A Grid Sourcing and Adaptation Study Using Unstructured Grids for Supersonic Boom Prediction

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NASA created the Supersonics Project as part of the NASA Fundamental Aeronautics Program to advance technology that will make a supersonic flight over land viable. Computational flow solvers have lacked the ability to accurately predict sonic boom from the near to far field. The focus of this investigation was to establish gridding and adaptation techniques to predict near-to-mid-field (<10 body lengths below the aircraft) boom signatures at supersonic speeds using the USM3D unstructured grid flow solver. The study began by examining sources along the body the aircraft, far field sourcing and far field boundaries. The study then examined several techniques for grid adaptation. During the course of the study, volume sourcing was introduced as a new way to source grids using the grid generation code VGRID. Two different methods of using the volume sources were examined. The first method, based on manual insertion of the numerous volume sources, made great improvements in the prediction capability of USM3D for boom signatures. The second method (SSGRID), which uses an a priori adaptation approach to stretch and shear the original unstructured grid to align the grid and pressure waves, showed similar results with a more automated approach. Due to SSGRID’s results and ease of use, the rest of the study focused on developing a best practice using SSGRID. The best practice created by this study for boom predictions using the CFD code USM3D involved: 1) creating a small cylindrical outer boundary either 1 or 2 body lengths in diameter (depending on how far below the aircraft the boom prediction is required), 2) using a single volume source under the aircraft, and 3) using SSGRID to stretch and shear the grid to the desired length.

Nomenclature

\[ p = \text{pressure} \]
\[ p_\infty = \text{free-stream pressure} \]
\[ \Delta p/p = (p - p_\infty)/p_\infty \]
\[ h/l = \text{distance below the model normalized by model length (or body length)} \]
\[ x = \text{distance in the stream wise direction, inches} \]

1. Introduction

The desire to transport people and material at velocities greater than the speed of sound has led to considerable research by both industry and the government. In the 1990’s, NASA’s High-Speed Research Program (HSR) made numerous advances in the areas of aerodynamics and sonic boom.1,2 In the 2000’s, the Super 10 consortium of airframers identified the reduction of sonic boom over Pressures on the ground as a key element to making a viable supersonic business jet.3 With the creation of the Supersonic Project as part of NASA’s Fundamental Aeronautics Program, sonic boom modeling again became a priority. The prediction of the intensity of the sonic boom has usually been computed by obtaining a near-to-mid-field (<10 body lengths below the aircraft) pressure distribution (\( \Delta p/p \)) and extending it to ground level using atmospheric propagation methods.4 Using unstructured grids, where it can be difficult to control the distribution and orientation of the field grid beneath the model, pressure signatures in the mid-field typically are insufficiently predicted. Improved results have been obtained using an error-driven adjoint-based grid adaptation method5,6, but multiple runs using the flow and adjoint solvers can make the process cumbersome. Several hybrid methods7,8 have been developed that use overset or unstructured grids to compute the

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very near-fielded solution, then use these results as boundary conditions for a structured grid case that extends into the mid field. While these methods have also been successful, their complexity has motivated research on other methods.

At the beginning of fiscal year 2007, the state of art for boom prediction using USM3D was from a sourcing method produced by Wyle Labs in 2004 under NASA contract NAS1-98100. This grid sourcing method, shown in figure 1, involved sources coming from the body at the expected Mach angle and continued into the far field 1 body length below the aircraft. An additional set of line sources were used to form a cylinder around the aircraft with a radius of 1 body length. These sources and their locations, had to be manually calculated and inserted. Figure 2 compares the results from this method with experimental data at 1 and 2.5 body lengths. Since the sourcing is focused to the 1 body length, the computational prediction does an excellent job. However, at 2.5 body lengths, the predicted signature looses crispness and no longer is able to predict the initial shock or the recovery.

