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Calculating Vortices for Finned Missiles Using the WIND Flow Solver

by David J. Haroldsen and Walter B. Sturek

ARL-TR-2542

June 2001

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Aberdeen Proving Ground, MD 21005-5067

ARL-TR-2542 **June 2001**

Calculating Vortices for Finned Missiles Using the WIND Flow Solver

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Abstract

The U.S. Army Research Laboratory is interested in applying state-of-the-art computational tools to the study of projectile aerodynamics at angle of attack and moderate Mach number. The WIND flow solver has been used to study the aerodynamics of two missile configurations. WIND successfully incorporates grids generated by the GridPro grid generation package. WIND gives good scalability and good overall performance on parallel computer platforms. This report discusses several aspects of interest concerning generating grids to use with WIND and the process of obtaining solutions.

Acknowledgments

This work was supported by a grant of computer time from the Major Shared Resource Center at the U.S. Army Research Laboratory (ARL). The Scientific Visualization Laboratory at ARL also gave assistance.

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1. Introduction

Researchers in computational fluid dynamics at the U.S. Army Research Laboratory (ARL) are interested in investigating a wide array of complex fluid flow problems. These problems include flow around complex bodies, flow at moderate and high Mach number, and flow at moderate to high angles of attack. A recent study examined using the predictive capability of several different Navier-Stokes flow solvers applied to the case of an ogive-cylinder configuration at supersonic flow velocities and at several different angles of attack[1]. Since that study, considerable advances have been made in computer hardware and software technologies, permitting the investigation of more complicated flow scenarios. This study is an attempt to extend the previous work by investigating the predictive capability of the WIND flow solver to investigate flow problems for missiles with fins at angle of attack and moderate Mach number.

The WIND package has numerous capabilities that make it potentially attractive for computational researchers. Among these features are the numerous turbulence models, ease of use, portability, parallel processing capability, and the ability to incorporate grids with a generalized topology. This particular feature makes WIND attractive to use with the GridPro grid-generation package. GridPro produces structured multiblock grids with nonoverlapping block interfaces.

The primary focus of this effort is to investigate how well WIND can be adapted to use with complex flow problems and to use in conjunction with other state-of-the-art software. The focus of this work is on the methodology and practical aspects of incorporating WIND as a tool of computational researchers. Validating the WIND predictions by comparing them with experimental data will be considered in a later work. This study considers the application of WIND 1.0 to the study of two different missile configurations at angles of attack from 14–40°

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[1] Sturek, W. B., T. Birch, M. Lauzon, C. Housh, J. Manter, E. Josyula, and B. Soni. "The Application of CFD to the Prediction of Missile Body Vortices." 35th Aerospace Sciences Meeting and Exhibit, Reno, NV, 6–10 January 1997.

and at Mach numbers near 2.5. Generating grids for WIND using the GridPro package is discussed, and results for different turbulence models are presented.

2. Missile Configurations

Two missile configurations were examined in this study. Both missiles consist of a 3-cal. nose cone and a 10-cal. cylindrical body. Each missile has four fins with symmetry about the pitch plane. The specific fin geometry and placement is shown in Figures 1 and 2.

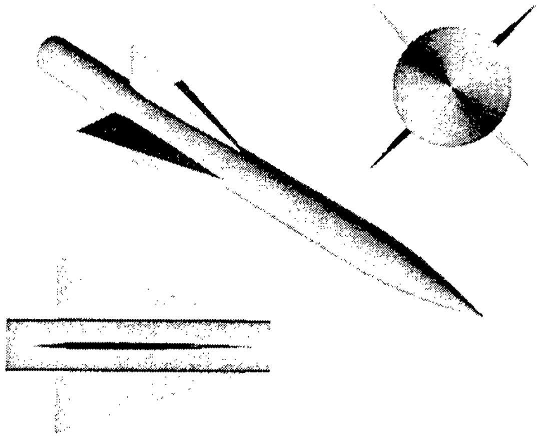

Figure 1. Missile 1 Configuration.

