuthal pressure gradients in the original generating flowfield are minimal, and thus neglected these to simplify the design process.[11] In the present effort, these gradients are calculated and shown to be negligible in all but extreme cases, though the design process can be modified to provide some correction, as will be described.

II. Modified Osculating Cone Solution

Nonweiler's original waverider concept used body-derived flowfields, which begin with an assumed flowfield associated with a chosen generator.[10] Because the generator must be chosen first, this exact approach can impose restrictions on the flowfield properties; for instance, waveriders that start with flow over a cone will always have conical flow in the final derived flowfield. There is also no direct connection between the overall aerodynamic performance of the generator and that of the final waverider; a minimum-drag generator does not necessarily produce a high L/D waverider because the body drag comes from surface pressures, but the waverider is carved from a region of flow in the shock layer above the original generating surface.

Sobieczky's osculating-cone method solves the problem of choosing a generator by starting directly from a desired shockwave shape,

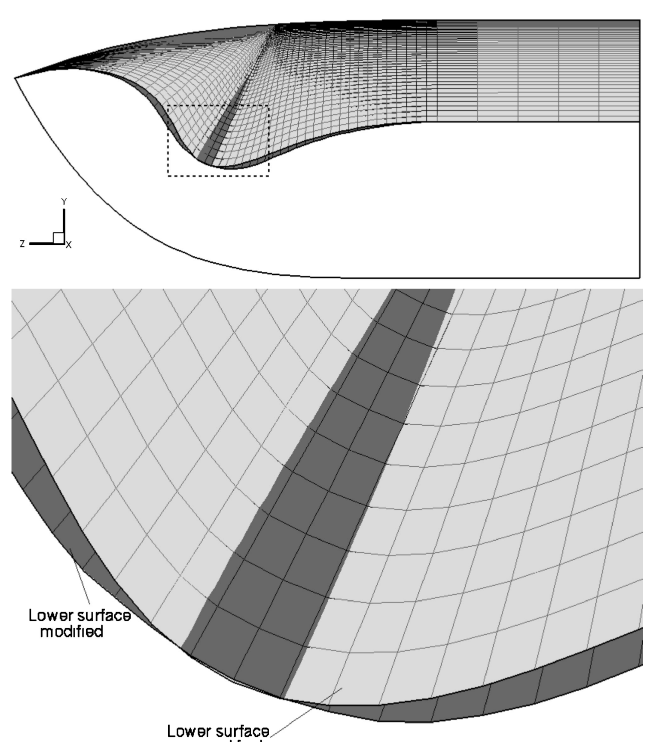


Fig. 1 Mach 3 waverider base plane.

Presented as Paper 2004-3405 at the AIAA/ASME/SAE/ASEE 40th Joint Propulsion Conference and Exhibit, Ft. Lauderdale, FL, 11–14 July 2004; received 24 August 2004; revision received 2 May 2005; accepted for publication 3 May 2005.

*Professor, Department of Aerospace Engineering; currently Chief Scientist, U.S. Air Force, Washington, D.C. 20330-1075; lewis@eng.umd.edu. Fellow AIAA.
†Graduate Research Assistant. Student Member AIAA.

not a generating body.[7] Slices of flow from the Taylor–Maccoll cone solutions are then assembled from the shockwave, derived as a function of local shock radius.[12,13] This makes for a more flexible solution, and one that can be more easily fit around desired inlet geometries, volumetric considerations, and so forth.[14–16]

The osculating-cone method does in fact produce a "virtual" flowfield generator associated with the specified shockwave, but the designer need not identify this directly. Wedge-derived waveriders and cone-derived waveriders may be thought of as limiting cases of the osculating-cone waverider method; wedge-derived forms correspond to an osculating region with an infinite radius of curvature, and cone-derived ones correspond to one with a constant radius of curvature.