Since the state-of-the-art boom prediction method was far from the goal of NASA’s supersonic program to predict boom up to 10 body lengths below the aircraft, grid sourcing and adaptation methods needed to be significantly improved. This paper details the study of grid sourcing and adaptation to obtain accurate near-to-mid field pressure signatures of supersonic configurations using the computational fluid dynamics (CFD) code USM3D. The study first examines body and far field sourcing, and the shape and sourcing of the outer grid boundaries. From there, several grid adaptation methods are evaluated. Finally, with the recent addition of volume sourcing in the grid generation code, VGRID, two different volume-sourcing techniques are evaluated. This study was conducted using two NASA configurations.9,10 These two configurations, shown in figure 3, consisted of a simple cone-cylinder, and a generic NASA wing body configuration called the Straight Line Segmented Leading Edge model (SLSLE).

II. Computational Code Information

This computational fluid dynamics (CFD) study used the NASA Tetrahedral Unstructured Software System (TetrUSS11) for all the computations. This CFD suite, created and maintained by NASA Langley Research Center, includes an unstructured grid generation program called VGRID, a postprocessor named POSTGRID, and the flow solver USM3D.

VGRID is an interactive, or batch, tetrahedral unstructured grid generation program. The grids produced by VGRID are suitable for computing Euler or Navier-Stokes flow solutions. The grid spacing is related to the strength of user-defined sources placed in the domain. The methodology is based on the Advancing-Front method (AFM)12 and the Advancing-Layers method (ALM).13 Both techniques are based on marching processes in which tetrahedral cells grown on an initial triangular boundary mesh and gradually form in the field around the geometry. Once the advancing front process is completed in VGRID, an additional post-processing step is required using POSTGRID to close any open pockets and to improve grid quality.

The USM3D code14 is a cell-centered, finite-volume Navier-Stokes flow solver that uses Roe flux-difference splitting15 to compute inviscid flux quantities across the faces of the tetrahedral cells. Several options for turbulent closure are available: the one-equation Spalart-Allmaras (S-A) model16 (with and without a wall function), and several two-equation models, including Menter’s Shear Stress Transport (SST) model.17 The parallel version of the flow solver was run inviscid and in the implicit mode for the cases presented in this study. The minmod limiter, used for supersonic conditions, was used to ensure during this study to ensure numerical stability.

III. Grid Sourcing

The study began with looking at the initial surface resolution requirements and how to properly source the configuration. Beginning with a basic cone-cylinder configuration, source strength, location and outer boundary shape were examined. The main goal of this study was to determine what type of sourcing would best obtain the peak and recovery pressures since these are typically under predicted by CFD methods.

A. Source Size

The goal of this study was to determine the minimum requirements for a surface mesh to capture sonic boom signature. The study began with a baseline mesh that had been created using what, was at the time, best practice sourcing. Variations from the baseline mesh included increasing the number of sources, adding stretching, and changing the source sizes.

The first part of the study looked at global changes. The baseline grid had 11.7 million grid cells and its sourcing is shown in figure 4. Linear sources were used on the body of the configuration while nodal sources were used for the far field. The first grid was produced by reducing all of the sources sizes by 20%, which resulted in a

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The ADAPT software is a collection of h-refinement tools in one package, developed by Dr. S. P. Pao of the NASA Langley Research Center. The user can activate one of the three parallel branches of the code for pre-marked cell division; h-refinement in designated spatial domains without a flow solution, adaptive mesh refinement based on functions of the flow solution, or user provided alternate functions. For this study, the adaptive mesh refinement based on pressure coefficient, \( C_p \), was used. Figure 13 shows the results of adapting and refining the grid twice using this code. The first adaptation increased the cell count by 26\% while the second adaptation/refinement increased the cell count by an additional 25\%. As can be seen, little to no change has been
made on the pressure distribution at a distance of 0.725 and 1.45 body lengths (H/L) below the cone-cylinder configuration.

B. ADV
The ADV adaptation code, by Richard Campbell of the NASA Langley Research Center, grew out of a grid movement method developed to modify an unstructured volume grid after surface design changes were made. In order to provide a grid adaptation capability, a simple approach based on differences in distance and flow variable value between a point and its connected neighbors was implemented. The method has two modes of operation, one that tends to cluster points in regions of high gradient and a second that draws points into zones of high absolute value of the selected flow variable. The second option has been used to provide better wake definitions for high-lift and aeroacoustic computations. A smoothing function can also be invoked to balance the distances to the surrounding points and provide some control over cell aspect ratios. For this part of the study, ADV was used twice: once to produce a grid that just adapted the grids to the area of interest (adv) and the second to both adapt and refine the grid to better capture Cp (adpx). The results from applying ADV on the cone-cylinder configuration are shown in figure 14. The grid produced by adapting the grid had a considerably greater impact than the final grid after refining and adapting the grid.