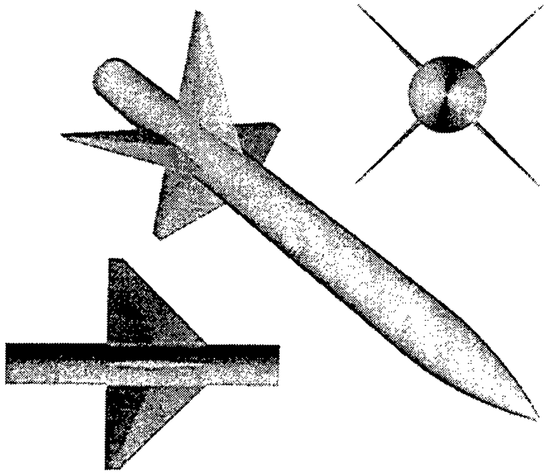

Figure 2. Missile 2 Configuration.

Missile 1 was studied at roll angles of 0° and 45°, Mach 2.5, and angle of attack 14° with a Reynolds number of 1.12×10^6. Missile 2 was studied at a roll angle of 45°, Mach 1.6 and 2.7, and angle of attack 40° with a Reynolds number of 250,000.

3. Grid Generation

The grid generation for this investigation was done using the GridPro grid generation software. GridPro is a product of Program Development Corporation in White Plains, NY. This package is of interest because it incorporates a topology-based approach to generating grids. This approach emphasizes the underlying topology of the geometric shapes and of any flow features rather than focusing on the geometry of the problem. The package consists of a GUI for topology design, the grid generation software, and utilities for manipulating grids. GridPro produces multiblock structured grids capabable of outputing data in a variety of formats. An important consideration when using GridPro is that the adjacent zones abut but do not overlap. The user can also customize GridPro to output initial boundary data relevant to a particular flow solver.

The user designs the topology by constructing a coarse, unstructured, hexahedral mesh in the region of interest. The hexahedral elements become the individual blocks of the final multiblock grid. The user controls only the topological structure of the grid; the grid generator automatically calculates precise placement of grid lines. Because the gridding process is largely automatic, the user has a significant amount of flexibility in designing the fundamental topology of the grid. This flexibility includes being able to locally define the grid in regions of interest while leaving a coarser grid in regions with insignificant flow variation. After the topology design is complete, the user invokes the grid-generation software. The resulting grid for a complex shape may result in hundreds of blocks.

The utilities included with the package allow a variety of operations to the final grid. Two of particular interest are the block-merging utility and the clustering utility. The block merging utility merges the (often) large number of blocks to a more manageable number. The user can control the number of grid nodes that are allowed in each block of the final configuration. Thus, the merging utility together with the initial topology design can be used as an *a priori* "domain decomposition" tool. The other utility of interest clusters grid lines to a particular surface. In practice, the grid generation package is always used to generate Euler grids, and the clustering utility is used to obtain a viscous grid. This significantly reduces the time required to obtain a viscous grid.

For the missiles under consideration, the topology design required several days to construct a reasonable topology. The grids were generated using a SGI ONYX with R12000 CPUs. The grid generation generally required on the order of 6–8 hr of CPU time. The initial grids in each case had on the order of 375 blocks for 1/2 of the flow volume (symmetry assumed). This number of blocks was reduced by merging to a more tractable number. The final grid configurations are listed in Table 1.

Table 1. Grid Details

Missile No.	Roll Angle (degrees)	Blocks	Grid Points (millions)
1	0	35	4.1
1	45	42	4.3
2	—	26	4.2

The topology designed for the missiles did not have rotational symmetry; therefore, different topologies and grids had to be generated for missile 1 at different roll angles. Samples of the grids generated are shown in Figures 3 and 4. In each figure, the darker lines indicate the block boundaries and are suggestive of the topology design that was used to create the grid. For the purposes of display, the figures show coarse versions of the final grid before a viscous boundary layer was added to the grid.

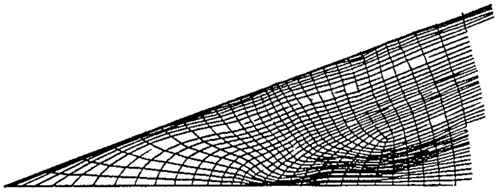

Figure 3. Sample of a Grid on a Fin From Missile 1.

