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# A Multidisciplinary Approach to Aerodynamic Loading of a 2.75-in Rocket With Fins

by Karen R. Heavey, James F. Newill,  
and Jubaraj Sahu

ARL-MR-520

September 2001

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## A Multidisciplinary Approach to Aerodynamic Loading of a 2.75-in Rocket With Fins

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Weapons and Materials Research Directorate, ARL

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## Abstract

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A multidisciplinary effort was undertaken to investigate the effect of structural loading on a rocket of interest to the U.S. Army. This report addresses the element of aerodynamic loading. Computational fluid dynamics techniques have been used to obtain numerical solutions for the flow field of a rocket with and without fins. Computed results have been obtained for a Mach number of 2.0 at 0° and 5° angles of attack. Qualitative flow field features show the surface pressure on the surface of the rocket. The surface pressure data was then extracted from the solution files. Software was developed to couple this data to a structural dynamics solver. The results provided the aerodynamic loading component used during the initial portion of the rocket flight. Preliminary results showing  $x$ -stress on the rocket at a 5° angle of attack are shown. Additional efforts are needed to generalize and fine tune the CFD/SD methods.

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## Contents

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<b>List of Figures</b>	<b>v</b>
<b>1. Introduction</b>	<b>1</b>
<b>2. Solution Technique</b>	<b>2</b>
2.1 Numerical Technique .....	2
2.2 Chimera Composite Grid Scheme .....	2
2.3 Boundary Conditions .....	3
<b>3. Model Geometry and Computational Grid</b>	<b>4</b>
<b>4. Results</b>	<b>5</b>
<b>5. Application to Structural Dynamics</b>	<b>8</b>
<b>6. Conclusion</b>	<b>14</b>
<b>7. References</b>	<b>15</b>
<b>Distribution List</b>	<b>17</b>
<b>Report Documentation Page</b>	<b>21</b>

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## List of Figures

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Figure 1. Photograph of a 2.75-in rocket with wraparound fins. ....	1
Figure 2. Computation model of a rocket with wraparound fins. ....	1
Figure 3. Computational grid for rocket body section. ....	4
Figure 4. Expanded view of surface grids on finned model. ....	5
Figure 5. Circumferential view of grids in aft section. ....	6
Figure 6. Pressure contours, body only. ....	7
Figure 7. Expanded view of surface pressure contours, body only. ....	7
Figure 8. Surface pressure contours, with and without fins. ....	8
Figure 9. Expanded view of surface pressure contours, finned model. ....	9
Figure 10. Pressure contours, finned model. ....	10
Figure 11. Expanded view of circumferential pressure contours, finned model. ....	11
Figure 12. Comparison of computational meshes. ....	12
Figure 13. Aerodynamic surface pressure loaded onto structural mesh. ....	12
Figure 14. Initial loading of the rocket. ....	13
Figure 15. Axial stresses at first maximum yaw, composite section. ....	13
Figure 16. Axial stresses at first maximum yaw, entire rocket. ....	14

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## 1. Introduction

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The advancement of computational fluid dynamics (CFD) is beginning to have a major impact on projectile design and development [1-4]. Improved computer technology and state-of-the-art numerical procedures enable scientists to develop solutions to complex, three-dimensional problems associated with projectile and missile aerodynamics. The research effort has focused on the development and application of a versatile overset grid numerical technique to solve geometrically complex singlebody and multibody aerodynamic problems. This numerical capability has been used successfully to determine the aerodynamics on a number of projectile configurations [4-6] at transonic and supersonic speeds. Earlier applications involved axisymmetric flow computations [4, 5]. Recently, this technique has been used to investigate the submunition dispersal from an Army tactical missile system [6] involving three-dimensional (3-D) flow computations.

This report describes the application of the advanced numerical technique to a finned rocket of interest to the U.S. Army (see Figure 1). The computational model for this system, which consists of a rocket body with three wraparound fins, is shown in Figure 2. This problem involves 3-D flow computations of a finned rocket at angle of attack. The particular problem here is to determine the resulting surface pressure on the rocket with the fins deployed.

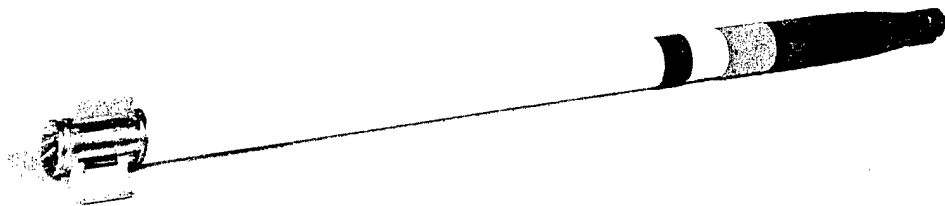


Figure 1. Photograph of a 2.75-in rocket with wraparound fins.

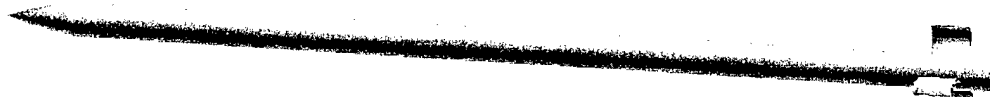


Figure 2. Computation model of a rocket with wraparound fins.