A. Pressure-Gradient Corrections

Since osculating-cone solutions are built from slices of conical flows with varying radii of curvature, they are not exact, because they neglect the cross-flow pressure gradients that would result between adjacent conical flow slices. The present work introduces a simple methodology to account for the azimuthal pressure gradients. Because the generated flowfield is entirely inviscid, Euler's equation, $\mathrm{d}V^2 = -2\,\mathrm{d}p/\rho$, is applied to determine the local pressure gradients between osculating-cone slices. This is a valid approach, as opposed to using the fully viscous equations, because boundary effects cannot be added in until the vehicle surface is defined, after the flowfield has been determined. At each streamwise plane, a velocity correction is applied between adjacent points in the azimuthal direction:

$$\left(\Delta V_i^2\right)_{\mathrm{corr}} = -(2/\rho_i)\Delta P_i = -(2/\rho_i)[(P_{i+1} - P_{i-1})/2]$$

$$V_i = V_i + \sqrt{\left(\Delta V_i^2\right)_{\mathrm{corr}}} \tag{1}$$

Typical results of this correction, for shapes with large gradients at Mach 3 and Mach 6, are presented in Figs. 1 and 2, respectively. Note that in neither case is the modified geometry significantly different than the original design. This suggests that previous osculating-cone solutions are actually quite accurate, and azimuthal pressure gradients should be small. For the Mach 3 waveriders, some geometric differences between the corrected lower surface and the uncorrected lower surface can be observed in Fig. 1. Not surprisingly, the modifications introduced by the correction method are most significant primarily in the region where the gradients of shock wave curvature are highest, which is where the highest spanwise pressure gradients are located. For the Mach 6 waveriders, differences between uncorrected and corrected forms are less significant. At Mach 10, the inclusion of azimuthal pressure gradient introduces virtually no significant changes.

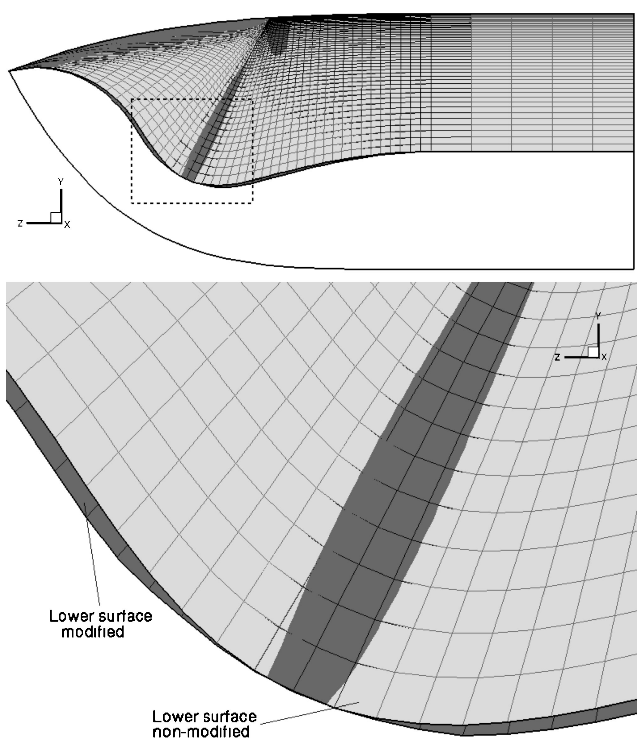
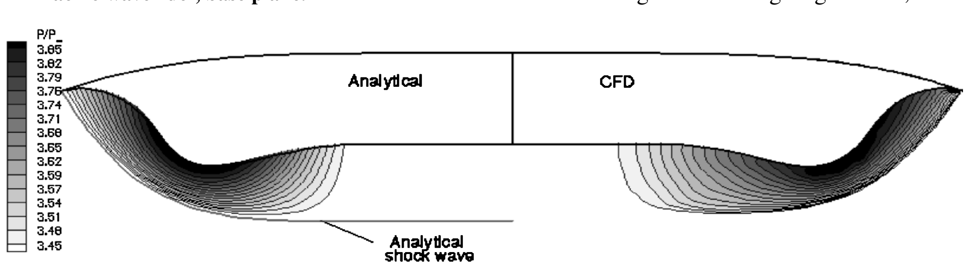


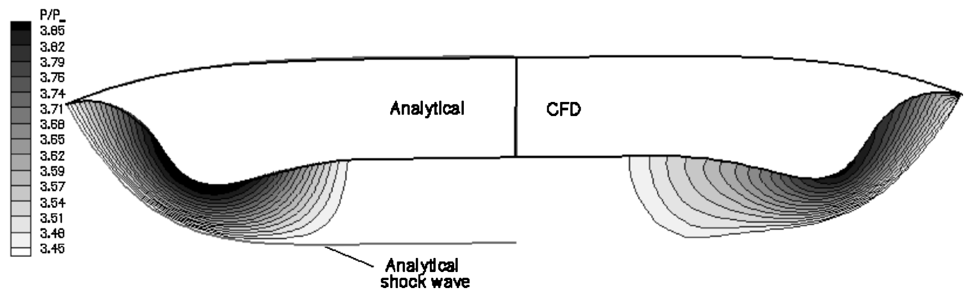
Fig. 2 Mach 6 waverider, base plane.

