AIAA 2004–1060

Numerical and Mesh Resolution Requirements for Accurate Sonic Boom Prediction of Complete Aircraft Configurations

S. Choi, J. J. Alonso, and E. Van der Weide
*Department of Aeronautics & Astronautics
Stanford University, Stanford, CA 94305-3030*

**42nd AIAA Aerospace Sciences Meeting & Exhibit
January 5–8, 2004/Reno, NV**

Numerical and Mesh Resolution Requirements for Accurate Sonic Boom Prediction of Complete Aircraft Configurations

S. Choi*, J. J. Alonso†, and E. Van der Weide‡

*Department of Aeronautics & Astronautics
Stanford University, Stanford, CA 94305-3030*

In this paper we conduct a careful study to assess the numerical mesh resolution requirements for the accurate computation of sonic boom ground signatures produced by complete aircraft configurations. The details of the ground signature can be highly dependent on the accurate prediction of the pressure distribution in the near-field of the aircraft. For this purpose it is necessary to describe the geometric detail of the configuration including the wing, fuselage, nacelles, diverters, etc. and to accurately capture the propagation of shock and expansion waves at large distances from the fuselage centerline. Unstructured, adaptive mesh technologies are ideally suited for this purpose since they use mesh points only in the appropriate locations within the flow field. In this work, we consider a supersonic business jet configuration (SBJ) which was tested at the NASA Langley Research Center and for which experimental near-field data was extracted at several locations underneath the flight track. The propagation of these near-field signatures from different altitudes can be shown to result in near N-wave ground booms. In order to examine the effect of both nacelles and empennage, results for three test cases are presented. These test cases represent the complete configuration with the large nacelles, the configuration without the nacelles, and the configuration without the nacelles and empennage. Inviscid solution adaptive unstructured meshes with up to 7.2 million nodes and 42.1 million tetrahedra are used to calculate the pressure distributions at several locations below each configuration where comparisons with experimental data are performed. All near-field pressure distributions are propagated to the ground (from an altitude of 50,000 ft) to predict the ground boom and the perceived noise level of the ground signature. For each case, the minimum number of mesh nodes and elements and the levels of refinement needed for accurate computations of near-field pressure distribution and ground boom signature are discussed.

INTRODUCTION

SONIC boom phenomena is one of the main reasons preventing the acceptance of supersonic flight over populated areas. The importance of minimizing the environmental impact cannot be understated. In addition, the business case for low-boom supersonic aircraft is also quite compelling: a much larger market can be found should the aircraft be allowed to fly supersonically over land. For these reasons research efforts have been recently focused on various techniques for sonic boom mitigation.¹⁻⁷ However, before sonic boom minimization design work can be credibly carried out, the accurate prediction of the fundamental sonic boom propagation problem has to be addressed in detail.

By the time the pressure disturbance created by an airplane reaches the ground, most boom signatures develop into the well-known N-wave shape. This sig-

nature is such that it contains two strong shocks at its beginning and end, causing a high perceived loudness (pdB). The propagation of this kind of N-wave signatures has been pursued in the past with significant success⁸⁻¹⁰ but without a clear understanding of the numerical requirements for the CFD portion of the problem. This has been mainly due to the lack of computational power necessary to carry out credible mesh refinement studies.

Most efforts directed towards sonic boom mitigation have been based on the tailoring (or *shaping*) of the sonic boom signature so that the magnitude of the front and rear shock waves in an N-wave are minimized.⁶ In fact, it has often been the approach to alter the boom signature such that ramps, flattops and multi-shock shapes are created. The accurate and efficient computation and propagation of such *shaped booms* is a much more challenging task than for N-waves; to date, there have only been a few studies relating to the ability of CFD-based sonic signature methods to predict the phenomenon accurately,^{4,5,11} and none of them has particularly focused on the prop-

*Graduate Student, AIAA Member

†Assistant Professor, AIAA Member

‡Research Associate

Copyright © 2004 by the authors. Published by the American Institute of Aeronautics and Astronautics, Inc. with permission.

agation of shaped booms.

There have been many difficulties in analyzing sonic boom signatures with CFD methods. These problems are associated with issues of mesh resolution, artificial dissipation formulation, two-dimensional versus three-dimensional signature propagation methods, and the actual formulation of these propagation procedures. Detailed studies are needed to establish minimum requirements for the accurate analysis and design of low-boom aircraft.

Especially regarding the mesh resolution issue, no actual guidelines have been issued yet as to the mesh element size and distribution required for accurate off-body pressure computation. This mesh resolution/distribution issue is tightly coupled with the fact that complex geometry representation (full configurations including nacelles, diverters, etc.) is typically necessary in the shaping of low sonic boom aircraft. Complete configurations also require higher mesh resolution for capturing shock and expansion waves around the aircraft.

Unstructured meshes are ideally suited to address the issues of automatic meshing around complete aircraft configurations and mesh resolution/distribution. In fact, unstructured meshes have more flexibility for adding or deleting points arbitrarily from the computational domain. They can be easily refined and coarsened adaptively with information provided by the flow solutions. This adaptive mesh refinement strategy can improve computational efficiency in the presence of finite computing resources. Depending on the resulting flow field and possible error estimates in the numerical solution, isotropic or anisotropic refinement may be more appropriate.

In this work we analyze a supersonic business jet (SBJ) configuration designed and tested at the NASA Langley Research Center that produces near N-waves at the ground plane. Basic variations of the original configuration are made by removing the nacelles and vertical tail to investigate their effects on the near field and ground boom signatures. All the analyses of aerodynamic performance and sonic boom are carried out using a tetrahedral unstructured adaptive flow solver and the PCBoom3 acoustic propagation software of Plotkin.⁸

Solution adaptive meshes are generated through several adaption and flow solution cycles. Using these meshes, near-field pressure distributions are extracted at distances of 9.5in, 12in and 18in below the aircraft for each configuration (corresponding to R/L values of 0.59375, 0.75, and 1.125 respectively) and are compared with the existing wind-tunnel data.