The complexity and uniqueness of this type of problem result from the aerodynamic interference of the individual components, which include 3-D shock-shock interactions, shock-boundary layer interactions, and highly viscous-dominated separated wake flow regions. The overset grid technique [7-9], which is ideally suited to this problem, involves generating numerical grids about each body component and then oversetting them onto a base grid to form the complete model. With this composite overset grid approach, it is possible to determine the 3-D interacting flow field of the system and the associated aerodynamic forces and moments without the need for costly regridding. The solution procedure of the developed technique is to compute the interference flow field at multiple locations until final converged solutions are obtained and then to integrate the pressure and viscous forces to obtain the total forces and moments.

A description of the numerical technique and the Chimera technique follows. Next, the model geometry and the various computational grids used in the numerical computations are described in detail. The steady-state computational results for various configurations and angles of attack are presented. Finally, the surface pressure data is interpolated and applied to the structural analysis of the rocket.

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## 2. Solution Technique

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### 2.1 Numerical Technique

A structured overset grid Navier-Stokes solver was used for this study. OVERFLOW [10, 11], a thin-layer, Reynolds-averaged Navier-Stokes solver, was developed at NASA. This code has recently been used extensively in the study of a slender body projectile [12]. It uses a finite-volume, implicit, factored diagonal scheme to solve the Navier-Stokes equations. For the finned rocket study, the one-equation Spalart-Allmaras  $R_T$  turbulence model (fully turbulent) was used.

### 2.2 Chimera Composite Grid Scheme

The Chimera overset grid scheme [7-9] is a domain decomposition approach where a configuration is meshed using a collection of overset grids. It allows each component of the configuration to be gridded separately and overset into a main grid. Overset grids are not required to join in any special way. Usually, there is a major grid that covers the entire domain or a grid generated about a dominant body. Minor grids are generated about the rest of the other bodies. Because each component grid is generated independently, portions of one grid

may be found to lie within the solid boundary contained within another grid. Such points lie outside the computational domain and are excluded from the solution process.

In the finned rocket study, the grid surrounding the rocket body serves as the major grid, while the grids around the fins are minor grids. The minor grids are completely overlapped by the major grid; thus, each boundary can obtain information by interpolation from the major grid. Similar data transfer or communication is needed from the minor grids to the major grid. However, a natural outer boundary that overlaps these grids does not exist. The Chimera technique creates an artificial boundary (also known as a hole boundary) between grids that provides the required path for information transfer from the fin grid to the rocket body grid. The resulting hole region is excluded from the flow field solution in the rocket body grid. The set of grid points that form the border between the hole points and the normal field points are called intergrid boundary points. These points are updated by interpolating the solution from the overset grid that created the hole.

A major part of the Chimera overset grid approach is the information transfer from one grid into another by means of the inter-grid boundary points. Again, these points consist of a set of points that define the hole boundaries and outer boundaries of the minor grids. These points depend on the solutions in the overlapping regions. In the present work, the PEGSUS code [13] has been used to establish the linkages between the various grids that are required by the flow solver or aerodynamics code described earlier. These include determining the interpolation coefficients and the setting up of Chimera logic for bodies making holes in overlapping grids.

### **2.3 Boundary Conditions**

For simplicity, most of the boundary conditions have been imposed explicitly [1]. For the rocket body grid, a combination of symmetry and extrapolation boundary conditions are used at the center line (axis). A symmetry boundary condition (with one plane overlap) is imposed at the circumferential edges of the projectile grid. A no-slip boundary condition is used on all surfaces of the model, including the fins. The pressure at the wall is calculated by solving a combined momentum equation. Boundary conditions are not applied at the outer boundaries of the fin grids; instead, they are updated through the Chimera interpolation procedure.

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### 3. Model Geometry and Computational Grid

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The computational model consists of a 2.75-in rocket with three wraparound fins. The rocket is an ogive cylinder, 81 inches in length. The fins are located at circumferential positions of  $0^\circ$ ,  $120^\circ$  and  $240^\circ$  near the base of the rocket. Each fin is 3 in long and has a  $10^\circ$  beveled leading edge. The entire grid system contains approximately 6.9 million grid points and consists of 10 separate sections. Figure 3 shows a cross-sectional view of the longitudinal grid for the body of this complex configuration. One large grid provides the mesh for this section of the model. The computational mesh for the fins, however, is more complex. Three grids are used to model each fin—one near the rocket/fin junction, one on the main surface of the fin, and one on the back edge of the fin. Each grid section was obtained separately and then combined to provide the full grid. The grid dimensions for the rocket body grid are  $194 \times 181 \times 158$ , in the longitudinal, circumferential, and radial directions respectively. Likewise, the fin grid sections are  $194 \times 24 \times 41$ ,  $77 \times 121 \times 24$ , and  $29 \times 67 \times 20$ . The final computational meshes were created using the various tools found in the OVERGRID grid generation software package [14].

