ARMY RESEARCH LABORATORY

Application of Multi-Block, Patched Grid Topologies to Navier-Stokes Predictions of the Aerodynamics of Army Shell

by David J. Haroldsen and Walter B. Sturek, Sr.

ARL-TR-2594 September 2001

Approved for public release; distribution is unlimited.

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5067

ARL-TR-2594 **September 2001**

Application of Multi-Block, Patched Grid Topologies to Navier-Stokes Predictions of the Aerodynamics of Army Shell

David J. Haroldsen
U. S. Military Academy

Walter B. Sturek, Sr.
Computational and Information Sciences Directorate, ARL

Abstract

The U.S. Army Research Laboratory (ARL) 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. Computations have been done for several turbulence models. Numerical results are compared with experimental data for body surface pressures, flow field pitot pressures, and body loads.

Acknowledgments

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

INTENTIONALLY LEFT BLANK.

Contents

INTENTIONALLY LEFT BLANK.

List of Figures

INTENTIONALLY LEFT BLANK.

List of Tables

INTENTIONALLY LEFT BLANK.

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 international study [1] investigated the ability of computational fluid dynamic techniques to predict the flow field for missile bodies at significant angles of attack for transonic and supersonic velocities. The current research is an extension of that effort to include finned-missile configurations. Preliminary results of this current study focused on the ability to incorporate advanced grid generation technology with the WIND flow-field capability [2]. Reference [2] reported how readily WIND could be adapted for use with complex flow problems and for use in conjunction with other state-of-the-art software. The focus of the work was on the methodology and practical aspects of incorporating WIND as a tool of computational researchers.

This report concludes this study and seeks to validate the numerical results obtained using WIND with experimental data. The study considers the application of WIND 1.0 to predict the flow fields for two different missile configurations at angles of attack from 14° to 40° and at Mach numbers near 2.5. The generation of grids for WIND using the GridPro package is briefly reviewed, and results for different turbulence models are presented. The comparisons include surface-pressure measurements, outer flow-field pitot-pressure measurements, and load calculations.

2. Missile Configurations

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

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.

Figure 1. Missile 1 configuration.

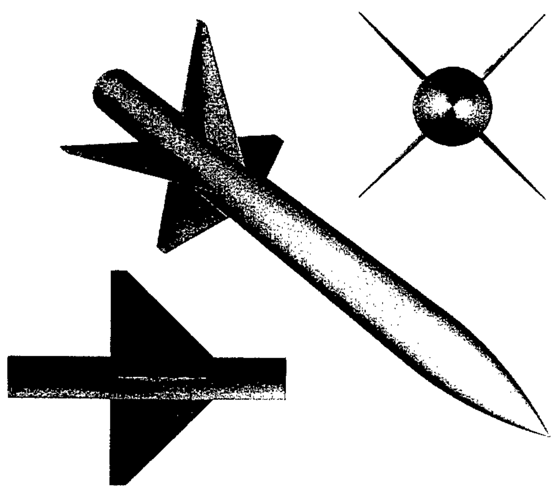

Figure 2. Missile 2 configuration.

3. Grid Generation

Grids for the calculations were generated using the GridPro grid-generation software package. The solution was assumed to be symmetric with respect to the pitch plane, so the computational volume is effectively reduced by 50%. The number of grid zones was determined by a utility that was used in an attempt to optimize the grid for parallel processing. Table 1 lists the size and number of blocks used for each of the configurations considered.

Table 1. Grid details.

Missile	Blocks	Grid Points (in millions)
1 (0° roll)	35	4.1
1 (45° roll)	42	4.3
2	26	4.2

4. Boundary and 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 R. For missile 2, the static freestream pressure was 0.5637 psi and the static freestream temperature was 248.4 R. 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 0.4.

5. Performance and 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 3 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.

6. Results

The primary quantity of interest for the study is the pressure coefficient at different stations on the body and fins of both missiles. In addition, pitot-pressure profiles of the outer flow field at several axial stations, and loads on the body of missile 1 are considered. The computational data was interpolated to the stations available in the experimental data sets. The computational results for missile 1 at roll angles 0° and 45° were similar in terms of comparisons with experimental results. For brevity, only the results for roll angle 0° are shown.

The pitot-pressure predictions 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 that is more like the experimental data in terms of qualitative features. 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 Figures 3 and 4. An overall assessment suggests that most turbulence models tend to smooth out the vortex features that are physically present.