4. Boundary/Initial Conditions

In all cases, the freestream inflow condition was used on the inflow boundary, the reflection boundary condition was used on the symmetry plane, the freestream outflow condition was used on the outflow plane, and the viscous wall condition was used on the viscous surfaces of the missile body.

For missile 1, the total freestream pressure was 20.628 psi, and the total freestream temperature was 554.4° Rankine. For missile 2, the static freestream pressure was 0.5637 psi and the static freestream temperature was 248.4° Rankine. The WIND default initialization was used to initialize the flow field variables.

Runs were conducted using the following turbulence models: Baldwin-Lomax (BL), Baldwin-Barth (BB), Spalart-Allmaras (SA), and Shear Stress Transport (SST). The BL was run both with and without the option of choosing the maximum number of grid points to search for F_{max}. For the former case, maximum grid points 10 and 30 were studied (BL10 and BL30, respectively).

To avoid transient instabilities, the FIXER keyword was used. For missile 1, an initial solution was calculated at a low angle of attack, and this solution was used as an initial solution for calculating the solution at a higher angle of attack. For missile 2, the TVD factor was reduced to 1, the CFL crossflow factor was set to 1, and the CFL number was reduced to 4.

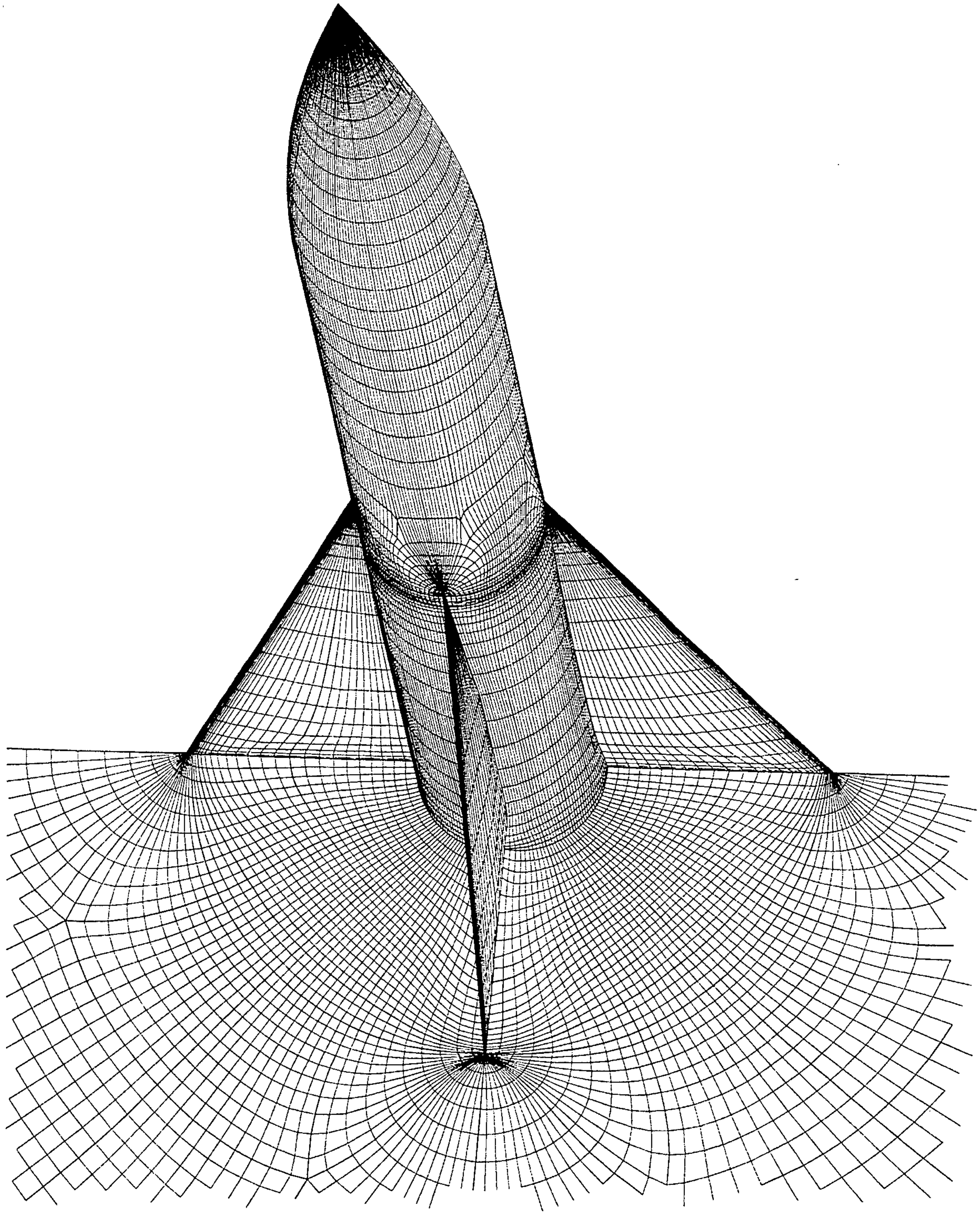

Figure 4. Sample of a Coarse Euler Grid for Missile 1. The Dark Lines Indicate Block Boundaries.

5. Performance/Convergence Criterion

Runs conducted on Silicon Graphics Origin 2000 or Onyx platforms with multiple processors typically used 8 processors, and converged solutions could be obtained in 8–12 hr.