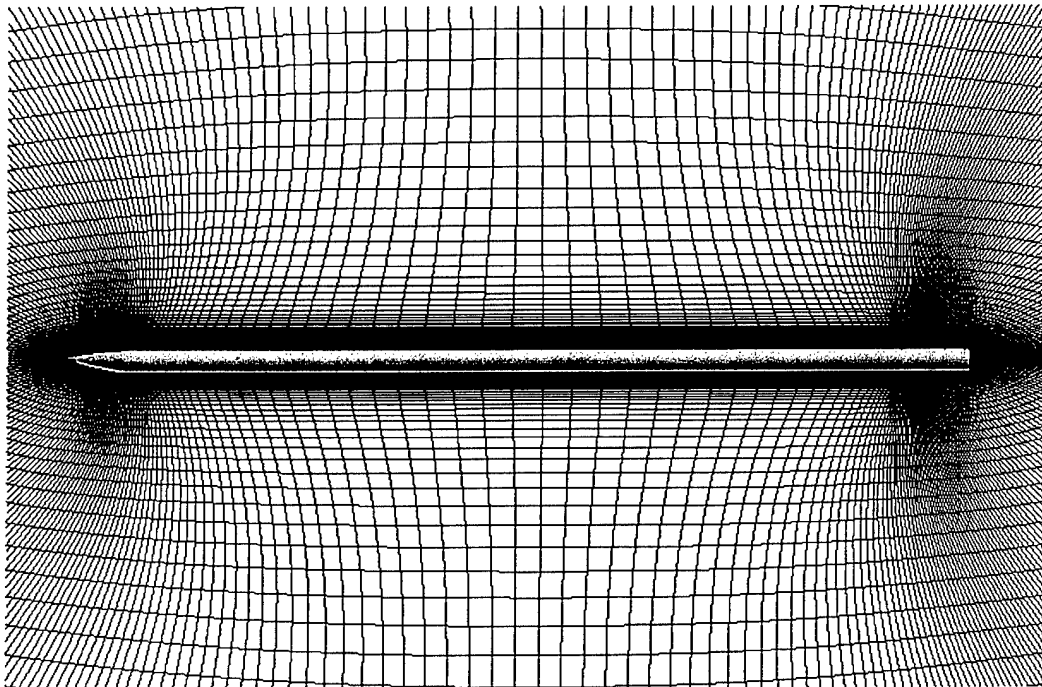


Figure 3. Computational grid for rocket body section.

As stated earlier, the Chimera technique allows individual grids to be generated with any grid topology, thus making the grid generation process easier. For this study, the rocket was initially modeled without the fins. Meshes were built for a single fin at the  $0^\circ$  position. A geometric transformation was used to place it at additional circumferential locations of  $120^\circ$  and  $240^\circ$ . Figure 4 shows an expanded view of the surface grids on the aft section of the finned model. A circumferential view of the grids at an axial location near the middle of the fin is shown in Figure 5.

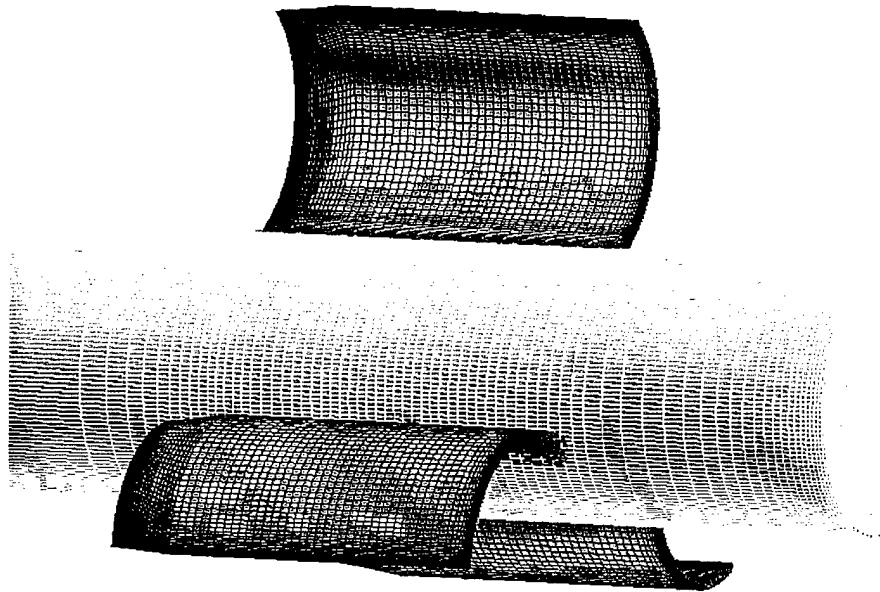


Figure 4. Expanded view of surface grids on finned model.

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## 4. Results

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In this study, 3-D steady-state numerical computations were performed for the rocket body alone and with fins. Computations were completed for a Mach number of 2.0 and at  $0^\circ$  and  $5^\circ$  angles of attack. Atmospheric flight conditions were used. The computations were done using the Silicon Graphics Origin 2000 supercomputers at the ARL Major Shared Resource Center (MSRC). The calculations for each body alone case required approximately 60 hr of computer time. With the addition of the fin grids (and the Chimera calculations), the time requirement increased to approximately 140 hr.