B. Calculated Flowfield Changes with Modification

Computational solutions were obtained to evaluate the impact of the geometry modifications of the pressure corrections on the waverider flowfield. The inviscid flowfield predicted by the analytical solution of the osculating-cone generated flowfield was compared to the results from an inviscid computational simulation obtained with CFD-FASTRAN from CFD Research Corp., a fully implicit finite-volume code using local time. At each time step, flux vectors were evaluated using Roe's upwind flux-difference splitting with an Osher-Chakravarthy flux limiter to achieve third-order spatial accuracy. The solutions were allowed to converge until the L_2 norm of the density residual dropped at least by three orders of magnitude. The changes in lift and drag coefficients were also less than 10^{-3} over 100 iterations. Finite-volume grids were constructed using a Cartesian grid generator, CFD-GEOM. Waverider



a) Pressure-gradient modified osculating cone waverider



b) Unmodified osculating cone waverider

Fig. 3 Mach 6 waverider, normalized pressure contours, isometric view, and inlet plane.

configurations present the double challenge of a sharp leading edge with a strong shock wave attached to it; the grid was locally refined in order to capture the solution details at the leading edge and to sharply resolve the gradients associated with the shock wave. Computational grids were shock-fitted in order to reduce freestream points, with $100 \times 100 \times 70$ points around the waverider half-body.

A comparison of the normalized base pressure contours at Mach 6 is presented for both a corrected and an uncorrected waverider in Fig. 3. Design shock angle is 17 deg, with a design altitude of 28 km, corresponding to velocity 1800 m/s and L/D approximately 4. The shock was selected to provide nearly planar flow down the ventral axis and conical flow near the leading edge. In both cases, the predicted shock-wave location agrees very well with the CFD result. Also in both cases, the pressure contours exhibit some smearing in the azimuthal direction, though the uncorrected waverider shows more distortion and pressure contours deviate more from purely conical form. Note also that the uncorrected waverider shape has a smaller region of uniform ventral flow uniformity, though the differences are subtle. Overall, the differences between corrected and uncorrected osculating-cone solutions are indeed small for this chosen example, and though the azimuthal correction adds little computational complexity, a form derived without it would still offer good agreement between predicted and derived performance. As the Mach number increases, the flow tends to become unidirectional in the streamwise direction; as a result, the influence of azimuthal pressure gradients becomes even less significant.

Interestingly, the overall aerodynamic performance of the corrected and uncorrected designs is quite similar. The lift coefficient calculated for the corrected waverider, $C_L = 0.0496$, is 0.106% higher than the analytical prediction for that shape; that of the uncorrected waverider, $C_L = 0.0485$, is 0.196% lower. However, the overall L/D of the uncorrected shape (both predicted and calculated) is actually higher than that of the corrected one by about 0.5%, dropping from 3.92 to 3.90 with the azimuthal correction. These small differences suggest some interesting trends but are of minimal practical significance.

III. Conclusions

In the present work a modified osculating-cone waverider design technique has been introduced. When applied, the derived geometry could be modified to provide a better match between predicted analytical flowfields and actual computed flowfields, especially in the location of pressure gradients. However, only small modifications of the streamlines were observed. The differences between the corrected and uncorrected configurations are most significant in the regions of high gradient of the shock-wave curvature. As the Mach number increases, the effect of azimuthal pressure gradients decreases, so that the streamlines tend to remain in their original osculating plane even without correction. Overall, for the different configurations studied, the modified waveriders are quite similar to the waveriders derived with the previous osculating-cone waverider method, with a decreasing effect of the modifications with increasing Mach number. This effect is characteristic of hypersonic flow, for which Mach number independence rules high-Mach-number flowfields.

From a vehicle integration standpoint, this study has shown the influence of the azimuthal pressure gradients on the inlet-plane flowfield distribution. At low Mach numbers, those gradients will have a small but noticeable effect. For high hypersonic Mach numbers this work has confirmed that the geometry of the streamlines was not perceptibly affected by azimuthal gradients. The geometry of the lower surfaces of waveriders for such configurations is consequently not strongly impacted by the corrections incorporated within the present osculating-cone waverider design. This study validates the assumption made in earlier osculating-cone waverider solutions that the azimuthal pressure gradients along the waverider geometry are negligible at sufficiently high Mach number (over Mach 4–5). This conclusion is of course dependent on the particulars of the individual waverider design. However, with a minor modification, some modest improvement in the prediction of the streamline location can be had, albeit with a small decrease in overall aerodynamic performance.