Comparison of surface pressure predictions on the body of missile 1 at various axial stations shows minimal variation between the different turbulence models and the experimental results, with the exception of the turbulence model BL10. Sample comparisons are shown in Figures 5–7. The primary differences are present near the point of separation on the missile body. These differences are particularly evident at X/D station 5.5. In this instance, the BB and SST models seem to give the best agreement with the experimental data.

In addition, Figure 6 shows the sensitivity of the Baldwin-Lomax model to the limiting value for the search for Fmax. These comparisons suggest that an optimal search value would be between 10 and 30 points off of the wall, with 30 giving results essentially equivalent to an unlimited search (the standard Baldwin-Lomax) and 10 points being, perhaps, too few.

Comparisons of experimental calculated loads with the computations are shown in Figure 8. The experimental results are shown for a wide range of angles of attack. The computational results are shown at a single angle of attack. The numerical results do not differ widely for the various turbulence models. The numerical results underpredict the axial force by up to 10%. This is not unexpected, as the axial force depends considerably on the viscous drag term which is largely determined by the turbulence model.

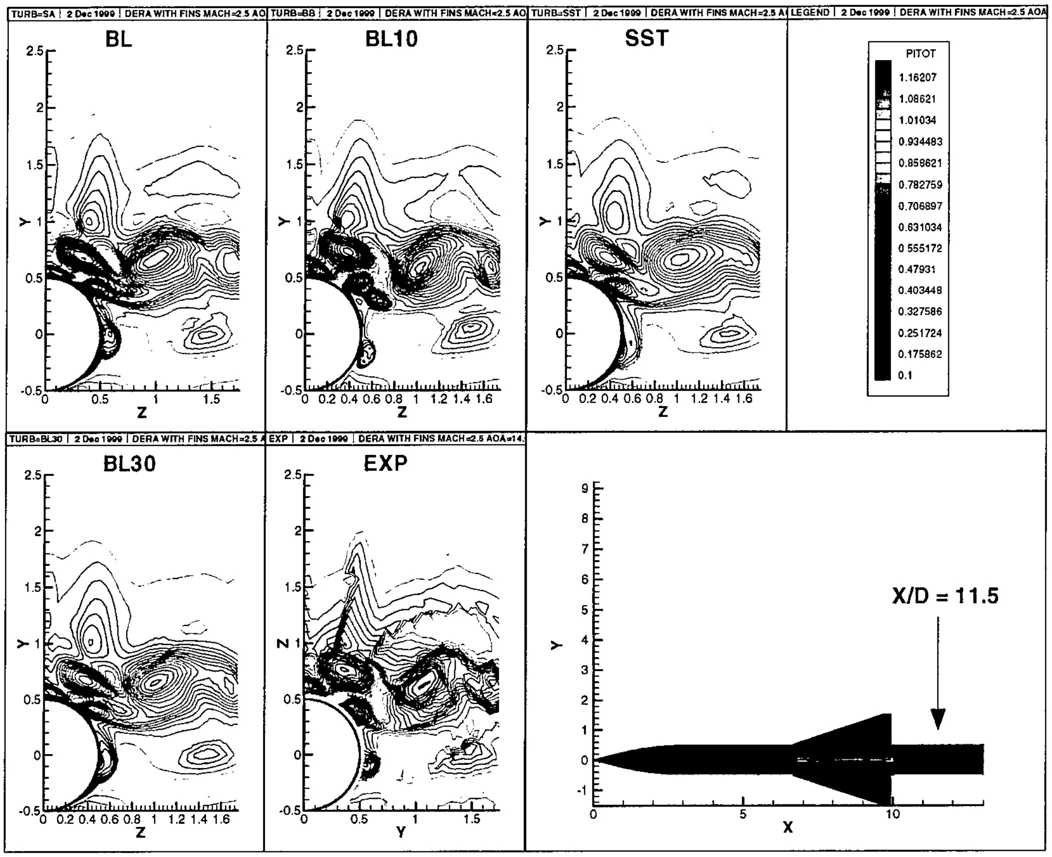

Figure 3. Pitot-pressure contours at X/D = 11.5 on missile 1 for turbulence models BL, BL10, BL30, and SST compared to experiment.

In order to compare some results with experimental data, the loads on the body were calculated as a function of time, and the computation was stopped when the normal force was approximately steady and compared reasonably well with the experimental result. Comparisons between experiment and computation are shown in Figures 9–11. In addition, the geometry of the case is presented in Figure 11. Although the experimental data is somewhat sparse, the computational result seems to give good agreement with the experimental data.

Figures 12 and 13 show three-dimensional views of predicted pitot pressures. Also shown are lines showing the location of the vortex cores for missile 1 at both roll angles. These visualizations were obtained using the PV3 package developed by Dr. Robert Haimes of the Massachusetts Institute of Technology (MIT).

