COMPUTATIONAL AND EXPERIMENTAL INTERFEROMETRIC ANALYSIS OF A CONE-CYLINDER-FLARE BODY

By John R. Cipolla, Aerospace Engineer

Work performed from February 1989 to November 10, 1989, while working in the CFD Section, Aerodynamics Branch, Air Force Armament Laboratory (AFAL), Eglin AFB, Florida

Abstract

A series of computational fluid dynamic (CFD) analysis and experiment is discussed that probes the interaction between multiple shock waves and the adjacent boundary layer at high supersonic speed. For a cone-cylinder-flare configuration the viscous boundary layer and its interaction with the outer flow field is computationally determined and then compared to an experimental technique using holographic interferometry. Ultimately, the base flow region of a projectile can be modeled using CFD and its results compared to experimental interferometric data during the validation stage of code development.

I. Introduction

This proposed paper will present results of an experimental study applying holographic interferometry to determine the flow field of a three-dimensional cone-cylinder-flare model in free-flight. Comparison of experimental results with numerical predictions using the Eglin Arbitrary Geometry Implicit Euler (EAGLE) code has been performed to access the performance of this steady-state finite volume Euler flow solver. Also, the experimental work provides a valuable database for future design of high-speed projectiles because more detailed flow field information can be captured by this unique optical technique than by any other optical method. For example, the fringe distribution and spacing in the flow field indicates the relative magnitude of the local density distribution throughout the region of interest. The density field can be deduced from an interferometric analysis based on the Abel transform and a reconstruction of a holographic image. This study demonstrates the feasibility of using interferometric data to assess the performance of a computational method in the validation stage of its development.

II. Background

In supersonic and hypersonic flow an area of extreme importance to the designer is the interaction of shock waves with the boundary layer of a high-speed projectile or vehicle. These phenomena, called viscous interaction, will produce a greater pressure distribution than would otherwise be predicted from inviscid theory alone. In addition, the effect of a shock wave impinging on a boundary layer will produce localized high temperature effects and boundary layer separation. Hypersonic boundary layers are thick in comparison to slow speed boundary layers, and as a result the ability to measure and predict the flow field in this region is extremely important. A thick boundary layer leads to a major interaction or coupling between the growth of the boundary layer and the properties of the outer inviscid flow. Whether this interaction is strong or weak greatly influences the ability of existing computational fluid dynamics codes to resolve the physics of a flow in a particular region of hypersonic flow. The ability to measure these effects and to calibrate and validate existing computational methods is essential to designing efficient high-speed vehicles and to minimize heating and ablation effects. A nonintrusive technique to measure these effects and to produce a database for comparison with CFD results is essential to remove the uncertainty of physical measurement systems.

The optical method described is an ideal way to measure properties within a hypersonic flow field without altering the flow field and, as a consequence, reducing the reliability of comparison with theoretical results.

III. Test Configuration

A model was fabricated to demonstrate the basic features of supersonic flow. The chosen configuration was a cone-cylinder-flare model, which, at supersonic speed, will produce a bow shock in close proximity to an associated expansion wave at the edge of the cone section, and another shock at the compression corner of the aft flare. Figure-1 presents a sketch of the configuration that was tested at the Aeroballistic Research Facility (ARF) at Eglin AFB, Florida. The model was accelerated to Mach 3 and examined within the free-flight facility using a holographic interferometric technique. The ARF is an enclosed concrete structure used to examine the exterior ballistics of various munitions while in free flight. The instrumented section of the range is 207 meters in length and has 131 locations available for instrumentation sites. However, for this experiment the optical equipment was located at just one section.