Acknowledgments

This work has been sponsored in part by the NASA-DoD University Institute, Grant NCC-3989. Claudia Meyer of the NASA Glenn Research Center is program manager, and appreciation is expressed for her efforts, as well as those of Mark Klem and Harry Cikanek, also of NASA Glenn. Appreciation is also expressed to John Schmisseur and Walter Jones of the Air Force Office of Scientific Research and Ken Harwell, Special Assistant to the Director, Defense Research and Engineering.

References

[1]O'Neil, M. K. L., and Lewis, M. J., "Design Tradeoffs on Scramjet Engine Integrated Hypersonic Waverider Vehicles," *Journal of Aircraft*, Vol. 30, No. 6, 1993, pp. 943–952.

[2]Lobbia, M., and Suzuki, K., "Numerical Investigation of Waverider-Derived Hypersonic Transport Configurations," AIAA Paper 2003-3804, June 2003.

[3]Lewis, M. J., and McRonald, A. D., "Design of Hypersonic Waveriders for Aeroassisted Interplanetary Trajectories," *Journal of Spacecraft and Rockets*, Vol. 29, No. 5, 1992, pp. 653–660.

[4]Strohmeyer, D., Eggers, T., and Haupt, M., "Waverider Aerodynamics and Preliminary Design for Two-Stage-to-Orbit Missions, Part 1," *Journal of Spacecraft and Rockets*, Vol. 35, No. 4, 1998, pp. 450–458.

[5]Heinze, W., and Bardenhagen, A., "Waverider Aerodynamics and Preliminary Design for Two-Stage-to-Orbit Missions, Part 2," *Journal of Spacecraft and Rockets*, Vol. 35, No. 4, 1998, pp. 459–466.

[6]O'Brien, T. F., and Lewis, M. J., "Rocket Based Combined-Cycle Engine Integration on an Osculating Cone Waverider Vehicle," *Journal of Aircraft*, Vol. 38, No. 6, 2001, pp. 1117–1123.

[7]Sobieczky, H., Dougherty, F., and Jones, K. D., "Hypersonic Waverider Design from Given Shock Waves," *Proceedings of the First International Hypersonic Waverider Symposium*, Univ. of Maryland, College Park, MD, Oct. 1990.

[8]Takashima, N., "Optimization of Waverider-Based Hypersonic Vehicle Designs," Ph.D. Dissertation, Dept. of Aerospace Engineering, Univ. of Maryland, College Park, May 1997.

[9]Miller, R. W., et al., "Experimental Verification of the Osculating Cones Method for Two Waverider Forebodies at Mach 4 and Mach 6," AIAA Paper 98-0682, Jan. 1998.

[10]Nonweiler, T. R. F., "Aerodynamic Problems of Manned Space Vehicles," *Journal of the Royal Aeronautical Society*, Vol. 63, 1959, pp. 521–528.

[11]Graves, R. E., and Argrow, B. M., "Aerodynamic Performance of an Osculating-Cones Waverider at High Altitudes," AIAA Paper 2001-2960, June 2001.

[12]Leipman, H. W., and Roshko, A., *Elements of Gasdynamics*, Wiley, New-York, 1953, pp. 85–88.

[13]Taylor, G. I., and Maccoll, J. W., The Air Pressure on a Cone Moving at High Speeds, I, II, Proceedings of the Royal Society, Ser. A, Vol. 139, No. 838, 1933, pp. 278–311.

[14]Center, K. B., Sobieczky, H., and Dougherty, F. C., "Interactive Design of Hypersonic Waverider Geometries," AIAA Paper 91-1697, June 1991.

[15]Jones, K. D., Sobieczky, H., Seebass, A. R., and Dougherty, F. C., "Waverider Design for Generalized Shock Geometries," *Journal of Spacecraft and Rockets*, Vol. 32, No. 6, 1995, pp. 957–963.

[16]Jones, K. D., and Center, K. B., "Waverider Design Methods for Non-conical Shock Geometries," AIAA Paper 2002-3204, June 2002.