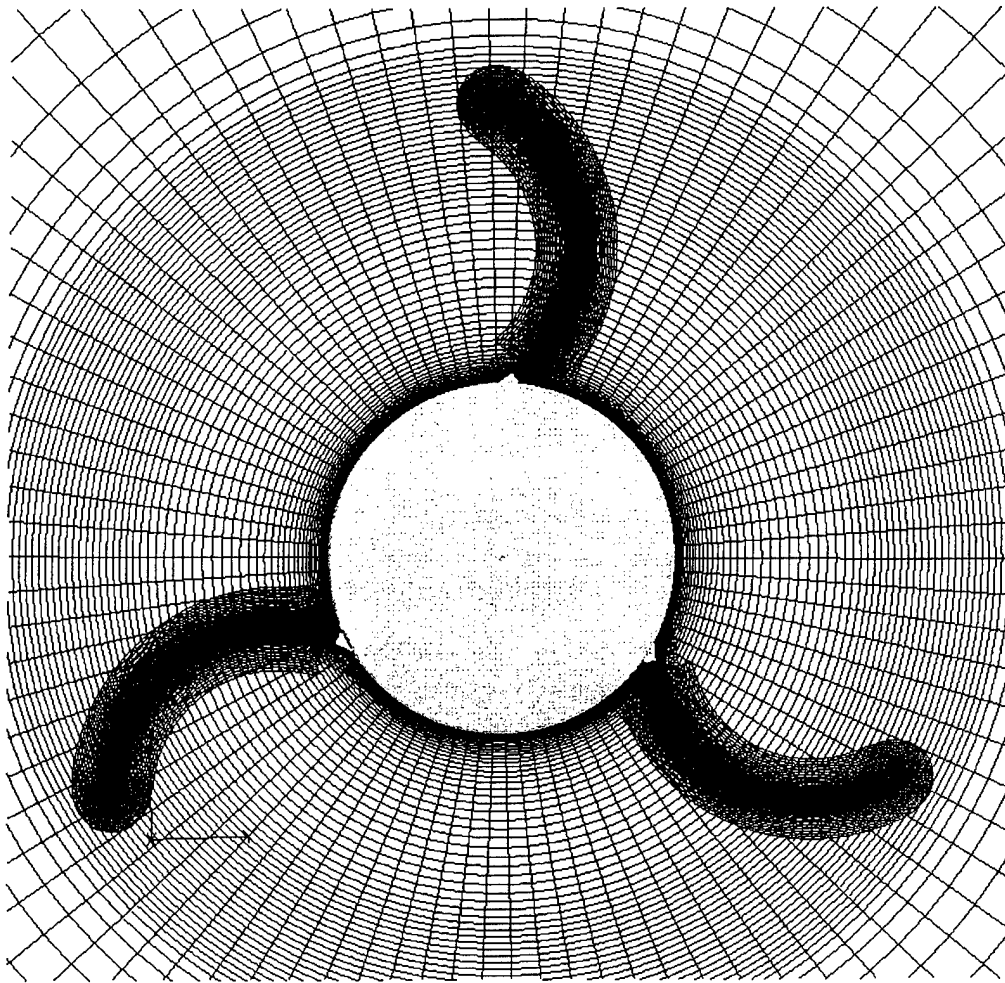
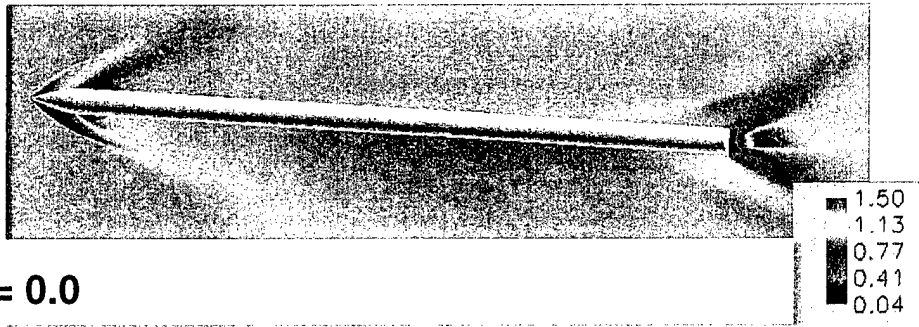


Figure 5. Circumferential view of grids in aft section.

Results are shown first for the rocket body alone. Figure 6 shows pressure contours for the rocket body at  $0^\circ$  and  $5^\circ$  angles of attack. This figure shows differences in the flow field at the nose, along the cylinder, and on the base area of the rocket, at different angles of attack. At a  $0^\circ$  angle of attack, the flow field is quite symmetric, while the  $5^\circ$  angle of attack computation shows asymmetric flow in these areas. An expanded view of the surface pressure on the base area of the rockets is shown in Figure 7. The rocket at a  $5^\circ$  angle of attack shows higher pressure values on the windside of the rocket body. Modified pressure distribution on the base of the rocket is also shown.

As can be expected, the addition of the fins to the rocket body results in a much more complex flow field. Figure 8 shows the surface pressure on each configuration at a  $5^\circ$  angle of attack. The flow field near the nose of the rocket shows little influence attributable to the addition of the fins. The changes to the flow field are obvious in the aft area of the rocket.