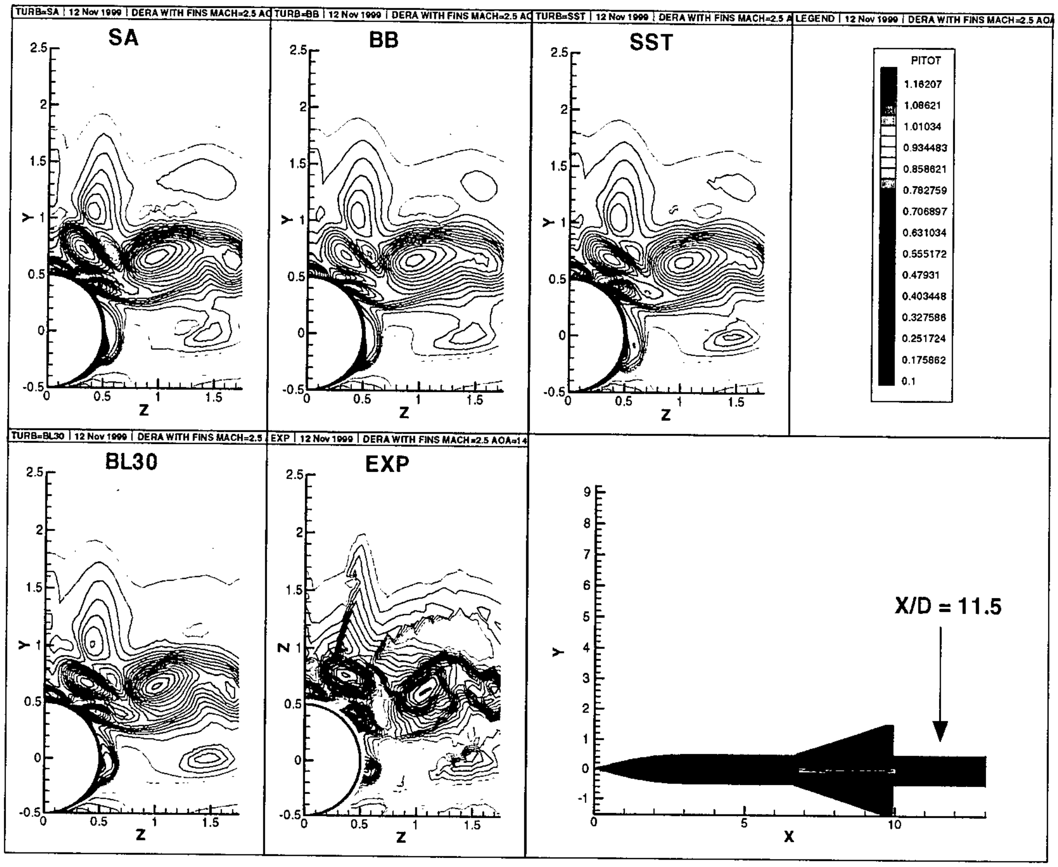

Figure 4. Pitot-pressure contours at X/D = 11.5 on missile 1 for turbulence models SA, BB, SST, and BL10 compared to experiment.

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 extreme flow conditions caused some difficulties. For the cases studied, WIND gives good agreement with experimental data both in the flow field and on the surface of the missile. WIND is well suited for use in a high-performance computing environment such as that in use at ARL.