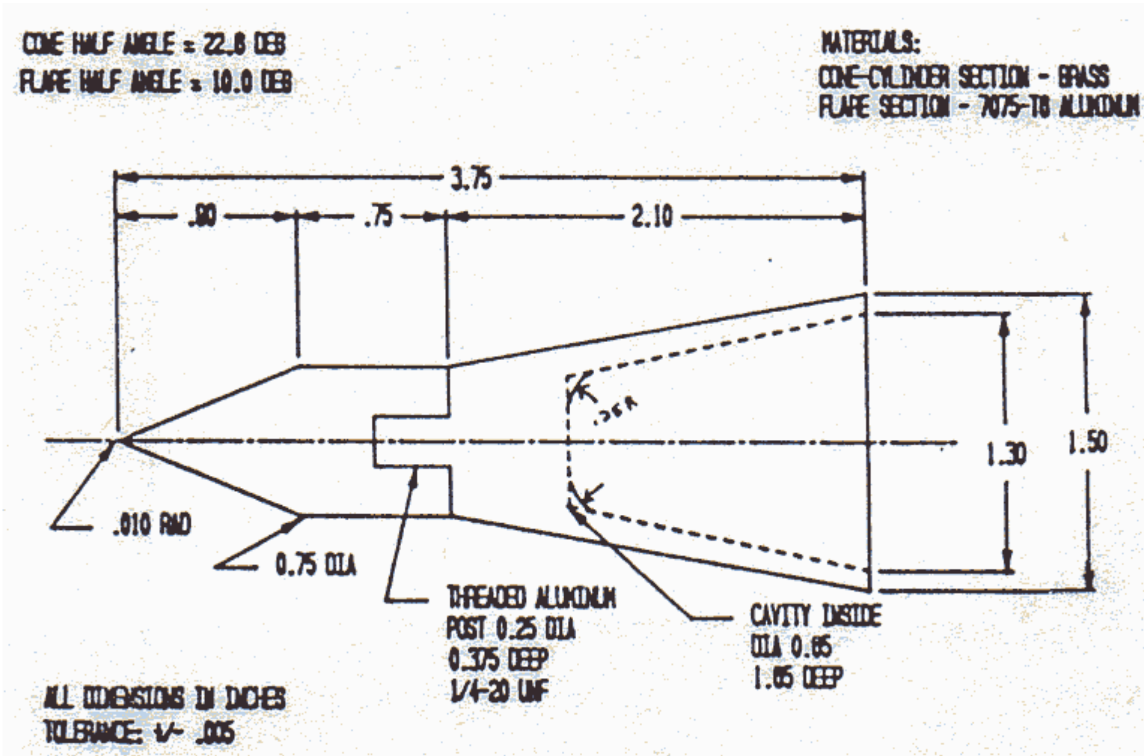

Figure-1. Sketch of Cone-Cylinder-Flare Body

IV. Experiment

Holographic interferometry, which is used in this experiment, utilizes light waves traveling the same path but separated from each other in time by a precise increment. The light waves generated by a coherent source, such as a laser, encounters the same optical path, lenses, mirrors, and tunnel windows, and as a result the effective pathlength variations are restricted to the refractive index field within the test section. The density variations in a flow field around a projectile provide the optical properties, which refract the waves to produce an interference fringe pattern. The phase variations caused by the density field produce the constructive and destructive interference of the light waves, which produce the fringe lines of the interferogram. Object waves containing information of interest, such as local density, and a mutually coherent reference wave are combined to produce a hologram construction. Integration over time of the superposition of these waves through the test section yields an intensity field of recorded flow field data. The data can be obtained by illuminating the hologram with a reconstructing wave, which simulates the original reference wave. Superposition of two holographically reconstructed waves traveling along the same path produces a second interference condition where the spatial-phase difference of the two beams produce an intensity field of spatial information, i.e., flow variables such as density and pressure. The interferogram may be analyzed to deduce the spatial variation of flow field data, such as density, for comparison with results from a computational method. Figure-2 presents a hologram generated in this series of tests of a cone-cylinder-flare model flying at Mach 3.