**AoA = 5.0**



**AoA = 0.0**

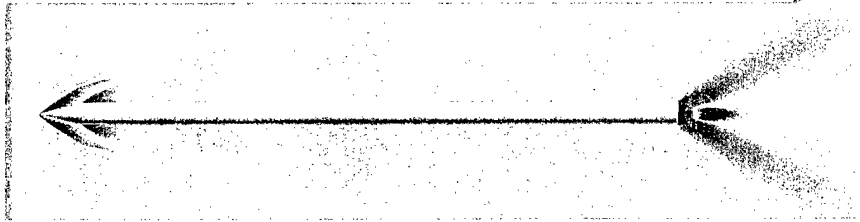
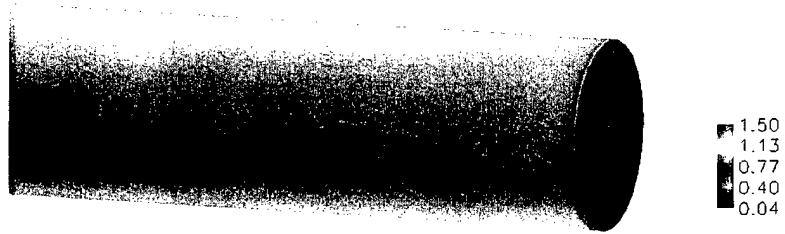


Figure 6. Pressure contours, body only.

**AoA = 5.0**



**AoA = 0.0**

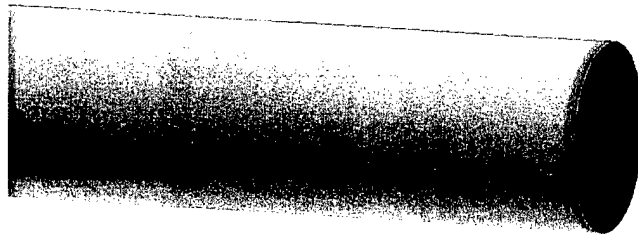


Figure 7. Expanded view of surface pressure contours, body only.

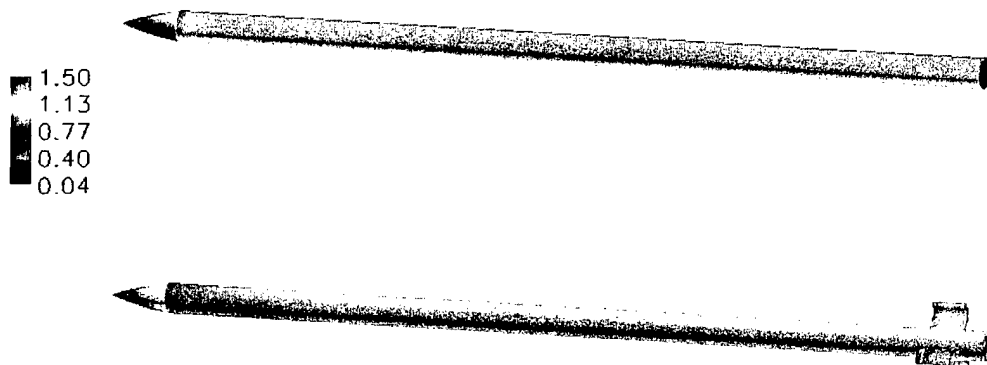


Figure 8. Surface pressure contours, with and without fins.

The next few figures show the effect of angle of attack on the aft section of the rocket body and the fins. In Figure 9, an increase in surface pressure on the underside of the rocket and fins is apparent. The difference on the base of the rocket can also be seen. Figure 10 shows circumferential pressure contours at an axial location in the middle of the fin sections. The contour line plots in Figure 11 show the pressure difference from a slightly different angle.

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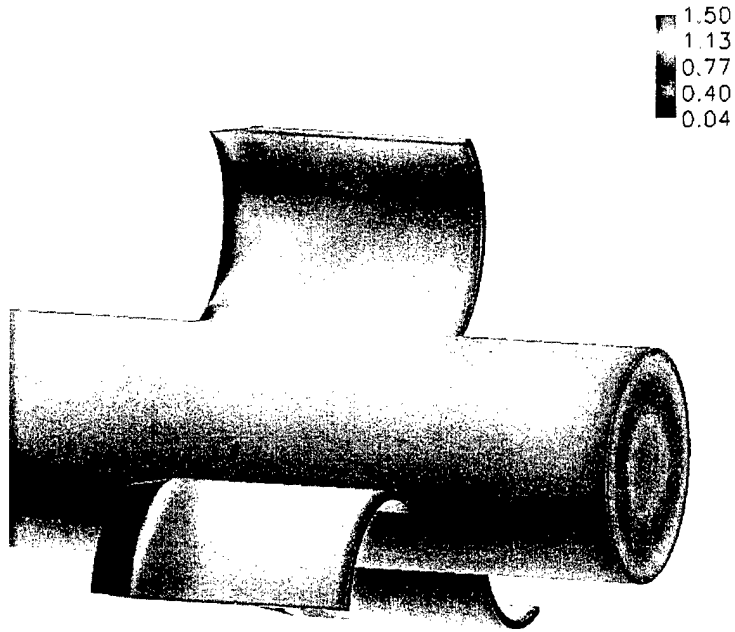
## 5. Application to Structural Dynamics