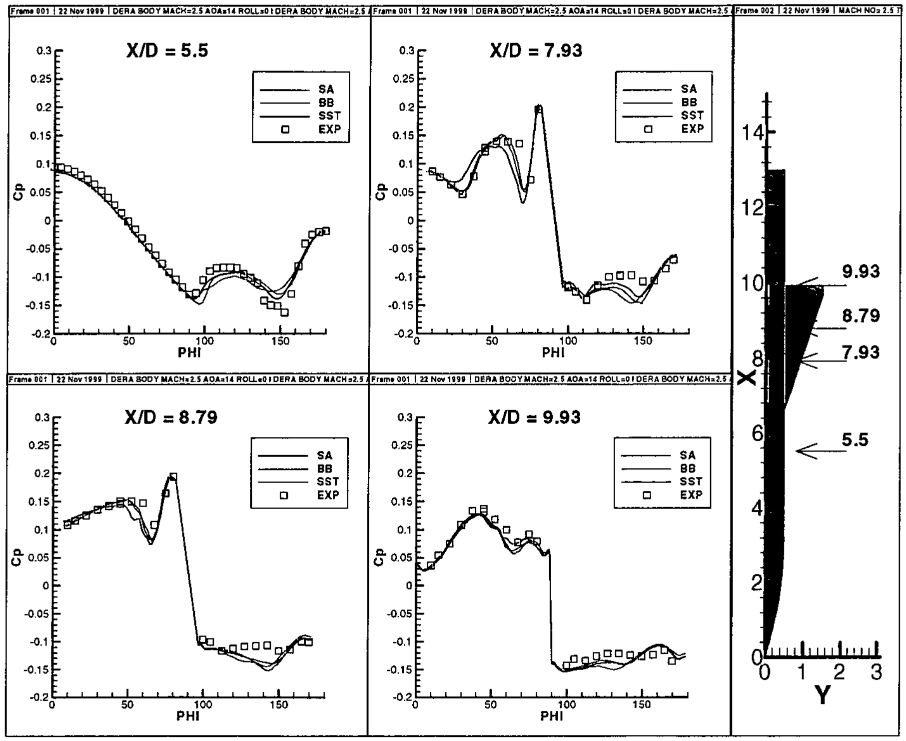

Figure 5. Cp vs. phi on the body of missile 1 for turbulence models SA, BB, and SST compared to experiment.

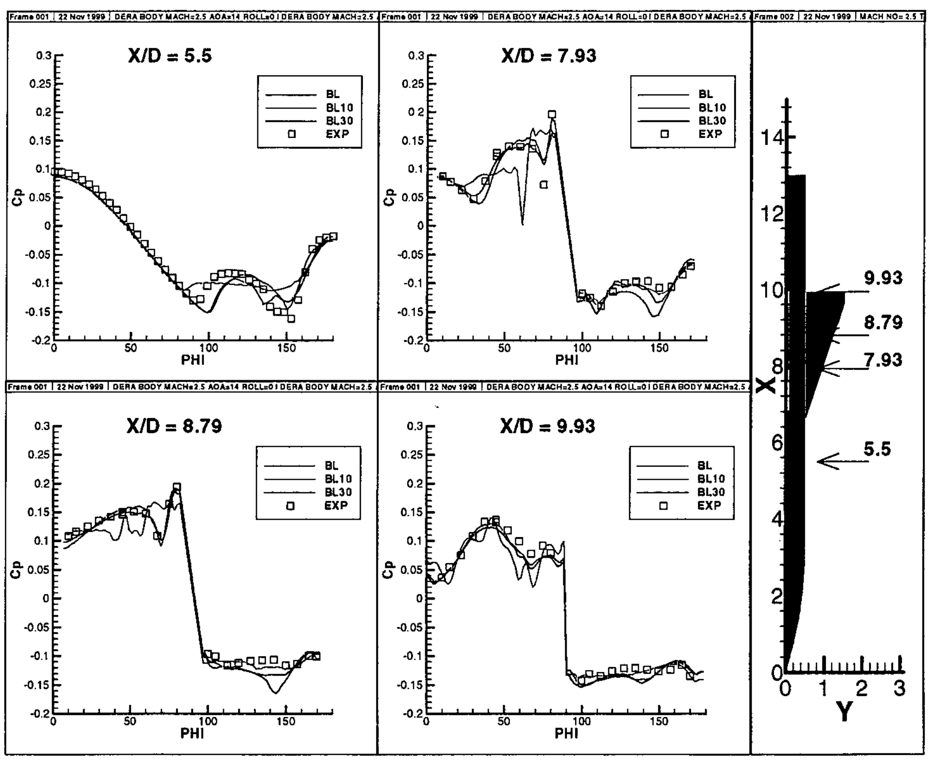

Figure 6. Cp vs. phi on the body of missile 1 for turbulence models BL, BL10, and BL30 compared to experiment.