Once the near-field data has been validated, signatures are propagated to the ground to determine the variations in signature shape and perceived loudness caused by disagreements in the near-field information. Additional comparisons with the results obtained with

a linearized, supersonic panel method are made in order to illustrate the differences that result from the use of high-fidelity CFD.

The objective of this work is to simply establish a minimum set of requirements that must be met by all computations of sonic boom phenomena. For that purpose, as the results are analyzed, we suggest typical mesh and element sizes that may be required in order to produce ground boom signatures with a level of error less than 5%.

METHODOLOGY : BOOM-UA

BOOM-UA is a nonlinear integrated tool for both sonic boom prediction and aerodynamic performance analysis based on fully nonlinear CFD. This tool couples a three-dimensional solver for unstructured tetrahedral meshes to a CAD-based geometry kernel for efficient surface mesh regeneration, to the Centaur¹² mesh generation and adaption system, and to the PC-Boom3 software (developed by Wyle⁸ Associates) for far-field signature propagation and noise and loudness computation.

The unstructured adaptive mesh generation/perturbation/regeneration capability of BOOM-UA is based on the Centaur mesh generation family of tools. Given the CAD definition of the geometry and a set of explicitly constructed far-field boundaries, Centaur uses an advancing-front method to generate both surface and volume meshes. Once a suitable mesh has been generated, the flow solution is carried out using the AirplanePlus solver of Van der Weide¹³ which uses an agglomeration multigrid strategy and MPI-based parallelization to solve Reynolds-Averaged Navier-Stokes (RANS) equations on unstructured tetrahedral meshes. Although the software is able to solve the RANS equations, all calculations in this work have been carried out using the Euler equations since the phenomena that result in ground boom signatures (shock waves and expansions) are largely of an inviscid nature, and no regions of separated flow were observed in the experiments.

The flow solution follows several levels of solution-based isotropic adaption until the near-field signatures are deemed to be fully converged. Once such a solution is obtained, the near-field pressure signature is extracted and handed over to the PCBoom3 software which propagates it to the ground plane subject to a pre-specified flight altitude, atmospheric temperature profile, and horizontally stratified winds (if any, although none were used in this work). The perceived loudness (pLdB) of the ground signatures are recorded using a 1.9 ground reflection coefficient and without the addition of a finite rise time.

The whole computation from geometry description to ground boom signature and perceived noise level computation is fully automated so that optimization loops can be wrapped around the BOOM-UA system.

Typical complete solution times (including all mesh generation and adaption) are on the order of 30 minutes using 16 processors of a Beowulf cluster made up of Athlon 2100XP processors.

Unstructured Tetrahedral Mesh Generation

In this work we focus on the use of unstructured tetrahedral meshes for the solution of the Euler equations around complete aircraft configurations. There are many methods available for the generation of tetrahedral meshes^{14–16} and they are typically based on either advancing front or Delaunay triangulation ideas. In our work, an automatic advancing-front method is used for mesh generation. Advancing-front methods¹⁷ involve the simultaneous generation of mesh points and their connectivity. The idea is to build the mesh element by element, adding new elements to previously generated ones, thus sweeping out a front across the entire domain. They usually rely on an explicitly defined element-size distribution function, which is most often constructed using a background grid.¹⁸ The success of the advancing-front technique relies on the existence of a smoothly varying field function.

The Centaur software¹² is used in our work to construct meshes for all aircraft configurations and to enhance grid quality through automatic post processing. Only the fine meshes need to be explicitly constructed since our multigrid algorithm is based on the concept of agglomeration and, therefore, coarser meshes do not need to be generated directly. As mentioned above, Centaur is based on the advancing front model and consists of various different modules that are used by BOOM-UA.

The traditional approach to mesh generation using Centaur is an interactive one: a geometry import and preparation module (*setupgrid*) is used to retrieve the surface of the aircraft configuration (usually in IGES format). This geometry representation nearly always has to be cleaned up significantly within *setupgrid* before mesh generation can proceed due to imperfections in the imported geometry definition. Once the geometry is ready for mesh generation, a surface mesh generator (*makegrid*) is used to produce the initial surface mesh on which the volume mesh will be based. Note that the IGES geometry representation is retained in the form of analytic patches so that posterior mesh adaption is allowed to introduce nodes on the true surface of the configuration.

As mentioned above, the volume mesh is then constructed (with the same *makegrid* program) using the advancing front method. The mesh generation process includes various procedures to ensure mesh quality, including mesh smoothing.

Once a complete mesh has been created, a flow solution can be computed and the features of this flow solution can be used to add/remove nodes and elements to the mesh. This process of isotropic mesh

adaption is also carried out automatically by the Centaur module *adaptgrid*. The flow solution and mesh adaption procedure is repeated as many times as necessary until a converged flow solution is reached, or until the memory resources of the available supercomputer were exhausted.

The process of generating a suitable mesh for sonic boom computation seems, at first, relatively user-involved. Since the requirement for user involvement can prevent the full automation of the whole BOOM-UA process (which is absolutely necessary for design) we have taken steps to ensure that no user interaction is necessary for repeated evaluation of multiple variations of a baseline configuration. This automation is not fundamental to the work presented in this paper, but is essential for design efforts that are currently being pursued within our group.

For this purpose, we can create parametric aircraft models¹⁹ which can be easily regenerated when any of the shape parameters is altered. The regeneration of this CAD parametric model is driven by the CAPRI API of Haimes.²⁰ Once a new geometry has been constructed, the necessary information can be generated to automatically construct a volume mesh using the Centaur software modules described above and, possibly, a mesh perturbation module called *perturbgrid*. The CAPRI CAD interface also has the capability of generating surface triangulations of high quality that can be used in lieu of the ones generated internally by Centaur.²⁹

Figure 1 shows a typical triangular surface mesh around the NASA SBJ configuration of interest in this work. The figure contains only the triangles on the surface of the aircraft and it has been substantially coarsened for visualization purposes. Notice that the sting used for the wind-tunnel test has also been gridded.