In each case, the residuals decreased by no more than three orders of magnitude over several thousand cycles. To test convergence, solutions were monitored until they were judged to be converged. In the case of missile 2, the loads on the body were calculated using the LOADS keyword in WIND, and the solution was considered to be converged when the loads had converged and remained steady for a few hundred cycles.

The parallel performance obtained varied widely, depending on the grid used. The grids used for missile 1 were reduced to the final number of blocks while trying to balance the number of nodes in each block. Speedup factors as high as 7.5 were obtained using 8 processors, and as high as 14 were obtained for 16 processors. The performance for missile 2 was considerably worse (speedup factor for 8 processors was around 5) because the block merging process was done to minimize the number of blocks rather than to optimize for parallel performance. An example of the best parallel performance is shown in Figure 5.

6. Results

Quantities of interest for the study are the pressure coefficient at different stations on the body and fins, as well as pitot-pressure profiles of the outer flow field at several axial stations. The data presented show examples of the results for missile 1 that were obtained using WIND. The stations and data displayed in the figures were selected with the intention of eventually comparing the computational data with experimental data. Figures 6 and 7 show three-dimensional views of predicted pitot pressures and vortex cores for missile 1 at both roll angles.

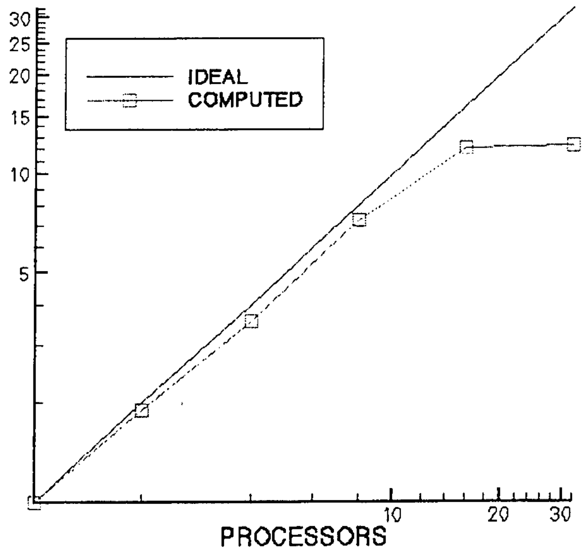

Figure 5. Measured Speedup Using Grid for Missile 1, Roll Angle 0.