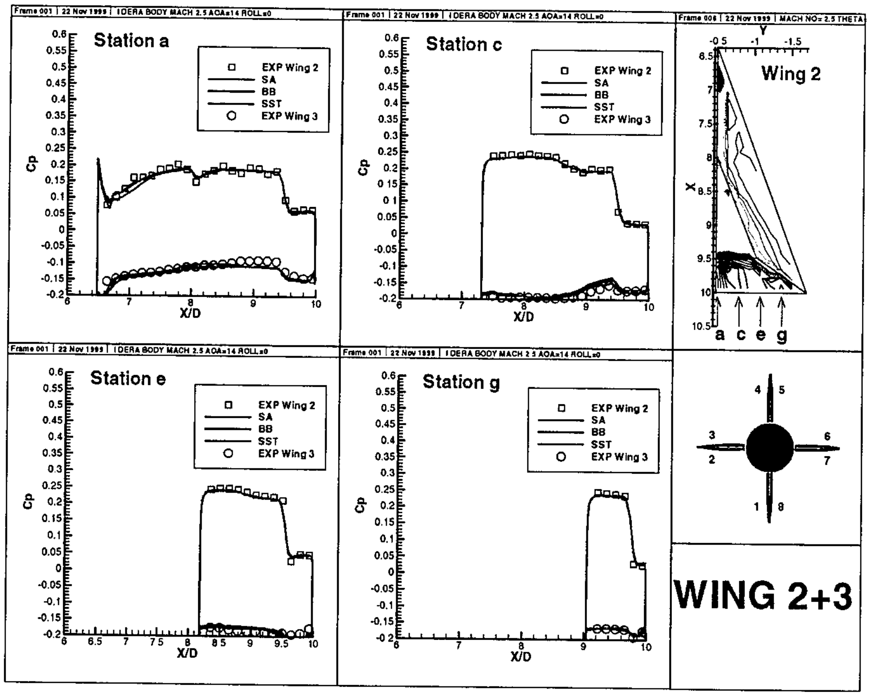

Figure 7. Cp vs. phi on one wing of missile 1 for turbulence models SA, BB, and SST compared to experiment.

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

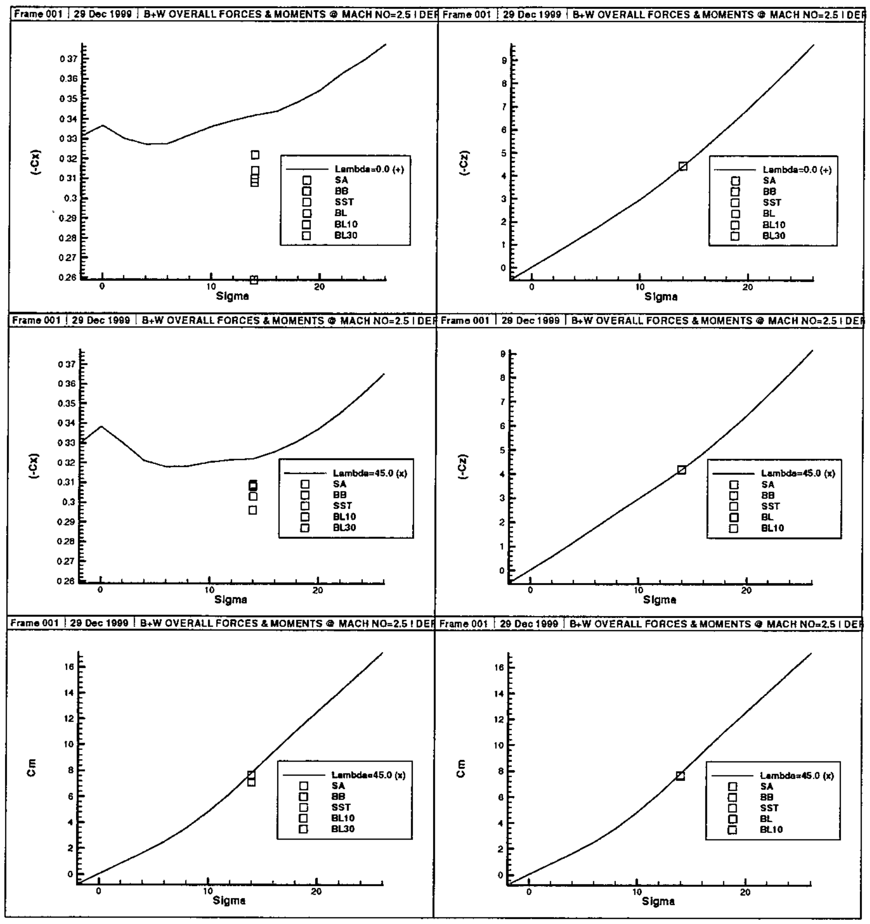

Figure 8. Comparison of computational and experimental loads for missile 1.