Fig. 1 Surface mesh for NASA SBJ configuration.

Unstructured Flow Solver and Solution Approach

The three-dimensional AirplanePlus flow solver of Van der Weide¹³ is used in this work. AirplanePlus is a C++ implementation of the original AIRPLANE flow solver of Jameson²¹ developed during the third author's time at the military aircraft division of EADS in Munich. AirplanePlus contains substantial enhancements to the baseline algorithm, the agglomeration multigrid strategy, parallelization (of both the solver and pre-processor), load balancing algorithm, and the solution of the Reynolds-Averaged Navier-Stokes (RANS) equations.

An edge-based discretization is used to minimize the computational and memory requirements of the solver. The usual 4-stage Runge-Kutta method is modified with appropriately tailored coefficients to speed up the convergence rate by allowing high CFL numbers, aided by multigrid, residual smoothing and enthalpy damping for better convergence properties. Several options for artificial dissipation and the block-Jacobi preconditioning method are all available in the solver and can be used when needed.

An efficient, MPI-based, parallelization has been shown to produce linear scalability up to 32 processors in even small meshes with around 600,000 nodes. For the type of calculations that we have done in this work, much larger meshes are required and, therefore, our flow solver will scale linearly up to more than 512 processors. Typical calculations for this work have been run using 16 or 32 processors and therefore, near-linear scalability was obtained. The number of processors used was only limited by the availability of additional computational resources.

AirplanePlus has been validated on a number of configurations during its earlier use at EADS and was used to calculate accurate near-field pressure distributions for each of three configurations in this work. In addition, the flow solver from which it derives, AIRPLANE, has also undergone substantial validations studies over the years. Figures 7, 8 and 9 show the surface pressure distributions obtained by the AirplanePlus flow solver on each of the three configurations of interest in this work. Notice that each successive set of figures presents the configuration with components (nacelles and empennage) removed. The accuracy of the flow solutions can be seen in the level of detail present in the shock structure caused by the presence of the nacelles and diverters in the aft portion of the geometry.

Again, it must be noted that all the calculations in this work have been made using the Euler equations since they are suitable to the physical phenomena we are trying to predict here. However, neither the mesh generation/adaption procedure, nor the flow solver, are limited to the Euler equations: the Reynolds-Averaged Navier-Stokes equations could also be solved at additional expense due to the increased mesh size

requirements resulting from the resolution of boundary layers, shear layers, and wakes.

Mesh Adaption Procedure

Once an initial solution has been computed on a tetrahedral mesh, the grid needs to be locally adapted to better capture specific features with higher accuracy at lower cost (than that obtained with either multi-block structured approaches²² or uniform refinement of the grid.) This can be achieved through an improved distribution of grid points for each computed solution: unstructured tetrahedral elements are well suited for cell adaption. For the cases that we have studied, coarsening has only a minor performance benefit in steady-state calculations and was omitted in this study.

The adaption procedure utilizes h-refinement or subdivision techniques. For each edge that is flagged by the error estimation technique, new mesh nodes are inserted at the midpoint. For boundary edges, these points are repositioned onto the spline patch surfaces which define the original geometry from the CAD package. The current post-adaption grid-improvement scheme employs face and edge swapping. Undesirable shape measures are investigated and new local tetrahedra configurations with more desirable shape measures are selected.

The adaption procedure is, of course, recursive, and it proceeds until a certain level of error has been achieved or a maximum number of refinement levels has been accomplished. Figure 2 below shows the initial mesh around the configuration before any adaption has taken place. The selection of the initial mesh resolution is important to capture the underlying pressure gradients which will later be enhanced in the adapted meshes. Since the presence of shock waves and expansions are the driving features to be captured in this study and since the average shock angle is relatively predictable, our approach consists of performing two uniform local adaptations (mainly in the region under the aircraft) followed by several cycles (typically two or three) of solution-based adaption. Note that in the current study we are only interested in the effect of the primary boom carpet, and, therefore, no attempt is made to capture the shock waves that emanate from the upper surface of the configuration (which may be refracted down to the ground due to atmospheric effects.) Figure 3 shows the solution-adapted mesh after three adaption steps. Typically, four or five consecutive adaption cycles are performed automatically (starting with the initial mesh) to reach the necessary solution quality. These meshes become too fine for display purposes, but exhibit the same features represented in Figure 2. An appropriate choice of refinement criterion is very important to capture desired flow features and to obtain higher solution accuracy. The most popular refinement options for fluid-flow

Fig. 2 Original mesh without adaption. Mesh nodes=607,787

Fig. 3 Mesh after three adaptions with mesh nodes=1,893,110

problems are heuristically-derived gradient-based criteria, which involve a single or multiple physical flow variables. The gradient of pressure can be used to identify inviscid flow features. But in sonic boom prediction problems the pressure gradient in the near-field is as important as in the neighborhood of the aircraft. In addition, the direction of the gradient should be taken into account as well. In this study, a pre-specified range of velocity gradient magnitudes which are projected onto the direction of the local pressure gradient work successfully to predict shock locations

and to capture small pressure gradients in near-field. Since the initial mesh resolution is essential to capture the presence of the small pressure gradients in the near-field, an initial mesh that is too coarse is avoided. In addition, the initial steps of local uniform refinement underneath the aircraft are helpful to resolve the final solution with highest accuracy. The initial uniform refinements were done in an area under the aircraft that is between the Mach cones of the initial and final shock waves of the fuselage of the configuration (the initial portion of the sting is also included.)