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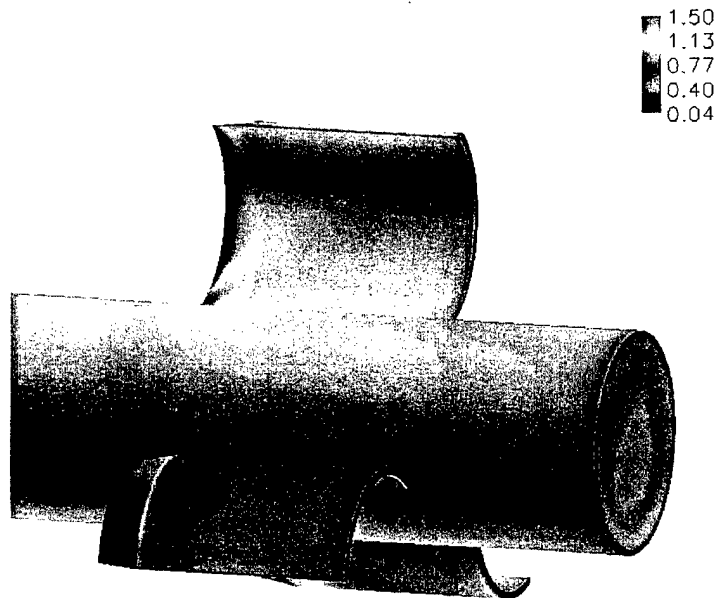
For this problem, a one-way coupling was employed where the pressure loads from the CFD calculation were transferred and reacted by the structure. The resulting structural deformations were not reflected back to the fluids problem, since the body chosen is very stiff in the axial direction and the pressure differentials are relatively small.

In order to transfer the pressure loads, an averaging method is required since typically, the meshes used for dynamic structural calculation are much coarser than the grids used for computational fluids problems (Figure 12). The averaging method must conserve total force, although minor changes in the distribution result from the mesh dissimilarities. The mapping is unique and can be applied to each time calculation from the CFD solution.

The method employed was to use the CFD data to calculate the pressure at the gauss points of the faces of the elements on the surface of the rocket and integrate the total pressure in order to apply an area averaged pressure on the face. Obviously, as the mesh in the structural calculation is refined, the more exact the distribution of the pressure. Figure 13 shows the pressure contours on the nose of the rocket. When the CFD pressure distribution is compared to the



**AoA = 0.0**



**AoA = 5.0**

Figure 9. Expanded view of surface pressure contours, finned model.

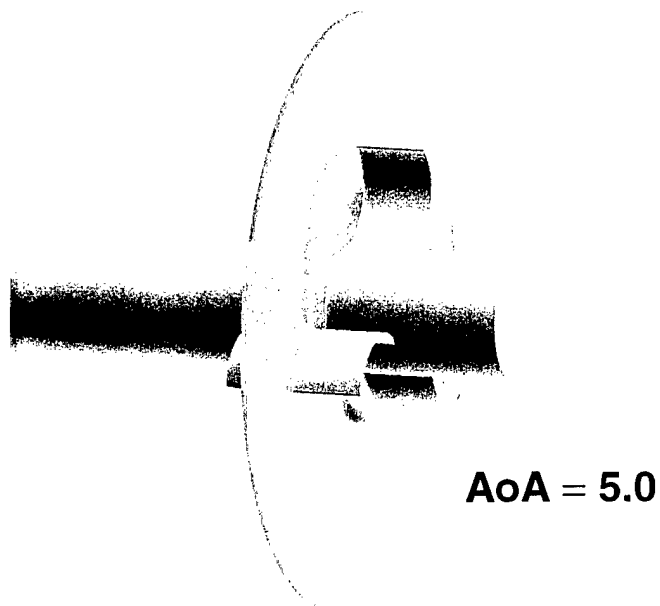
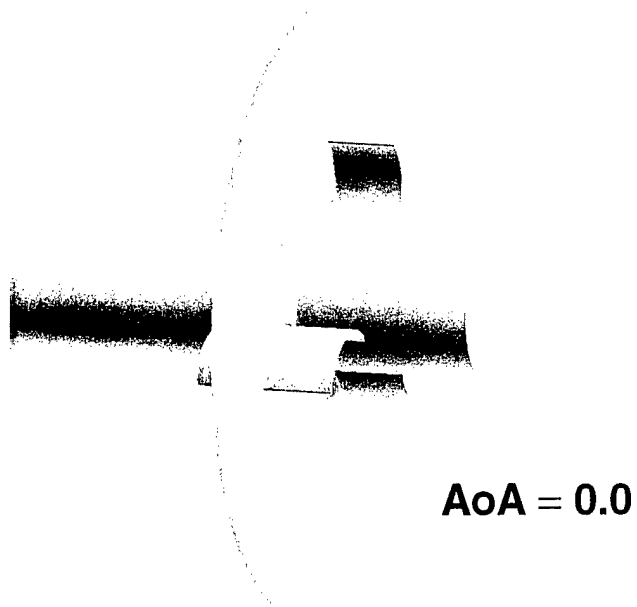
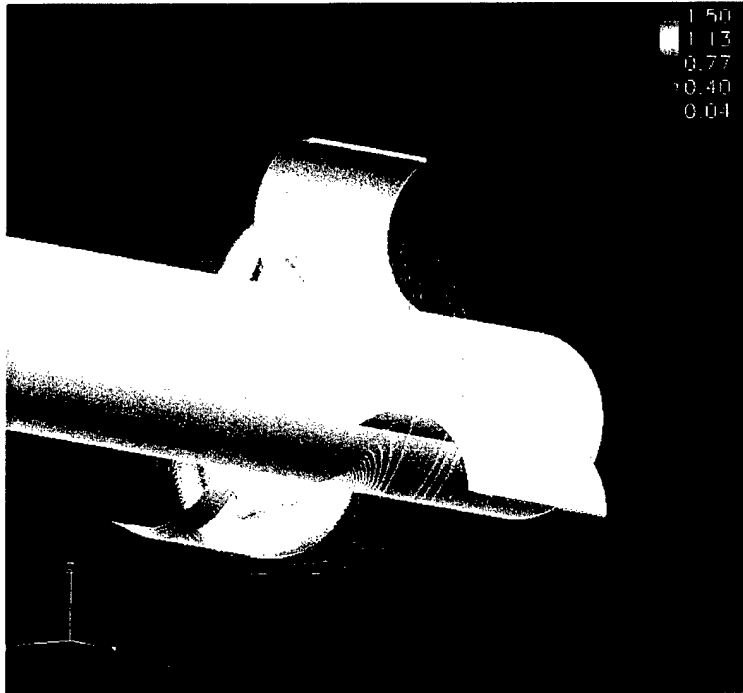