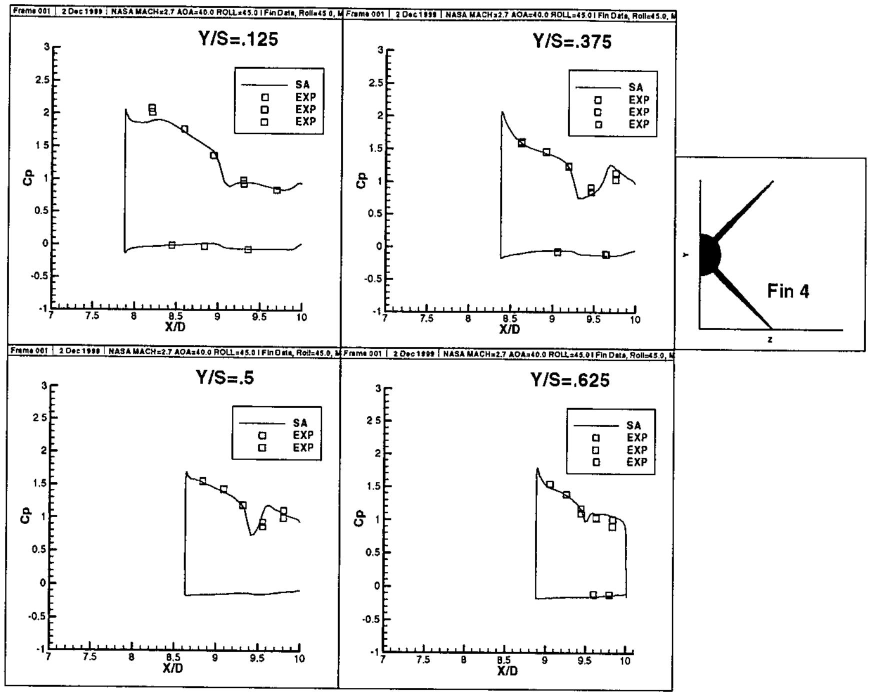

Figure 9. Comparison of computational and experimental Cp on one wing of missile 2.

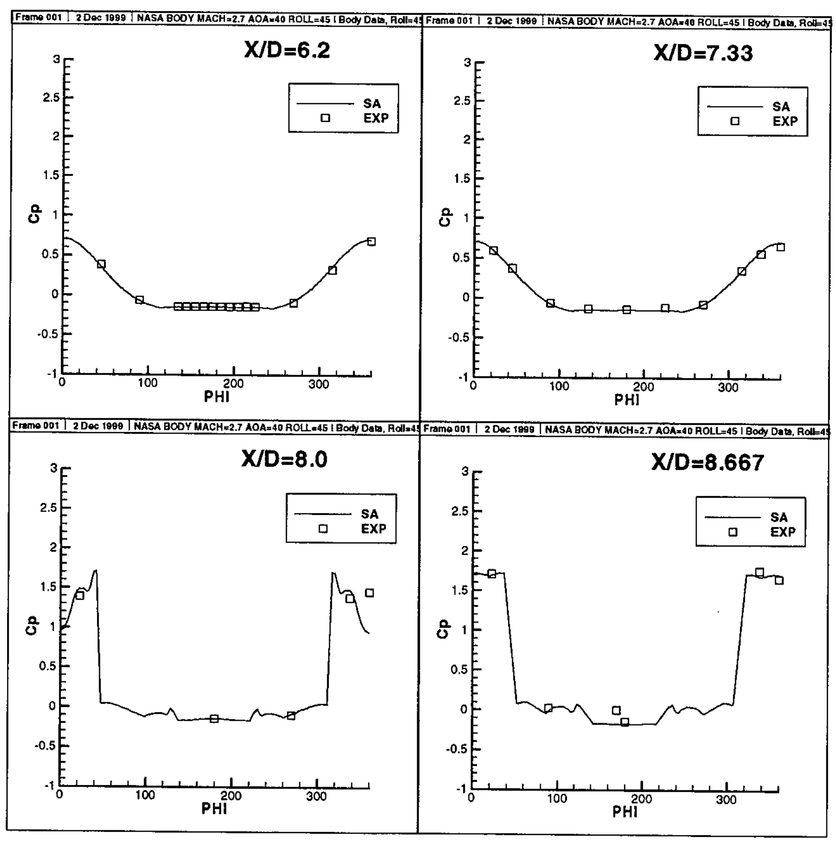

Figure 10. Comparison of computational and experimental Cp on missile 2 body.