Our adaption criteria is based on the local value of an adaption function (ϵ or ϵ') and a prescribed area that is eligible for adaption. If the value of the function is higher than a specified threshold value ($\epsilon = 10^{-4}$ has been used in our calculations) and the edge to be adapted is within the allowable region, the mesh is subdivided. A similar approach can be used for coarsening, although it did not result in significant computational savings and was therefore not used in this study. Initially, we had focused on the following expression to represent a good indicator of the need to adapt for sonic boom computations: $\mathbf{V}$ is the velocity vector, c is local speed of sound and Δx is a local mesh length scale.

$$\epsilon' = \frac{\mathbf{V}}{c} \cdot \frac{\nabla p}{|\nabla p|}. \quad (1)$$

However, experiments²³ by other investigators indicate that the modification of the previous equation to include a local mesh length scale such as:

$$\epsilon = \frac{\mathbf{V}}{c} \cdot \frac{\nabla p}{|\nabla p|} \Delta x \quad (2)$$

produces a more effective refinement criterion. This is partially due to the fact that while the simple gradient-based criteria decreases in magnitude as the mesh is refined in smooth regions of flow, it remains approximately constant in the vicinity of shock waves, since the shock wave profile steepens as the mesh is refined, and the jumps remain almost constant. However, even in the regions of smooth flow, the additional length scale (in the ϵ measure) weights larger cells more heavily than small cells, and drives the adaption process closer towards global refinement. In all of our computations, we have used the ϵ criterion for adaption using Centaur's *adaptgrid*.

Ground Boom Propagation

The basic strategy for the computation of ground boom signatures can be seen in Figure 4 below. A solution adaptive mesh using the criteria described above is constructed around the aircraft. It extends a certain distance away from it, but not to the ground plane as it would be computationally prohibitive to do so with appropriate resolution from the cruise altitude. At the near-field plane location, the pressure signature created by the aircraft is extracted, and it is propagated

down to the ground using extrapolation methods based on geometric acoustics.

The far-field boundaries of the CFD mesh must be located close enough so that the resulting mesh size is computationally manageable, but, at the same time, they must be located far enough so that the near-field flow field is axisymmetric and there are no remaining diffraction effects which cannot be handled by the extrapolation schemes. This fact embodies one of the fundamental difficulties of the computation of accurate sonic boom signatures: the near-field must be taken sufficiently far away for the aircraft and there must be adequate mesh resolution so that the near-field signatures are accurate enough. It must be noted that more refined procedures for signature propagation that allow the near-field signature to be taken closer to the aircraft have been developed⁹ but were not available to the authors.

In this study, the pressure field at the symmetry plane 0.59, 0.75 and 1.125 body lengths below the body, is obtained and provided as an initial condition to the boom extrapolation software. The pressure extraction algorithm (for the unstructured tetrahedral mesh) is based on advanced octree data structures and therefore incurs very little computational cost.

In this study, we have used both the Sboom²⁴ and PCBoom3⁸ extrapolation methods to convert near-field signatures into ground booms. Although the PCBoom3 software is far more capable than Sboom, we have only computed ground booms created by the aircraft in a steady-state cruise condition and, therefore, both codes are nearly equivalent. If ground booms caused by maneuvering aircraft were to be computed, the capabilities of the PCBoom3 software would have to be used.

The two sonic boom extrapolation methods account for vertical gradients of atmospheric properties and for stratified winds (which have been set to zero in this work.) Both methods essentially rely on results from geometric acoustics for the evolution of the wave amplitude, and both utilize isentropic wave theory to account for nonlinear waveform distortion due to atmospheric density gradients and stratified winds.

There are additional extrapolation/propagation methods that are based on the concept of an F-function²⁵ but these have not been used in this work as they assume no variation of the near-field signature in the azimuthal direction, which is normally not the case in our computations.

Obviously, depending on the type of acoustic wave propagation method used, the information extracted at the near-field can be two- or three-dimensional. In two-dimensional propagation cases (under the flight track) the pressure distribution along a line located on the aircraft symmetry plane is extracted and propagated vertically downwards. In three-dimensional wave propagation cases, the pressure data on a cylin-

drical surface centered along the aircraft longitudinal axis is extracted instead and propagated along rays in directions that are not necessarily perpendicular to the ground. The propagation scheme marches these *rays* down to the ground from all azimuthal directions that may eventually reach the ground. Depending on the atmospheric conditions and flight altitude, a cutoff angle will exist beyond which no disturbance will reach the ground: refraction effects divert the noise propagation back towards the upper atmosphere. Although the capability of extracting the signature on a cylinder around the aircraft is available in BOOM-UA, in this study we have chosen to extract and propagate information only under the flight track, since experimental near-field pressure data was only available on the symmetry plane.

Our earlier research on low-boom aircraft design was mainly focused on the reduction of the magnitude of only the initial peak of the ground boom signature.²⁶ This requirement, which had been suggested as the goal of the DARPA-sponsored Quiet Supersonic Platform (QSP) program ($\Delta p_0 < 0.3$ psf), hides the importance of the rest of the signature, which often arises from the more geometrically complex aft portion of the aircraft where empennage and engine nacelles and diverters create more complicated flow patterns. Moreover, such designs often have two shock waves very closely following each other in the front portion of the signature,^{11,27} a behavior that is not robust and is therefore undesirable.

For this reason, we have chosen to make comparisons based on the perceived loudness of the complete signature. In addition to computing the perceived loudness, another weighting, which is useful in estimating the attenuated noise when personal hearing protectors are used, the C-weighted sound level, is also obtained and compared with the perceived loudness. Frequency weighting methods are used here due to the unique property of the human hearing system which doesn't have an equal response to sounds of different frequencies. In these calculations, less weighting is given to the frequencies to which the ear is less sensitive.

VALIDATION TEST CASES

Configurations of Interest

In this paper, we focus our studies on a supersonic business jet (SBJ) configuration that was tested in the Langley Unitary Plan Wind Tunnel (UPWT), and which was used to extract near-field pressure information at various distances from the aircraft model. Variations of the baseline configuration are created by the removal of the nacelles and vertical tail in order to investigate their effect on both the near-field pressure distributions and the ground boom signature.