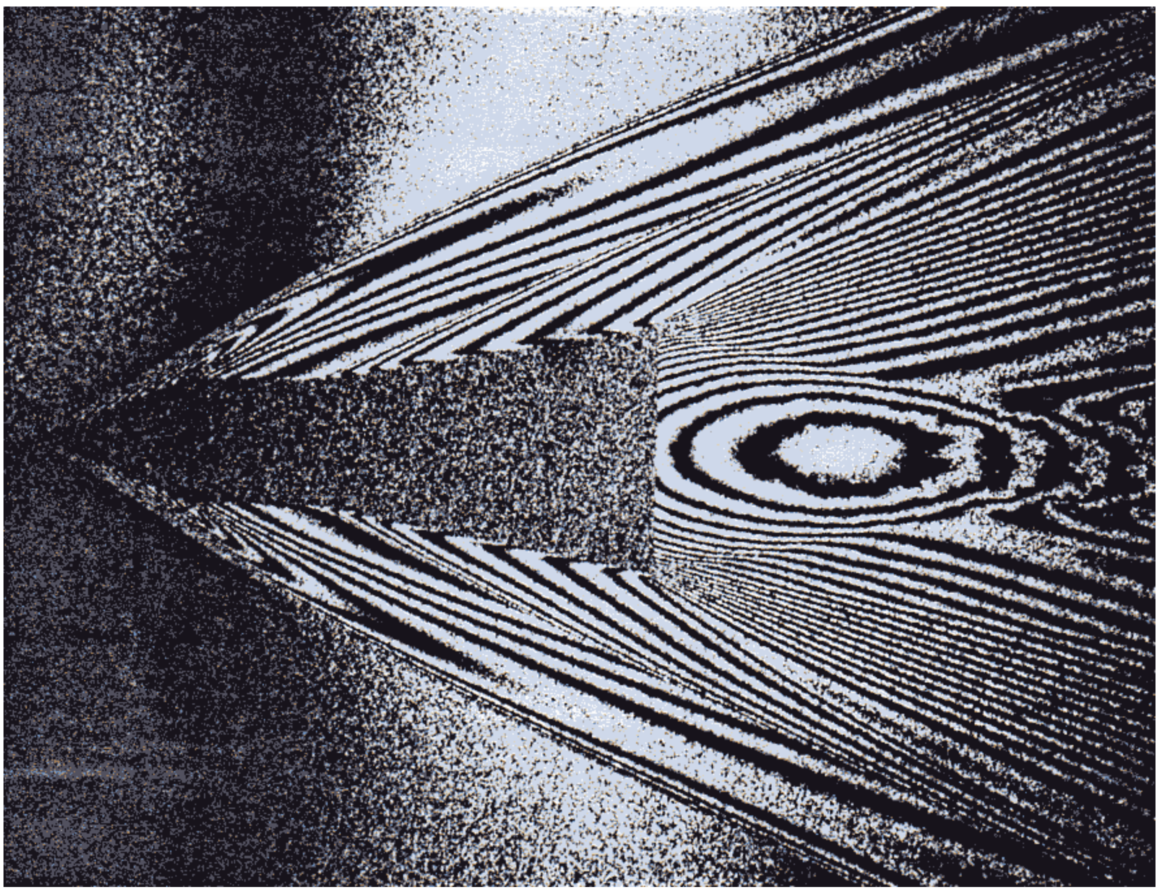

Figure-2 Experimental Interferogram

V. Computational Method

An H-grid was used to model the cone-cylinder-flare geometry by applying the EAGLE code. This process is a multi-block grid generation and steady-state flow solver system. For this configuration, a four-block construction was used as shown in Figure-3. This is a three-dimensional field of grid points used by the EAGLE flow solver to generate the required density distribution. The infinite fringe simulation computer program utilizes density distribution and free-field parameters such as temperature and pressure to generate a simulated interferogram. A perfect H-grid was generated by iteratively determining the spacing required at the block intersections. In this way, vertical lines of constant x coordinates were generated down the axis of the body. An H-grid construction is a requirement because the I_SIM fringe simulation program is, at present restricted to axisymmetric profiles of density in the vertical direction (y) at a number of arbitrary axial (x) locations.