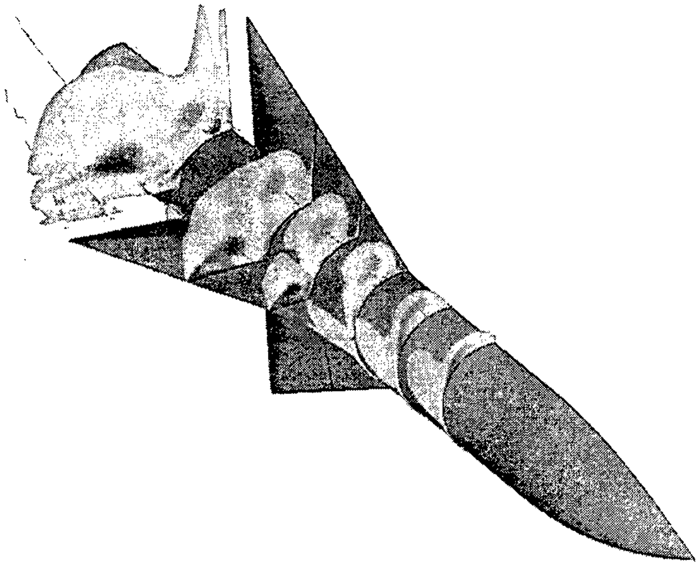

Figure 6. Pitot Pressure and Vortex Core Predictions on Missile 1 at Roll Angle 0 Using the SA Turbulence Model.

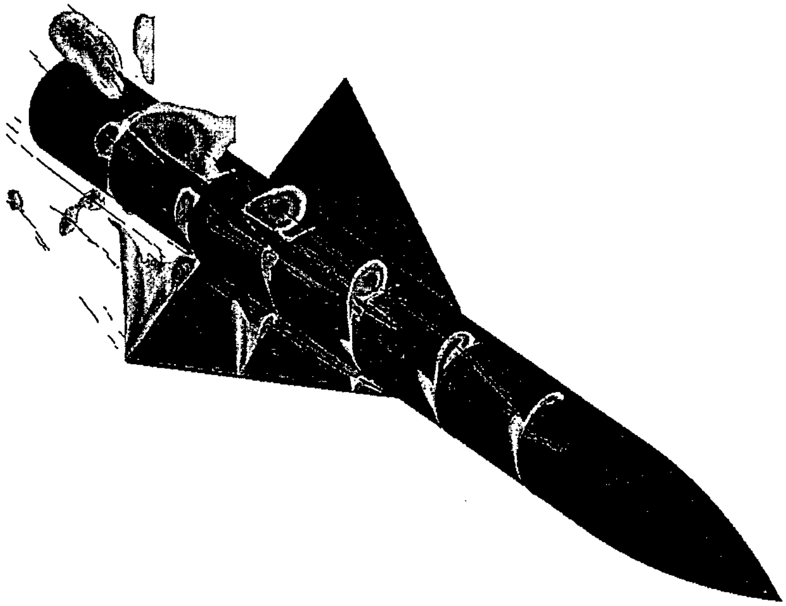

Figure 7. Pitot Pressure and Vortex Core Predictions for Missile 1 at Roll Angle 45 Using the SA Turbulence Model.

The pitot-pressure prediction for missile 1 at roll angle 0° and at axial station X/D = 11.5 show similar results for the SA, BB, and SST models. The BL10 turbulence model predicts a smaller, more intense primary vortex. In addition, this model predicts a more structured solution near the body of the missile. The BL turbulence model predicts a solution that more closely resembles the predictions of the one- and two-equation models. The predictions are shown in Figure 8.

Comparing surface-pressure predictions on the missile body at various axial stations shows minimal variation between the different turbulence models with the exception of BL10. Sample comparisons are shown in Figures 9 and 10.

A reasonable result could not be obtained for missile 2 at the desired angle of attack. Attempts were made to improve the stability of the problem by improving the grid quality and density, reducing the CFL number, and using smoothing options available with WIND.