The original configuration was developed by R. J. Mack and was tested by Wilcox and Coen²⁸ and con-

Fig. 4 Schematic of Sonic Boom Minimization Setup with Nomenclature.

sists of a wing with large outboard dihedral/winglet, fuselage, vertical tail, and aft-fuselage mounted nacelles with diverters attached to the fuselage. A second configuration (proprietary to the Lockheed Martin company) was also tested, but neither the geometry nor the results were available to the authors for comparisons. The top, front, side and perspective views of the configuration as analyzed (including the rear sting mount) can be seen in Figure 5. More details of the experimental model and the testing procedure can be found in reference.²⁸

For purposes of computing the ground boom signatures, the wind-tunnel models were scaled up by a factor of 100 (as suggested by the wind-tunnel test report) and were flown at a (somewhat arbitrarily chosen) cruising altitude of 50,000 ft on a U.S. Standard Atmosphere with no winds. For a target lift coefficient $C_L = 0.1$ based on a scaled reference area of $S_{ref} = 1560 \text{ ft}^2$ these conditions result in an aircraft cruise weight of 105,790 lbs. The model length is 16 in without the sting and 42 in with the sting included. The case with nacelles included uses what are referred to as *big nacelles* in the wind-tunnel report.

BOOM-UA is applied to all three configurations to extract the near-field overpressures and to predict accurate ground boom signatures. The near-field overpressures are extracted at three distances from the aircraft model (9.5 in, 12 in, and 16 in) corresponding to the locations where experimental data was taken. This allows us to compare the CFD predictions directly with experiment and to compute ground signatures extrapolated from these distances. In theory, if all three pressure signatures were sufficiently far from the aircraft the computed ground boom signatures would

fall on top of each other. As will be shown later, this is not the case, although the differences in both the ground boom signatures and the perceived loudness are relatively small.

Experimental Conditions

The wind tunnel test was conducted in the Langley Unitary Plan Wind Tunnel (UPWT) which is a continuous flow, variable pressure supersonic wind tunnel. The tunnel contains two test sections which are approximately 4 ft² and 7 ft long. The Mach number for the relevant experiments was set 2.0, while Reynolds number was 2.0×10^6 per ft.

The model and sting combination were pinned together and connected to an angle of attack mechanism and tunnel model support system. The angle of attack mechanism was used to vary the model angle of attack and the tunnel model support system had the capability to move the model longitudinally and laterally within the test section so that near-field pressure signatures could be extracted at varying distances from the model. The survey and reference probes were mounted on a track to measure the difference between the static pressure of each probe. The near-field pressure was measured at three different locations for each configuration with different angles of attack.

Figure 6 below is reproduced from the experimental report²⁸ and shows a brief view of the experimental model mounted in the wind tunnel.

Fig. 6 View of the model mounted in the wind tunnel.

Solvers and Flow Conditions

BOOM-UA was used to simulate the results from the wind-tunnel experiments. As mentioned earlier, the flow solver portion of BOOM-UA was used in inviscid mode only. In all of these computations, small discrepancies may therefore exist due to the lack of viscous effects, although these discrepancies are expected to be small, as viscosity only plays a minor role in the generation of the pressure signatures that we are

Fig. 5 Three-View drawing of NASA SBJ configuration.

interested in.

In addition, the angle of attack was set to match the experimental values for each of configurations and varies from 2.54° to 2.89° . No attempt was made to match the experimental lift coefficients exactly. As expected, the computed lift coefficients (at the matched angles of attack) are approximately 1% higher than the experimental values obtained. The lift coefficients are very close to $C_L = 0.1$ in all cases. The cruising altitude is set at 50,000 ft.

RESULTS

Pressure Distributions vs. Mesh Resolution

In order to assess the mesh resolution requirements for accurate near-field signature extraction, solution-adaptive computations were carried out for each of the three configurations in question (c1 = full configuration, c2 = configuration without nacelles, c3 = configuration without nacelles and tail). For each of these configurations, 5 flow solutions and 4 adaption cycles were carried out starting from relatively fine initial meshes.

Table 1 shows the number of mesh nodes in each mesh, for each adaption cycle, and for each configuration (c1 through c3.) As mentioned earlier, the resolution of the initial mesh is very important to ultimately capture all of the phenomena we intend to observe. This is particularly true of the small pressure gradients in the near field (compared to those in a close neighborhood of the body) which tend to be missed if the initial mesh resolution is not sufficiently fine (the adaption criterion explained before focuses

on the flow features near the aircraft and disregards the near-field flow features.) For this reason, all initial meshes contained between 500,000 and 600,000 nodes. The first two levels of adaption are purely geometric and simply add mesh nodes in the area between the expected location of the front and rear shocks of the configuration. The third and fourth adaption cycles are solution-based.

After four adaption cycles and five flow solutions, the near-field pressure distributions appear to have converged. In the case of the configuration without nacelles and tail (c3) a further attempt to an additional adaption level failed due to *adaptgrid* exceeding the memory requirements of our Origin300 computer (16 Gbytes maximum). Note that all of the final meshes, whose solutions will be used for experimental comparison, have between 7×10^6 and 8×10^6 nodes. This large number of nodes is necessary to obtain reasonable comparisons that capture all of the flow features of the experiment. This mesh size (on an adaptive mesh) is in contrast with our earlier work (using multiblock structured meshes which had been biased along the direction of the front and rear shocks) which used on the order of 3×10^6 nodes.

	Initial	1 st adpt	2 nd adpt	3 rd adpt	4 th adpt
c1	607,787	690,239	933,192	2,749,606	7,698,731
c2	543,201	591,056	854,781	2,737,821	7,973,972
c3	523,954	572,467	838,612	2,736,989	8,100,624

Table 1 Number of mesh nodes through all the adaption cycles

Figures 10 through 12 show the evolution of the near-field pressure distributions through the various adaption cycles for all three configurations. For each configuration, we present computational results for each of the three near-field distances at which (at least for the complete configuration) data was taken in the wind tunnel. The locations at which computational data was collected are lines on the symmetry plane located at distances of $r = 9.5$ in, $r = 12$ in, and $r = 18$ in under the aircraft. As expected, the finest mesh for each configuration resolves the pressure signatures with most detail: the pressure rise across the shock is largest at each location and some of the minor features of the signature are present, while for the coarser meshes they do not appear.