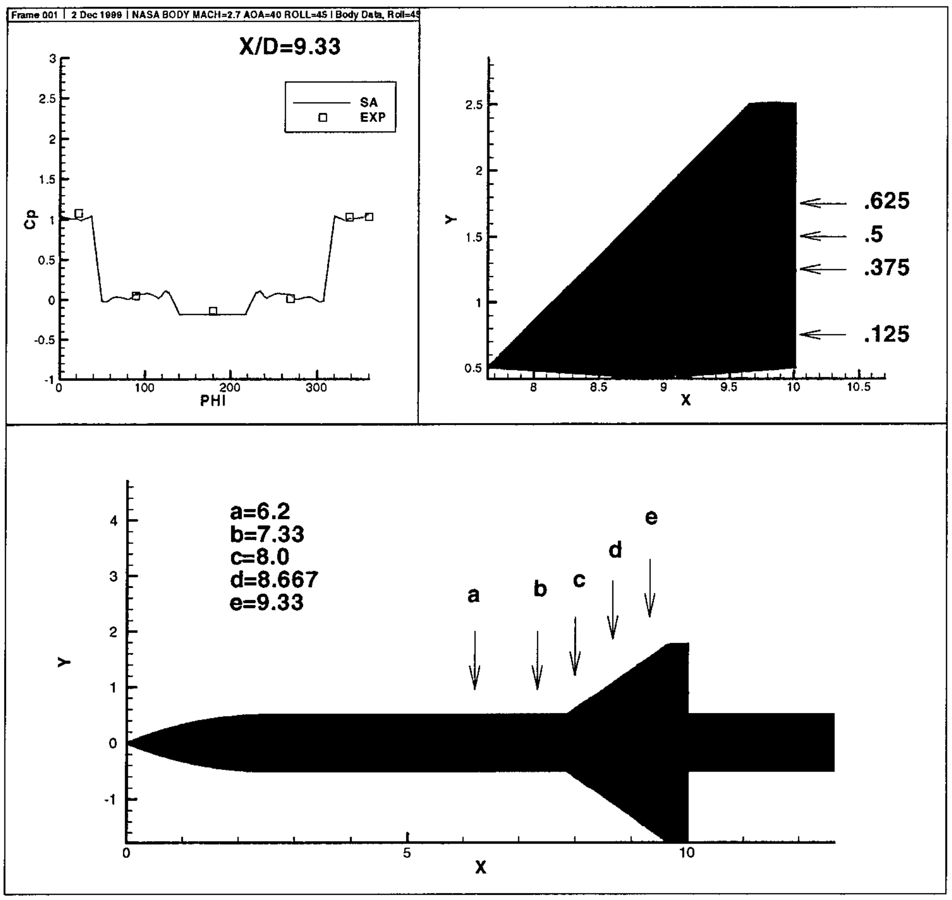

Figure 11. Geometry of missile 2 and comparison of computational and experimental Cp at one X/D station.

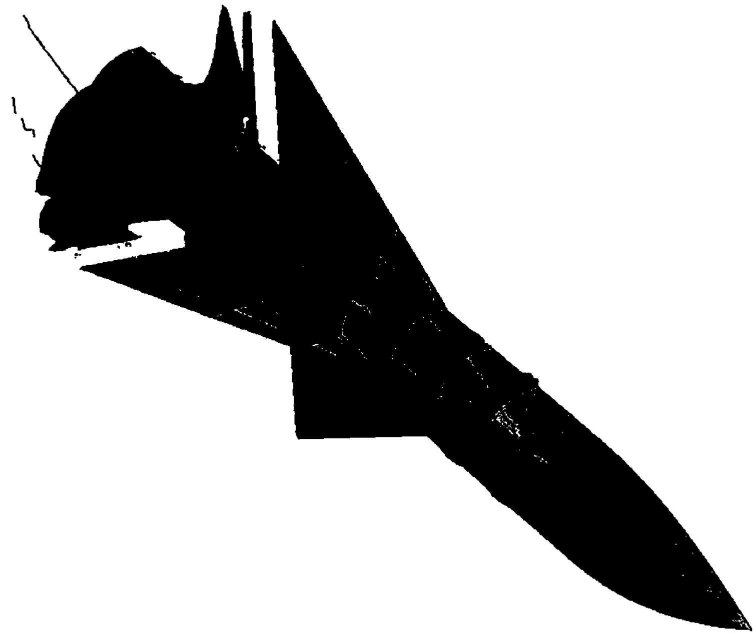

Figure 12. Pitot pressure and vortex core predictions on missile 1 at roll angle 0, SA turbulence model.