C. ADAPT/CRISP
An adaptation method using Dr. Paul Pao’s ADAPT code and the commercial adaptation code CRISP was suggested by fellow engineers examining boom predictions. CRISP CFD provides an automated grid refinement and coarsening capability. Grid refinement is implemented using a Delaunay procedure where grids of higher density are generated locally in regions where the grid quality fails to meet user specified gradient resolution criteria.

This adaptation method consisted of running ADAPT twice, then running CRISP and finally running ADAPT again. Each time, adaptation was done based on Cp. The original grid, produced by Wyle using the SLSLE model, was used as the baseline case. As shown in figure 15, the predicted boom from the CFD actually deteriorates during the adaptation process. The ability to predict the strength of the initial shock, the strength of the recompression and even the detail in the middle all deteriorate.

In order to ensure that the results weren’t due to the original grid already being able to predict the boom signature at 1 body length, another grid was tested using this adaptation method. Using the sourcing techniques from the first part of this study on the SLSLE model, a baseline grid was created and run through the ADAPT/CRISP adaptation method. The comparison of the CFD predicted boom signature with experimental data is shown in figure 16. Although during the process of the adaptation, some improvement was obtained, the CFD prediction was never as close to the experimental results as the Wyle grid without any adaptation.

V. Volume Sourcing
During the course of this study, a new version of VGRID was introduced. Software updates to VGRID included growth rates, surface sources, and volume sources. The outer boundary sources are no longer required for grid growth rates. The outer boundary sources were replaced with a user specified growth rate of the grid that dictates how the grids grow outwards from the aircraft and their maximum size. The new source types available in VGRID are shown in figure 17. In the older version of VGRID, only point and line sources were available. Now, users can define sources that are based on a surface, a sphere, a cylinder or a cone.

With this new capability, researchers looked at the difference in results between anisotropic and isotropic grids. During this study, isotropic refinement methods that add more points in the vicinity of shocks were tested and shown that although they made improvements near the model, they did not necessary improve the pressure signature prediction in the mid-field. This seems to imply that close grid spacing is required normal to the shocks and compression waves to adequately resolve the gradients, but a coarse grid spacing is needed in the propagation direction to minimize the number of cells traversed (and the resulting accumulated dissipation) to reach the mid-field. As a result, two approaches that used stretching of the grid in the shock direction, anisotropic grids, were examined. The first method focused on creating a grid with stretched grid cells aligned with the shocks. The second technique used the SSGRID code to stretch and shear the sources in order to capture the shock. The NASA Straight Line Segmented Leading Edge model (SLSLE) was used for both of these analyses.

A. VGRID Volume Sourcing
The location and set-up of the volumes sources used in VGRID are shown in figure 18, while the grid these sources produced is shown in figure 19. The grid was generated using volume sources that formed the desired grid
and captured the Δp/p without any further alterations to the grid or need for adaptation. The results from this grid are compared with the experimental data and shown in figure 20. This technique predicted the trend and most of the magnitudes in the boom signature, with the exception of the recovery at x=49 inches and the detail between 45 < x < 47 inches. The later exception appears to be the result of a missed geometric detail in the wind tunnel model that was not modeled in the computational mesh. Many researchers, using different codes with the same computational description of the geometry, have missed this same detail.