The differences in the near field pressure distributions of all three configurations are obvious in the Figures. The front portion of the signatures are almost identical as nothing has changed in the geometry in that area and the removal of the tail and nacelle are unable to affect the pressure distributions upstream. The rear portion of the signature is rather different. The omission of the nacelles results in a sharp decrease in strength of second to last shock in the distribution. This can be appreciated from Figures 7 and 8 where the complex system of shock waves in the aft portion of the fuselage has disappeared. The effect of the removal of the tail (see Figure 9) is not as dramatic, but does cause an alteration in the pressure signature: the strength of the last shock wave in the signature is reduced to a $\Delta p/p < -0.02$.

Note that the pressure distributions that result from the mesh after three adaption cycles (with around 3×10^6 nodes) do not necessarily capture all the details of the signature and certainly miss the peak values of all of the shocks in the signature. From these observations we conclude that tetrahedral unstructured adaptive meshes in the neighborhood of 10×10^6 nodes are necessary to ensure that the near-field pressure signatures are computed without numerical error. Ultimately, what matters most to a designer is not the level of error in the near-field pressure signature, but the resulting errors once the near-field signature has been propagated to the ground. As we will see in a later section, due to the process of shock coalescence (as the signature ages) if the ground boom has an N-wave character, the need for the absolutely highest resolution in the near field may not be justified. However, for cases where the signature is such that it is *shaped* the resolution we have discussed here is needed.

Comparison of Near-field Pressures with Experimental Data

From the results of the mesh resolution study, the solution from the finest mesh (after four or five solution adaptive refinements) was chosen for comparison

with the near-field pressures obtained in the wind tunnel. These comparisons are presented in Figures 13 to 15. Note that for the cases without nacelles and tail, experimental data was not collected at the $r = 12$ in location and, therefore, a direct comparison is not available. Note also that since the reference pressure during the experimental runs was not necessarily p_∞ , the signatures do not start and end at values of $\Delta p/p = 0$. For this reason, the experimental signatures have been biased (no scaling applied) in such a way that $\Delta p/p = 0$ was obtained at the front and rear of the signatures.

In general, good agreement between the experiment and computations is found, despite the fact that all computations were carried out using the Euler equations and viscous effects were neglected. Furthermore, the reader is reminded that all computations were carried out at the experimentally determined angle of attack (no attempt to match C_L was made.) In addition, the computations simulated the aircraft embedded in a free stream and did not enclose the model within the wind-tunnel walls.

The number and magnitude of all pressure peaks in the experimental near-field signatures are captured by the simulations for all three configurations. Some small details in the aft portion of the signatures, particularly for the configuration without nacelles and without tail are missing from the computations, however, denoting that an initially finer mesh in the back end of the aircraft may be necessary for the adaption procedure to capture these features. However, these features have very small magnitude and are absorbed by the aging of the signature as it propagates down to the ground.

There is a slight tendency to overpredict the absolute length of the signature (from initial to final shock) in comparison with the experiment, which indicates that either the angles of the leading and trailing shocks were not predicted exactly, or that the effect of the expansions on the shock angles in the near field were slightly off. Again, these slight discrepancies do not appear to translate into significant ground perceived loudness changes as we will see later.

Some of these effects can be seen in the symmetry-plane pressure plots shown for all three configurations in Figure 16. The effects of both the nacelles and tail on the near-field pressure can be seen by comparing the three symmetry-plane pressure plots. The shocks that emanate from the tail region in the cases without nacelles and/or tail weaken considerably in comparison with the wave pattern present for the full configuration.

Ground Boom Signature and Weighted Sound Levels

Finally, in this section we present the results of the propagation of both computed and experimentally-

determined near-field signatures to the ground. As mentioned earlier, the wind-tunnel model was scaled up by a factor of 100 for the full-scale aircraft. In addition, the cruise altitude for the full-scale aircraft was chosen to be 50,000 ft, and a Standard US Atmosphere with no winds was setup for propagation purposes. The cutoff angle for acoustic disturbances that reach the ground turns out to be $\pm 54^\circ$, although only signatures underneath the flight track are considered here. All ground boom signatures are computed using the PCBoom3 software.

The ground boom signatures obtained starting from both experimental and computational near-field pressure distributions are presented in Figures 17, 18 and 19. From these Figures we can see that the ground signatures for these configurations result in pressure distributions that are very close to an N-Wave, except for the fact that a small shock persists in the middle of the signature (that has not yet been absorbed by either the front or rear shocks.) The computationally determined signatures exhibit an additional shock (in the front of the signature) that is not present in the experimentally derived ground booms: it appears that the small differences in the computational and experimental near-field pressure (after the initial pressure rise) are such that they are delaying the final coalescence of the front two shocks (when compared to the experimental results). Additional propagations of the same computational signatures from 55,000 ft show a fully coalesced front shock.

The differences in character between the computational and experimental ground boom signatures are not very large. In fact, in this case where the ground signature is nearly an N-wave, even the coarser meshes result in ground signatures that match the shape of the experiment well. The most obvious trend, however, is that as the number of mesh adaption levels in increased, the peak overpressures in the ground signatures increase, sometimes by up to 20%. These peak overpressures are consistently 5-7% lower than the experiment. Therefore, in order to predict the actual values of the peak overpressures, it is necessary to use the finest meshes in the sequence, if not even slightly finer. Figures 17, 18 and 19 show the results of boom propagation for near-field pressure from experiment and from computations after one and five adaption cycles in order to highlight the differences that derive from the use of much smaller meshes.