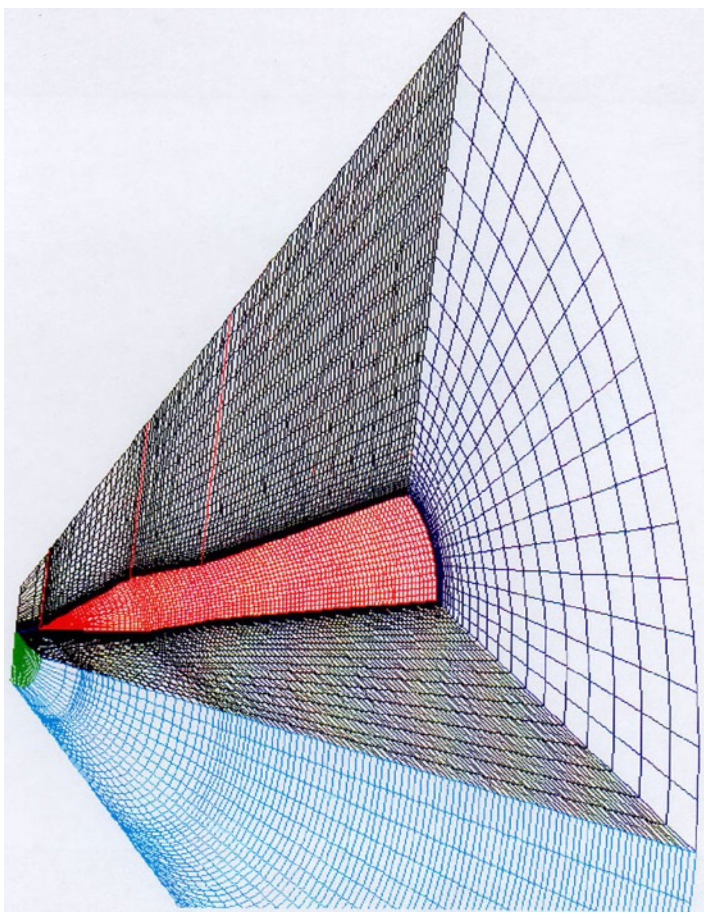

Figure-3, Four Block EAGLE Grid

A special computer program was developed to interface the flow solver to place density and grid point location data into the proper format for use by the I_SIM fringe simulation program. A single axial plane of EAGLE density information was converted to one block by combining blocks 2, 3, and 4 of the EAGLE solution. The single block H-grid measures 100 x 36 points in the axial and vertical directions, respectively. The density distribution data is converted into an optical pattern of fringes by the fringe simulation program. Figure-4 is the result of applying the I_SIM fringe simulation program using the EAGLE CFD density distribution. Conventional density contours generated by the EAGLE flow solver for the Mach 3 case is presented in Figure-5.