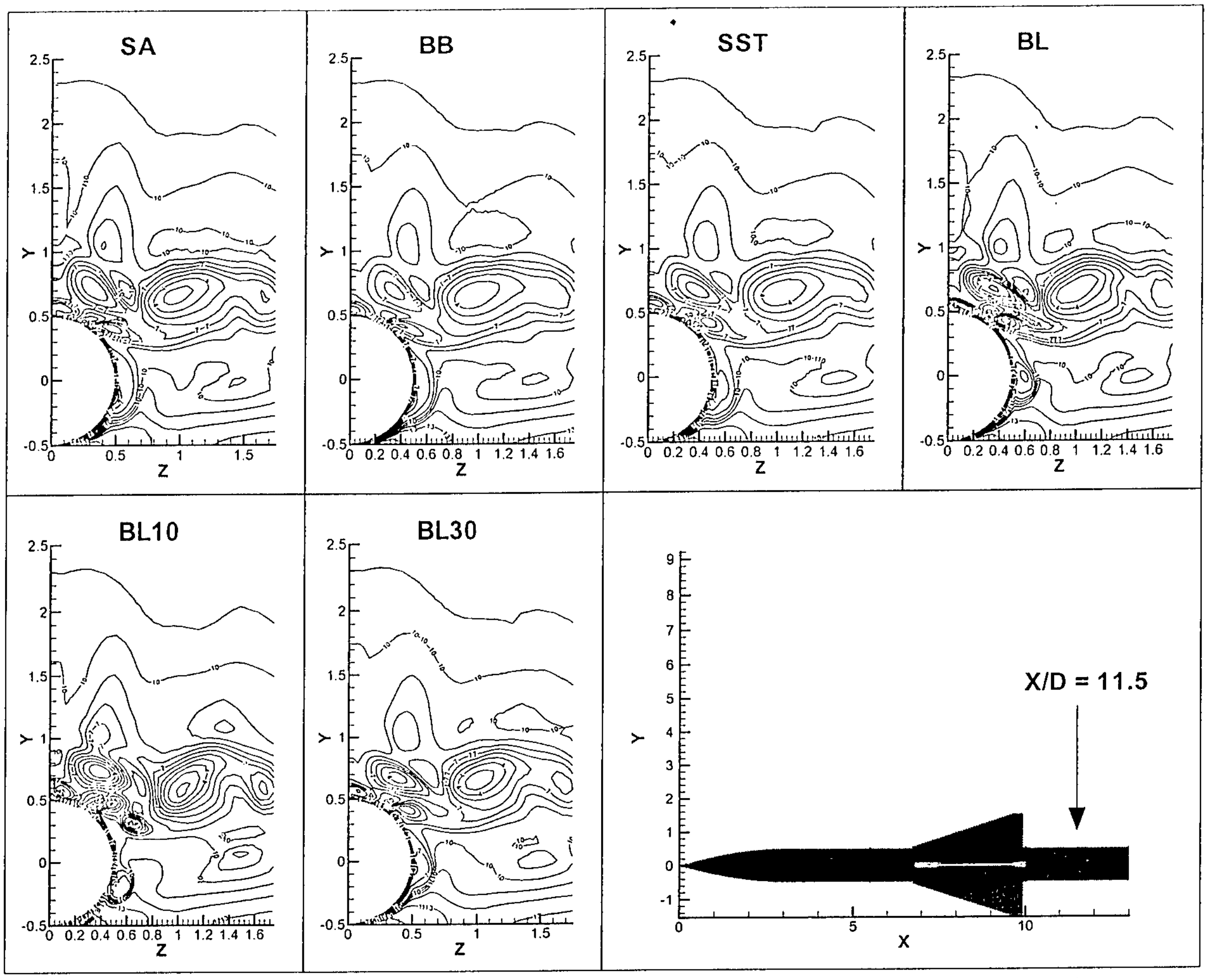

Figure 8. Comparison of Pitot-Pressure Predictions at X/D = 11.5 on Missile 1.

In every instance, the run aborted due to singularities in the flow field. It is most likely that the difficulty was due to the extreme 40° angle of attack. Runs using the same grid and the same flow conditions, but at a 20° angle of attack, converged successfully.

7. Conclusions

The WIND flow solver has been demonstrated to be an efficient tool for increasing and extending the predictive capability of researchers in computational fluid dynamics. WIND has proven to be particularly useful for flow problems with complex geometry although