A more quantitative measure of the differences in the ground booms is presented below. Both C-weighted sound level (a measure that is useful to determine human perceived noise when wearing protective equipment) and perceived loudness were calculated for both the computations and experiments. Tables 2, 3 and 4 show the two sound level representations for the boom signature derived from the experimental data. Each table corresponds to each of the different configurations

studied in this work. The errors in the two sound level representations between ground signatures obtained from the finest meshes and from experimental data are shown in Tables 5, 6 and 7. For all three configurations and at all three different near-field locations, the sound levels of the propagated ground boom produce only small errors. In fact, the average error is around 2% for the dBC weighting, and slightly larger (around 3.5%) for the perceived loudness.

location	C-weighted level (dBC)	perceived loudness (pldB)
r=9.5	101.60	95.70
r=12	101.80	96.15
r=18	102.25	95.46

Table 2 C-weighted sound level and perceived loudness from experimental data. Complete configuration.

location	C-weighted level (dBC)	perceived loudness (pldB)
r=9.5	100.27	93.38
r=18	100.78	91.87

Table 3 C-weighted sound level and perceived loudness from experimental data. Configuration without nacelles.

location	C-weighted level (dBC)	perceived loudness (pldB)
r=9.5	99.96	93.55
r=18	100.57	93.58

Table 4 C-weighted sound level and perceived loudness from experimental data. Configuration without nacelles and tail.

location	C-weighted level (%)	perceived loudness (%)
r=9.5	1.9587	4.1152
r=12	1.9205	3.7600
r=18	1.9810	5.0030

Table 5 Error in C-weighted sound level and perceived loudness between experiment and computation. Complete configuration.

location	C-weighted level (%)	perceived loudness (%)
r=9.5	2.4038	5.4846
r=18	2.3016	7.3211

Table 6 Error in C-weighted sound level and perceived loudness between experiment and computation. Configuration without nacelles.

location	C-weighted level (%)	perceived loudness (%)
r=9.5	1.2558	0.2642
r=18	2.1959	5.0967

Table 7 Error in C-weighted sound level and perceived loudness between experiment and computation. Configuration without nacelles and tail.

CONCLUSIONS

We have developed an environment for sonic boom analysis of complete aircraft configurations, BOOM-UA, which automates the complete process from parametric CAD definition to ground boom loudness measures. The environment is based on a direct CAD interface (CAPRI), the Centaur mesh generation and adaption system, the unstructured tetrahedral flow solver AirplanePlus, and the PCBoom3 signature extrapolation program. Our intent is to use BOOM-UA in a design environment, but this paper focuses on the validation of the results provided by this tool.

A set of unstructured adaptive solutions were calculated for three configurations of interest (obtained by removing the nacelles and tail from a baseline configuration) and near-field pressure distributions were extracted, for each case, at three distances underneath the aircraft on the symmetry plane. These near-field pressure distributions are compared with the experimental values and are found to be in quite good agreement for meshes with over 7×10^6 nodes.

The computed near-field pressure signatures were extrapolated to the ground from an altitude of 50,000 ft and the resulting signatures were compared with those obtained using the experimental near-field data. Errors in both perceived loudness and C-weighted sound level are found to be within 3-5% from the experimentally derived values.

ACKNOWLEDGMENTS

This work has been carried out under the support of the NASA Langley Research Center, under contract NAG-1-03046. We gratefully acknowledge the support of our point of contact, Dr. Peter Coen, in supplying us with the geometry and experimental data necessary to complete this study.

References

- ¹K. J. Plotkin. Review of sonic boom theory. *AIAA paper 89-1105*, 12th AIAA Aeroacoustics Conference, San Antonio, TX, April 1989.
- ²C. Thomas. Extrapolation of sonic boom pressure signatures by the waveform parameter method. *NASA TN D-6832*, 1972.
- ³G. B. Whitham. The flow pattern of a supersonic projectile. *Commun. Pure Appl. Math.*, V(3):301-348, 1952.
- ⁴S. H. Cheung and T. A. Edwards. Supersonic Airplane Design Optimization Method for Aerodynamic Performance and Low Sonic Boom. In *High-Speed Research Conference: Sonic Boom, Volume II*, February 1992, pp. 31-44.

⁵M. J. Siclari. Ground Signature Extrapolation of Three-Dimensional Near-Field CFD Predictions for Several HSCT Configurations. In *High-Speed Research Conference: Sonic Boom, Volume II*, February 1992, pp. 175-200.

⁶R. Seebass and B. Argrow. Sonic boom minimization revisited. *AIAA Paper 98-295*, June 1998, 2nd AIAA Theoretical Fluid Mechanics Meeting, Albuquerque, NM

⁷S. Nadarajah, A. Jameson, and J. J. Alonso. An adjoint method for the calculation of remote sensitivities in supersonic flow. *AIAA paper 2002-0261*, AIAA 40th Aerospace Sciences Meeting, Reno, NV, January 2002.

⁸Kenneth J. Plotkin. "PCBoom3 Sonic Boom Prediction Model-Version 1.0e," *Wyle Research Report WR 95-22E*, October. 1998.

⁹K. Plotkin, J. Page. *Extrapolation of Sonic Boom Signatures from CFD Solutions*. *AIAA Paper 02-0922*, 40th AIAA Aerospace Sciences Meeting and Exhibit, January 2002, Reno, NV.

¹⁰S. E. Cliff, and S. D. Thomas. Euler/experiment correlations of sonic boom pressure signatures. *AIAA Paper 91-3276*, September 1991.

¹¹M. Chan. *Supersonic Aircraft Optimization for Minimizing Drag and Sonic Boom*. PhD thesis, Stanford University, Stanford, CA 94305, 2003.

¹²*Centaur Users' Guide*. <http://www.centaursoft.com/support/manual>.

¹³L. Fornasier, H. Rieger, U. Tremel, E. Van der Weide. *Time Dependent Aeroelastic Simulation of Rapid Maneuvering Aircraft*. *AIAA Paper 02-0949*, 40th AIAA Aerospace Sciences Meeting and Exhibit, January 2002, Reno, NV.