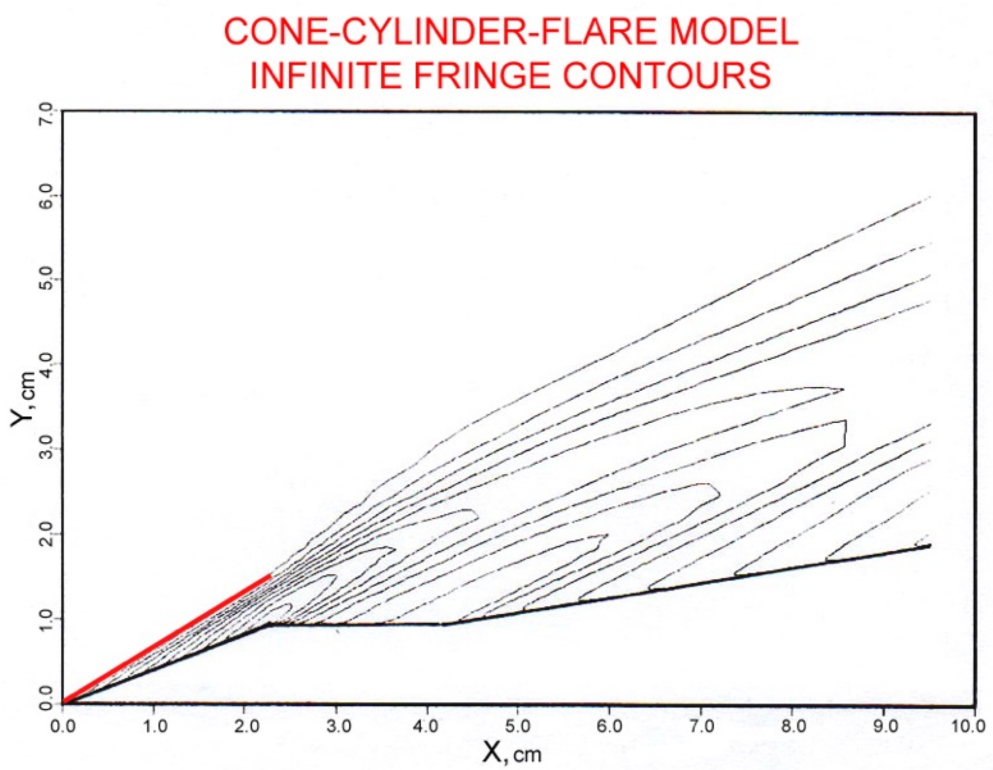

Figure-4, Theoretical Interferogram

The comparison of the simulated fringe pattern using the CFD density distribution (Figure-4) and the experimental fringe pattern (Figure-2) indicates good agreement along the surface of the model. Each corresponding segment of the model surface: cone, cylinder and flare have identical numbers of fringe lines and fringe distributions. The distribution and spacing comparison indicates that both fringe patterns, experimental and theoretical, are based on density data of equivalent density magnitude and spatial distribution. Agreement is also achieved in the regions between the shock and expansion waves. However, the shock waves are not clearly visible in the simulated fringe pattern. This is possibly due to smearing of the solution across several grid cells as the shock wave is captured in the time dependent iteration process. However, shock angle and expansion wave locations are all clearly identical for both the simulated and experimental interferograms.