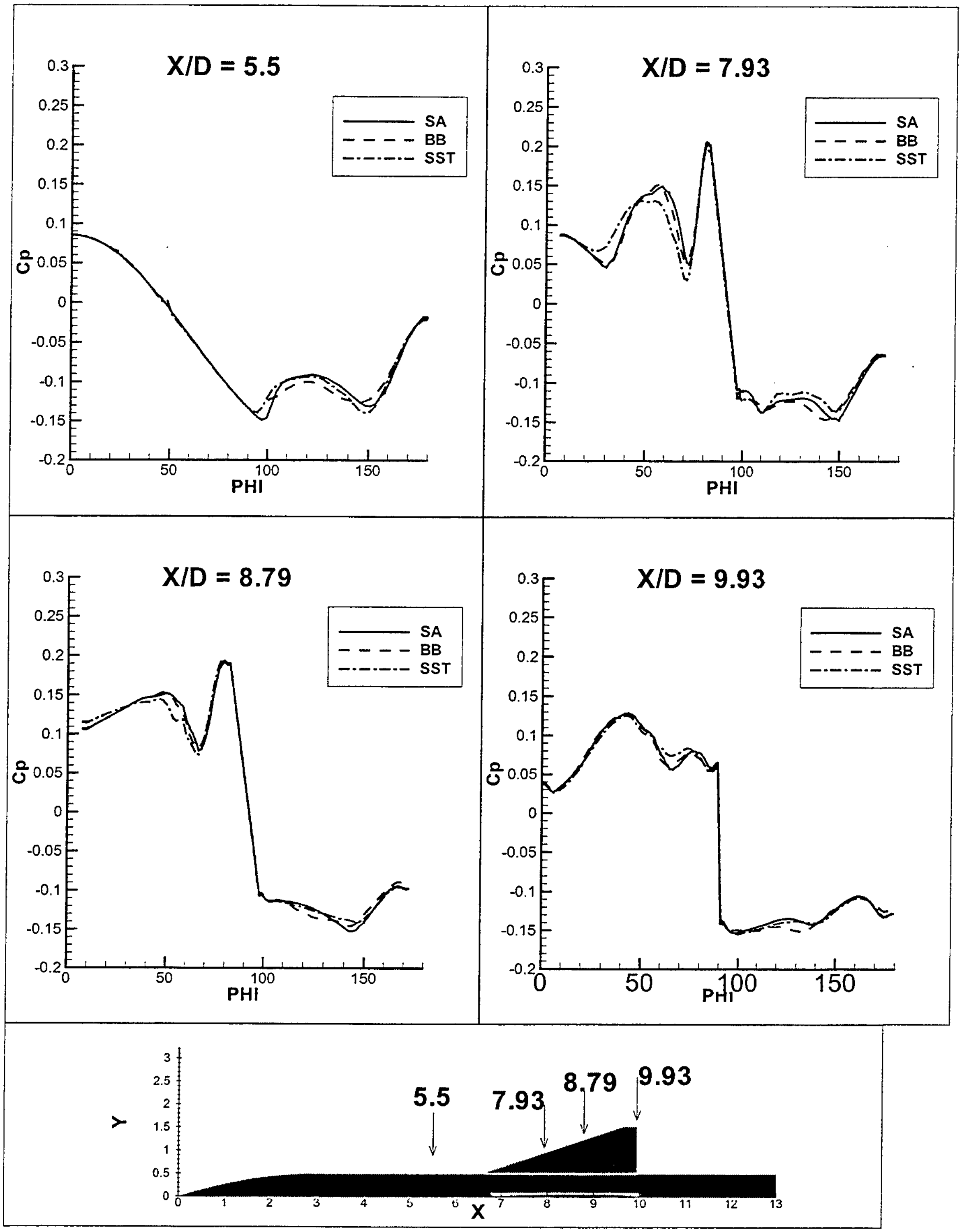

Figure 9. Comparison of Surface-Pressure Predictions on the Body of Missile 1.