Figure 10. Pressure contours, finned model.

**AoA = 0.0**



**AoA = 5.0**

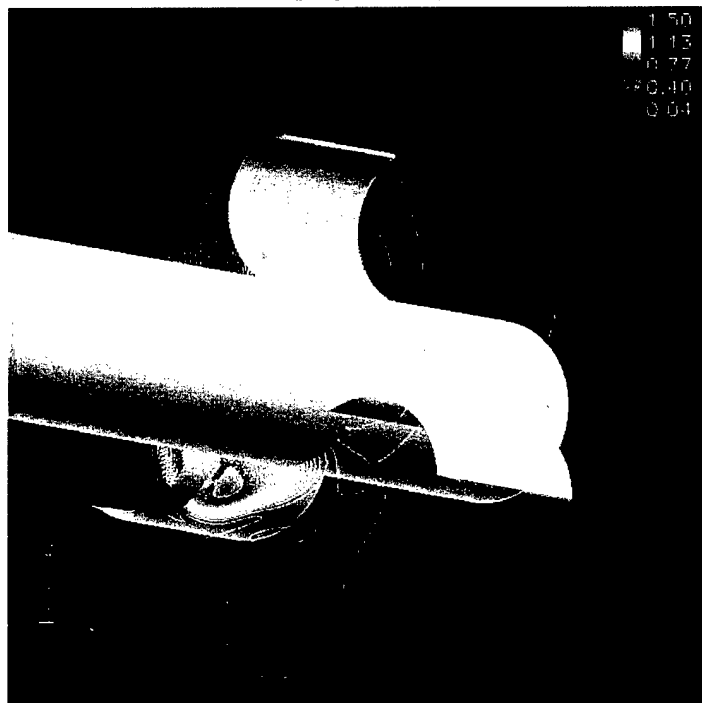


Figure 11. Expanded view of circumferential pressure contours, finned model.

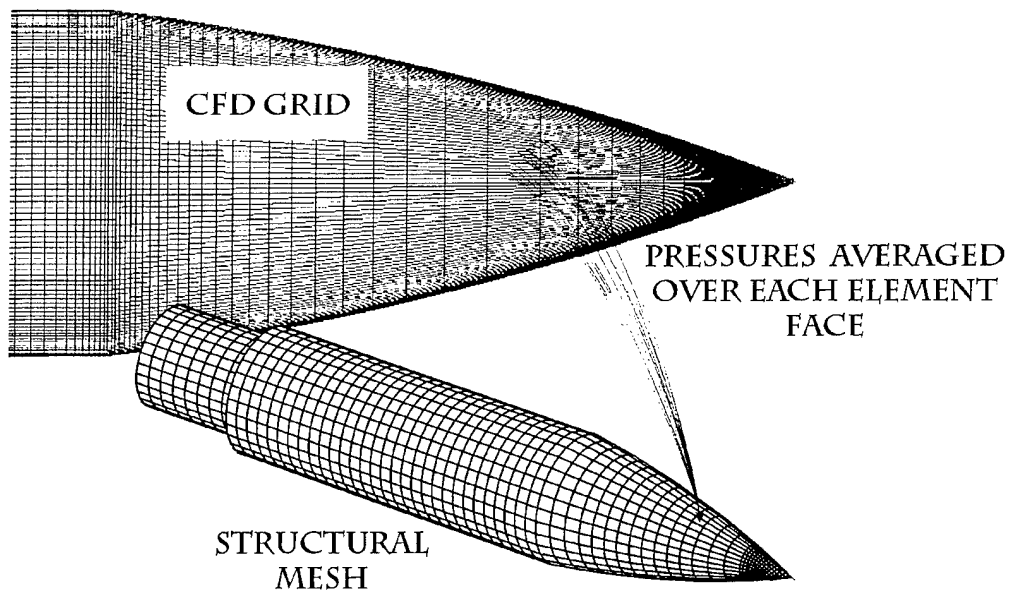


Figure 12. Comparison of computational meshes.



Figure 13. Aerodynamic surface pressure loaded onto structural mesh.

pressure distribution on the structures model, it is seen that the distributions are quite close. The aerodynamic pressure is only one source of the load on the projectile. Figure 14 shows the other sources of loading data for the initial portion of the rocket's flight. DYNA3D [15], an explicit finite element program for structural/continuum mechanics problems, was used to perform the structural analysis of the rocket. Using small time steps, it integrates the equations of motion to efficiently solve transient dynamic problems.