¹⁴T. J. Baker. Mesh Adaptation Strategies for Problems in Fluid Dynamics. *Finite Elements in Analysis and Design*, Vol. 25, 1997, pp. 243-273.

¹⁵M. A. Park. Adjoint-Based, Three-Dimensional Error Prediction and Grid Adaptation. *32nd Fluid Dynamics Conference*, June 24-27, 2002, St. Louis, MO

¹⁶R. Lohner. Generation of Unstructured Grids Suitable for RANS Calculations *AIAA Paper 99-0662*, 1999

¹⁷D. J. Mavriplis. Unstructured Mesh Generation and Adaptivity *ICASE 95-26*

¹⁸J. Peraire, M. Mahdavi, K. Morgan and O. C. Zienkiewicz Adaptive Remeshing for Compressible Flow Computation *Journal of Computational physics*, 72:449-466 October, 1987

¹⁹J. J. Alonso, J. R. R. A. Martins, J. J. Reuther, R. Haimes, C. A. Crawford. *High-Fidelity Aero-Structural Design Using a Parametric CAD-Based Model*. *AIAA Paper 2003-3429*, 21st AIAA Applied Aerodynamics Conference. Orlando, FL. June 2003.

²⁰R. Haimes CAPRI: Computational Analysis PProgramming Interface *Proceedings of the 6th International Conference on Numerical Grid Generation in Computational Field Simulations* July, 1998

²¹A. Jameson, T. J. Baker and N. P. Weatherill. Calculation of Inviscid Transonic Flow over a Complete Aircraft. *AIAA Paper 86-0103*, 24th Aerospace Sciences Meeting, January 6-9, 1986, Reno, Nevada

²²H. S. Chung, S. Choi, J. J. Alonso. *Supersonic Business Jet Design Using a Knowledge-Based Genetic Algorithm with an Unstructured, Adaptive Grid Methodology*. *AIAA Paper 2003-3791*, 21st AIAA Applied Aerodynamics Conference. Orlando, FL. June 2003.

²³G. Warren, W. K. Anderson, J. L. Thomas and S. L. Krist Grid Convergence for Adaptive Methods *AIAA paper 91-1592*, June 1991

²⁴Thomas, Charles L. "Extrapolation of Wind-Tunnel Sonic Boom Signatures without Use of a Whitham F-function" *NASA SP-255*, pp.205-217,1970

²⁵Wallace D. Hayes, Rudolph C. Haefeli and H.E.Djlsrud "Sonic Boom Propagation in a Stratified Atmosphere, with computer Program" *NASA CR-1299*,1969

²⁶J. J. Alonso, I. M. Kroo and A. Jameson. Advanced Algorithms for Design and Optimization of Quiet Supersonic Platforms. *AIAA Paper 02-0114*, 40th AIAA Aerospace Sciences Meeting and Exhibit, January 2002, Reno, NV.

²⁷H. S. Chung. *Multidisciplinary Design Optimization of Supersonic Business Jets Using Approximation Model-Based Genetic Algorithms*. PhD thesis, Stanford University, Stanford, CA 94305, 2004. To be published.

²⁸F. J. Wilcox. *Business Jet Sonic Boom Test - Unitary Plan Wind Tunnel Test 1870*. NASA Langley Research Center, February 2000.

²⁹R. Haimes Automatic Generation of CFD-Ready Surface Triangulations from CAD Geometry *AIAA paper 99-0776*, 1999

(a) Lower surface.

(b) Upper surface.

Fig. 7 Surface pressure distributions: complete configuration SBJ.

(a) Lower surface.

(b) Upper surface.

Fig. 8 Surface pressure distributions: SBJ without nacelles.

(a) Lower surface.

(b) Upper surface.

Fig. 9 Surface pressure distributions: SBJ without nacelles and empennage.

(a) Pressure distribution at $r=9.5$ in

(b) Pressure distribution at $r=12$ in

(c) Pressure distribution at $r=18$ in

Fig. 10 Near-field pressure distributions for all adaption cycles. Complete configuration.

(a) Pressure distribution at $r=9.5$ in

(b) Pressure distribution at $r=12$ in

(c) Pressure distribution at $r=18$ in

Fig. 11 Near-field pressure distributions for all adaption cycles. Configuration without nacelles.

(a) Pressure distribution at $r=9.5$ in

(b) Pressure distribution at $r=12$ in

(c) Pressure distribution at $r=18$ in

Fig. 12 Near-field pressure distributions for all adaption cycles. Configuration without nacelles and tail.

(a) Pressure distribution at $r=9.5$ in

(b) Pressure distribution at $r=12$ in

(c) Pressure distribution at $r=18$ in

Fig. 13 Comparison of near-field pressure with experiments. Complete configuration.

(a) Pressure distribution at $r=9.5$ in

(b) Pressure distribution at $r=18$ in

Fig. 14 Comparison of near-field pressure with experiments. Configuration without nacelles.

(a) Pressure distribution at $r=9.5$ in

(b) Pressure distribution at $r=12$ in

Fig. 15 Comparison of near-field pressure with experiments. Configuration without nacelles and tail.

(a) Pressure distributions for complete configuration.

(b) Pressure distribution for configuration without nacelles.

(c) Pressure distribution for configuration without nacelles and tail.

Fig. 16 Plot of near-field pressure distributions along symmetry plane.

(a) Ground boom from $r=9.5$ in.

(b) Ground boom from $r=12$ in.

(c) Ground boom from $r=18$ in.

Fig. 17 Ground boom comparisons. Complete configuration.

(a) Ground boom from $r=9.5$ in.

(b) Ground boom from $r=18$ in.

Fig. 18 Ground boom comparisons. Configuration without nacelles.

(a) Ground boom from $r=9.5$ in.

(b) Ground boom from $r=18$ in.

Fig. 19 Ground boom comparisons. Configuration without nacelles and tail.