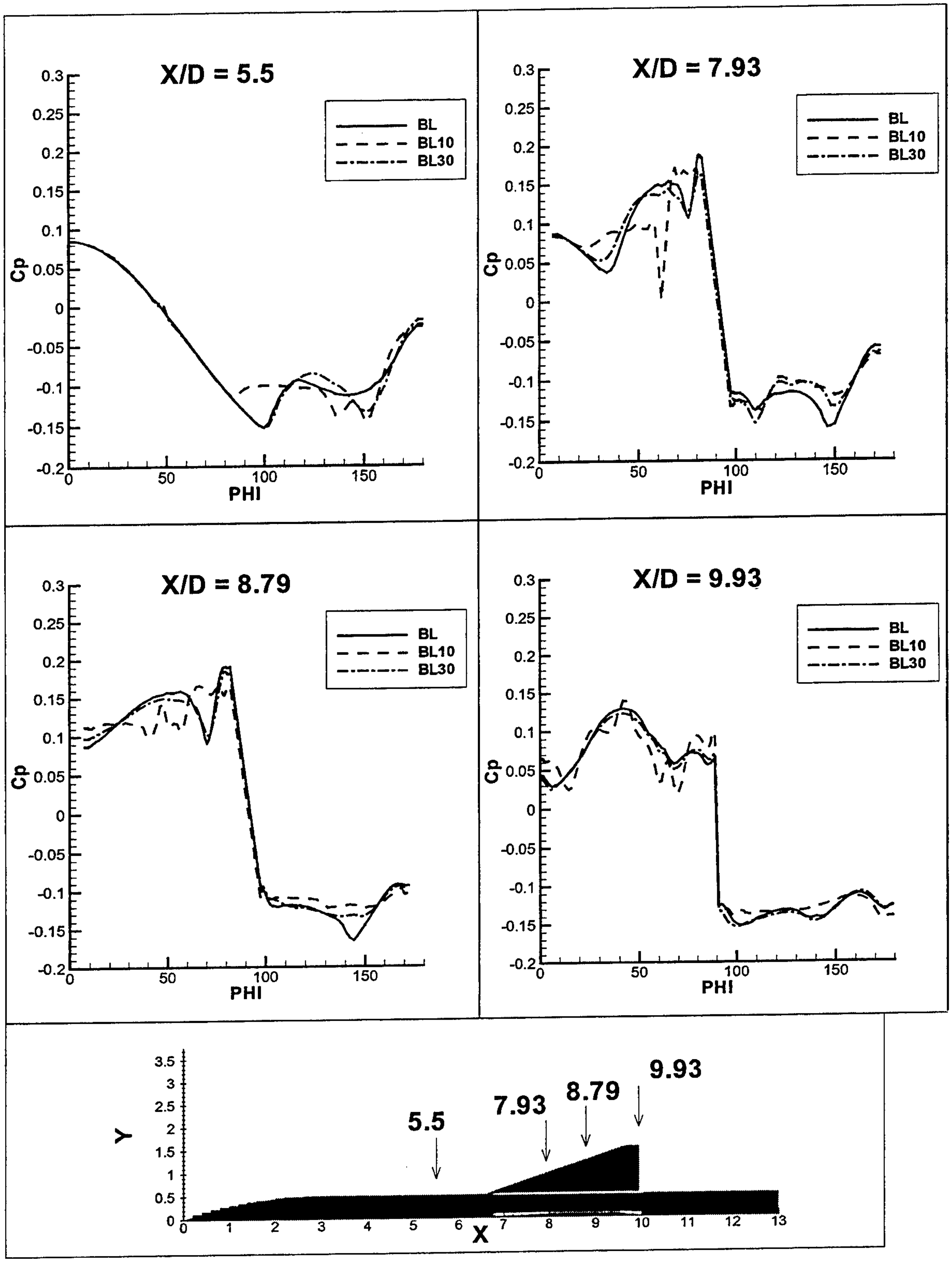

Figure 10. Comparison of Surface-Pressure Predictions on the Body of Missile 1.

extreme flow conditions caused some difficulties. WIND is well suited to use in a high-performance computing environment such as that at ARL. A complete validation of the predictive capability of WIND by comparing it with experimental results was not discussed, but will be considered at a later date.

Future work under consideration might involve studying projectiles with more complicated fin arrays or control jets, attempting to obtain valid solutions for more extreme flow conditions, and studying unsteady projectile aerodynamics.

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REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
June 2001

3. REPORT TYPE AND DATES COVERED
Final, July 1997–July 1999

4. TITLE AND SUBTITLE
Calculating Vortices for Finned Missiles Using the WIND Flow Solver

5. FUNDING NUMBERS
423612.000

6. AUTHOR(S)
David J. Haroldsen* and Walter B. Sturek

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-CI-H
Aberdeen Proving Ground, MD 21005-5067

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2542

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
*U.S. Military Academy, West Point, NY 10996

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT*(Maximum 200 words)*

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14. SUBJECT TERMS
supersonic flow, computational aerodynamics, missile aerodynamics

15. NUMBER OF PAGES
20

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT
UL

NSN 7540-01-280-5500

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