Figures 15 and 16 show results from the structural analysis. Figure 15 shows the deformation of a composite section of the rocket added to contain instrumentation and sensors. Figure 16 shows the reaction of the loading on the entire rocket.

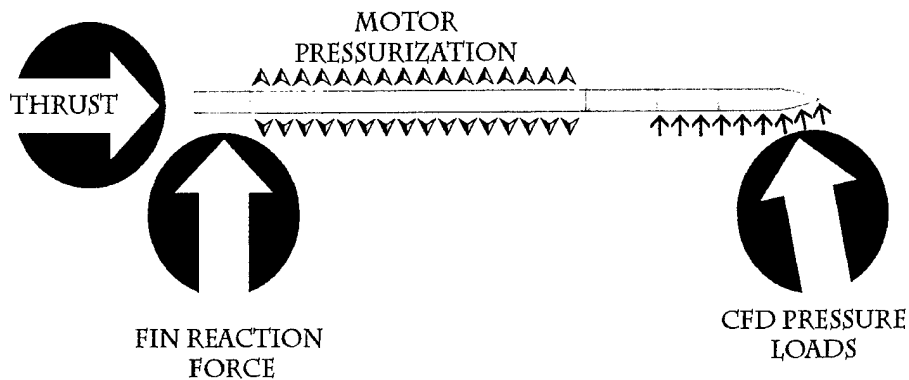


Figure 14. Initial loading of the rocket.

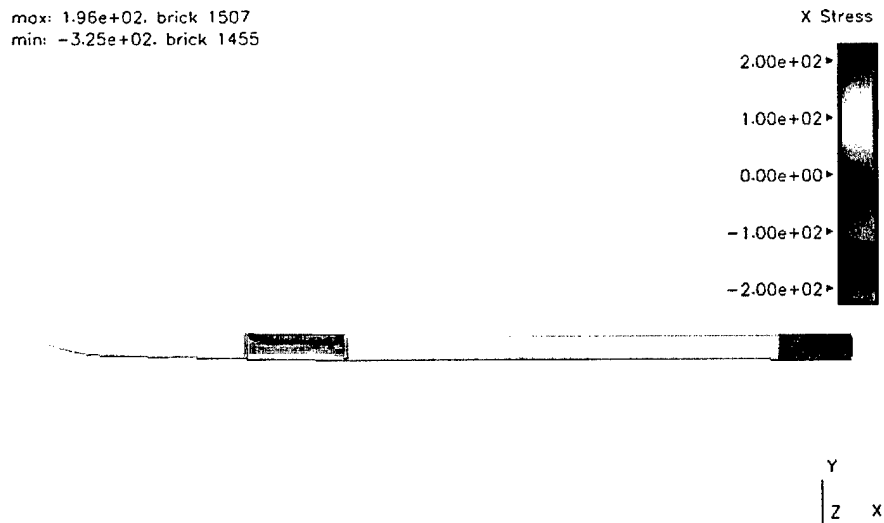


Figure 15. Axial stresses at first maximum yaw, composite section.

max: 1.03e+03, brick 1942  
min: -3.86e+02, brick 1677

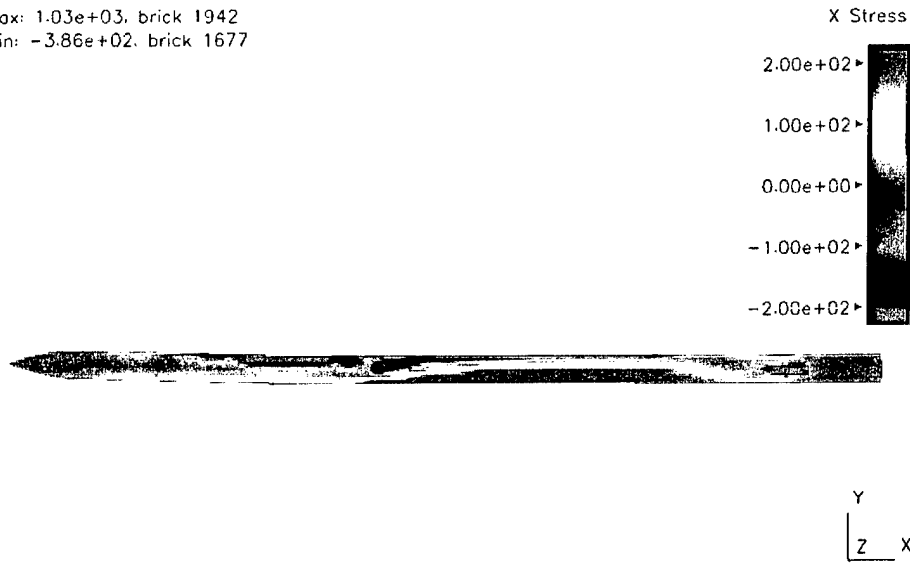


Figure 16. Axial stresses at first maximum yaw, entire rocket.

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## 6. Conclusion

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A computational study has been undertaken to compute the surface pressure on a rocket, body alone and with wrap-around fins. Flow field computations have been performed at a Mach number of 2.0 and  $0^\circ$  and  $5^\circ$  angles of attack, using an overset grid CFD solver and the Chimera composite grid discretization technique. The surface pressure at individual grid points was extracted for each case. The data was transferred to a dynamic structural analysis of the 2.75-in rocket using a generalized interface. A preliminary load mapping capability between CFD and SD has been demonstrated.

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