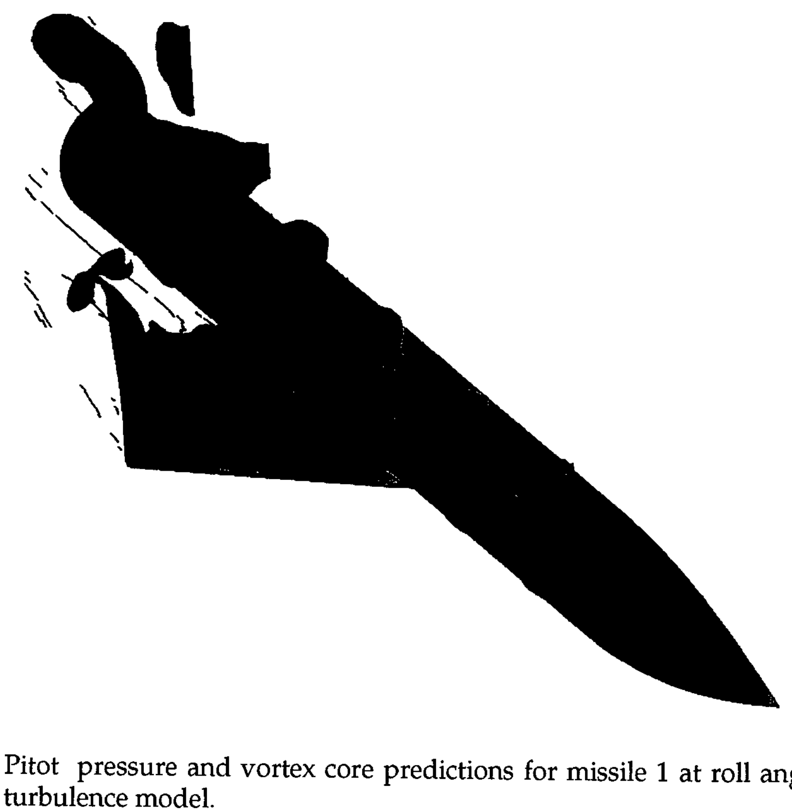

Figure 13. Pitot pressure and vortex core predictions for missile 1 at roll angle 45, SA turbulence model.

8. References

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.

2. Haroldsen, D. J., and W. B. Sturek. "Calculation of Vortices for Finned Missiles Using the WIND Flow Solver." AIAA Paper 2000-0752, 38th Aerospace Sciences Meeting and Exhibit, Reno, NV, 10–13 January 2000.

INTENTIONALLY LEFT BLANK.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	OSD OUSD(A&T)/ODDR&E(R) DR R J TREW 3800 DEFENSE PENTAGON WASHINGTON DC 20301-3800
1	COMMANDING GENERAL US ARMY MATERIEL CMD AMCRDA TF 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN 3925 W BRAKER LN STE 400 AUSTIN TX 78759-5316
1	US MILITARY ACADEMY MATH SCI CTR EXCELLENCE MADN MATH THAYER HALL WEST POINT NY 10996-1786
1	DIRECTOR US ARMY RESEARCH LAB AMSRL D DR D SMITH 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CI AI R 2800 POWDER MILL RD ADELPHI MD 20783-1197

NO. OF COPIES	ORGANIZATION
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI IS T 2800 POWDER MILL RD ADELPHI MD 20783-1197
	ABERDEEN PROVING GROUND
2	DIR USARL AMSRL CI LP (BLDG 305)

NO. OF COPIES	ORGANIZATION
1	UIUC DEPT OF MECHL AND INDUSTRIAL ENGRG J C DUTTON URBANA IL 61801
1	D J HAROLDSEN 1008 JOHNSVILLE ROAD ELDERSBURG MD 21784
1	DIR DIV OF ENGRG DESIGN G C CATALANO THE WATSON SCHOOL SUNY AT BINGHAMTON PO BOX 6000 BINGHAMTON NY 13902-6000
1	TETRA RESEARCH CORP R CHAMBERLAIN 2610 SPICEWOOD TR HUNTSVILLE AL 35811-2604
1	RICE MEMS M BEHR MS 321 6100 MAIN ST HOUSTON TX 77005

ABERDEEN PROVING GROUND

9	AMSRL WM BC P PLOSTINS B GUIDOS K HEAVEY J SAHU P WEINACHT J DESPIRITO AMSRL CI H C NIETUBICZ A MARK D PRESSEL

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2001	Final, July 1997 - July 2000

4. TITLE AND SUBTITLE
Application of Multi-Block, Patched Grid Topologies to Navier-Stokes Predictions of the Aerodynamics of Army Shell

5. FUNDING NUMBERS
423612.000

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

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

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2594

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)*
The U.S. Army Research Laboratory (ARL) 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. Computations have been done for several turbulence models. Numerical results are compared with experimental data for body surface pressures, flow field pitot pressures, and body loads.

14. SUBJECT TERMS
supersonic flow, missile aerodynamics, computational fluid dynamics, turbulence modeling

15. NUMBER OF PAGES
22

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

INTENTIONALLY LEFT BLANK.