B. SSGRID

The SSGRID code, created by Richard Campbell of the NASA Langley Research Center, uses a priori adaptation, by which the initial grid is clustered and oriented based on flow characteristics, such as Mach number. A small grid is created around the aircraft of interest, usually with an cylindrical outer boundary with a 1 body length diameter. Underneath the aircraft, a volume source is created that encompasses the length of the aircraft and goes from just underneath it to the lower boundary, as shown in figure 21. Then, the preliminary cylindrical grid, shown in figure 22, is run through SSGRID where the user specifies a desired outer boundary distance (in dimensions of body lengths). The grid points between the preliminary cylinder outer boundary and the desired conical outer boundary are first stretched in a radial direction to a specified distance, then sheared conically to match the free-stream Mach angle. This aligns the stretch direction with the shocks (figure 23) so that only a small flow gradient is encountered in that direction. The comparison of predicted Δp/p with experimental data, at 2.5 body lengths below the SLSLE aircraft, is shown in figure 24. As with the previous method, this technique correlates well with experimental data, with the exception of the recovery at x=49 inches and the detail between 45 < x < 47 inches. The benefits of this technique include small grid sizes and the ability to easily make new grids with different freestream conditions, by simply running SSGRID on the preliminary mesh with new Mach numbers.

VI. Further SSGRID Studies

Due to the ease of use of SSGRID and its ability to predict the boom signature, the rest of the study focused on using SSGRID.

A. Sting Modeling

The study now focused on accurately predicting the recompression at the aft of the signature. The first step was to test whether modeling the sting was necessary. Figure 25 compares the boom signatures of the SLSLE with and without the sting modeled using SSGRID. Although no difference is seen in the predicted recompression, by modeling the sting, the second recompression (at x=26) predicted by CFD is removed.

B. Adaptation

Since adaptation was tested with prior gridding techniques, ADV was used to adapt (not adapt and refine) the grid. Grid cells were clustered together based on Cp gradient. Adaptation was tried twice, once to a grid without the sting and once to a grid with the sting modeled. Figure 26 shows that although adaptation doesn’t make huge changes to the results, it does better capture the curvature of the initial shock (insert) and predicts a slightly larger recompression in the aft region (from x=164 to x=168) of the signature.

C. Size of Outer Boundary

Since the recompression was still being missed by the CFD predictions, the initial size of the grid produced was examined to ensure the grid cells were not being stretched and sheared too far. A new initial cylindrical grid with a radius of 2 body lengths was produced and using SSGRID stretched to obtain a 10 body length prediction. The results of the 1 body length and 2 body length radius cylinders are compared in figure 27. Additionally, the 2 body length radius cylinder’s solution was also adapted using ADV. The larger initial grid was able to predict the recompression and through additional testing, it was determined that a 1 body length radius cylinder could give reasonable boom predictions up to 5 body lengths below the aircraft while 2 body length radius was necessary in order to obtain predictions at 10 body lengths.

VII. Best Practice Conclusion

This paper detailed the sourcing and adaptation study that was conducted for NASA’s supersonic program. Although numerous gridding options were examined and adaptation techniques tested, it was the addition of volume
sources in VGRID that permitted accurate boom predictions using the USM3D CFD code. Figures 28 and 29 compare the previously best CFD predictions with results from SSGRID. At 1.5 body lengths below the aircraft, the strength of aft recompression is now predicted. At 10 body lengths, which was not obtainable previously, USM3D using SSGRID can now predict the boom signature strength and details. The best practice created by the study for boom predictions using the CFD code USM3D involves: 1) creating a small cylindrical outer boundary either 1 or 2 body lengths in diameter (depending on how far below the aircraft the boom prediction is required), 2) using a single volume source under the aircraft, and 3) using SSGRID to stretch and shear the grid to the desired length.

References

Table 1 Listing of Grids Analyzed While Altering Only the Body Sources

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Table 2 Listing of Grids Analyzed While Altering the Outer Boundary

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<td>1 Additional Source on each outer line (refined)</td>
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<td>Box Grid (refined)</td>
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<tr>
<td>Box Grid with Inner Box</td>
<td>3.8 mil</td>
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Figure 1 State of the Art Sourcing Technique from Wyle Laboratories
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a) Cone Cylinder Model

b) Straight Line Segmented Leading Edge (SLSLE) Model

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b) 1.45 Body Lengths Below Cone-Cylinder
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Previously could not predict at 10 Body Lengths

Figure 28 Comparison of the Best Results of CFD Prediction at 1.5 Body Lengths Below the Model

Figure 29 Comparison of the Best Results of CFD Prediction at 10 Body Lengths Below the Model