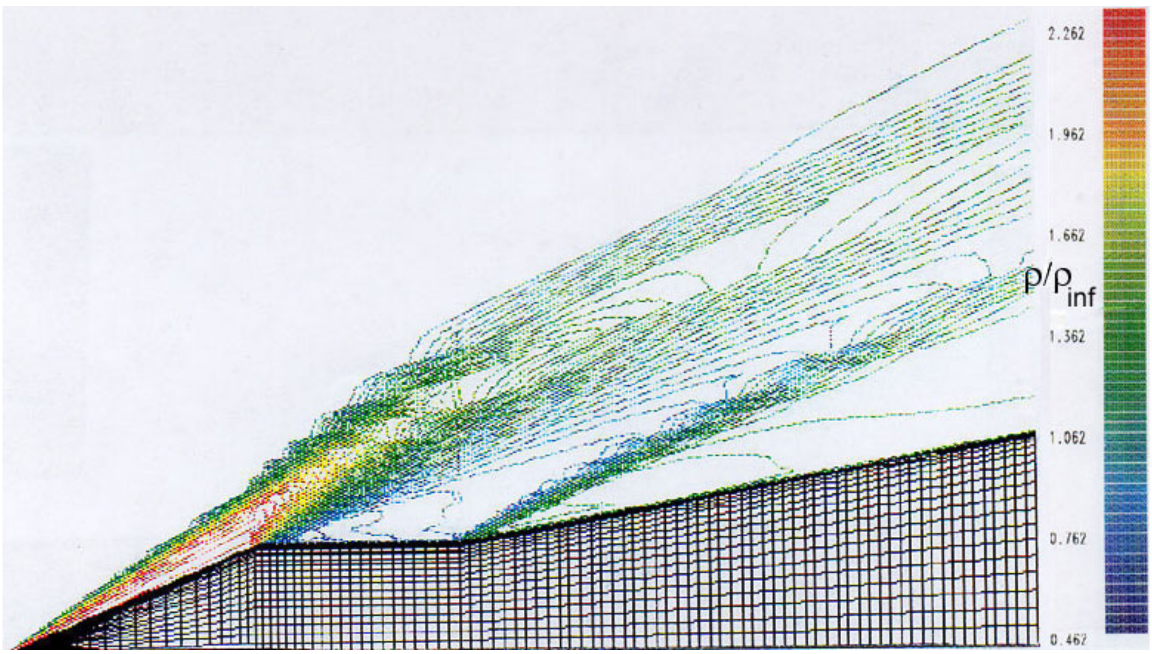

Figure-5, EAGLE Density Contours

EAGLE, an inviscid flow solver, is able to accurately model the Mach 3 flow condition because the boundary layer is thin in relation to the shock standoff distance for this configuration. This is an example of a weak interaction between the shock wave and the adjacent boundary layer. While Mach 3 may definitely be defined as supersonic, it does not yet classify as hypersonic flow normally defined to be greater than Mach 5.

The objective of this paper is to model the cone-cylinder-flare configuration using a full Reynolds averaged Navier-Stokes code, which is being developed at Eglin Air Force Base by the CFD section. The viscous boundary layer and its interaction with the inviscid flow field may then be computed and compared with the experimental interferograms. Also, the base flow region of the projectile will be modeled and compared to experimental data obtained by free-flight measurement.

VI. Conclusions

This study demonstrates the feasibility of using interferometric data to assess the performance of a computational method in the validation stage of its development. In addition, the non-intrusive nature of the experimental method assures that the flow is not disturbed by the presence of probes or other measuring instrumentation. This method represents a major development as a potential source for data used in the validation of computational fluid dynamics codes.

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Acknowledgements

NOTE 1: The author acknowledges Dr. J. E. Milton from the University of Florida, Eglin AFB for the background information provided about ARF's holographic interferometry technology and the ARF team who conducted the range shots that generated the CCF holographic image appearing in Figure-2.

NOTE 2: This paper is based on work the author performed from February 1989 to November 10, 1989, while working in the CFD Section, Aerodynamics Branch, Air Force Armament Laboratory (AFAL), Eglin AFB, Florida. This edition of the original paper is

identical to the report submitted November 10, 1989, except for the addition of an Abstract, Modern References and Acknowledgements.

NOTE 3: The author acknowledges Dr. L. Bruce Simpson for contributing the I_SIM fringe simulation tool used by the author to generate theoretical holographic simulations. Dr. Simpson stated he acquired this code from an engineer at NASA Ames. To achieve a workable computer program, I_SIM required debugging hundreds of lines of Fortran code. Finally, the author acknowledges Dr. Simpson for "initial instruction" for using the Cray 2 supercomputer's Fortran debugging tool.

NOTE 4: In a letter of recommendation dated August 28, 1990, Dr. L. Bruce Simpson stated the following about the work presented in this paper, ***"Working in conjunction with the Aeroballistics Research Facility (ARF), John numerically simulated holographic interoferometric fringe patterns from a CFD solution and compared these with experimentally obtained interferograms in the ARF. This proved to be a new and innovative method for CFD code validation methods and was reported on by John et al in an AIAA conference paper".*** According to Dr. Simpson portions of this paper were to be presented at the 28th Aerospace Sciences Meeting held January 8-11, 1990. John Cipolla was supposed to be one of the CFD coauthors for what eventually became AIAA-90-0621.

Dr. L. Bruce Simpson
Chief, Computational Fluid Dynamics Section
Air Force Armament Laboratory, Eglin AFB, Florida