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SONIC BOOM PREDICTION AND MINIMIZATION USING COMPUTATIONAL FLUID DYNAMICS

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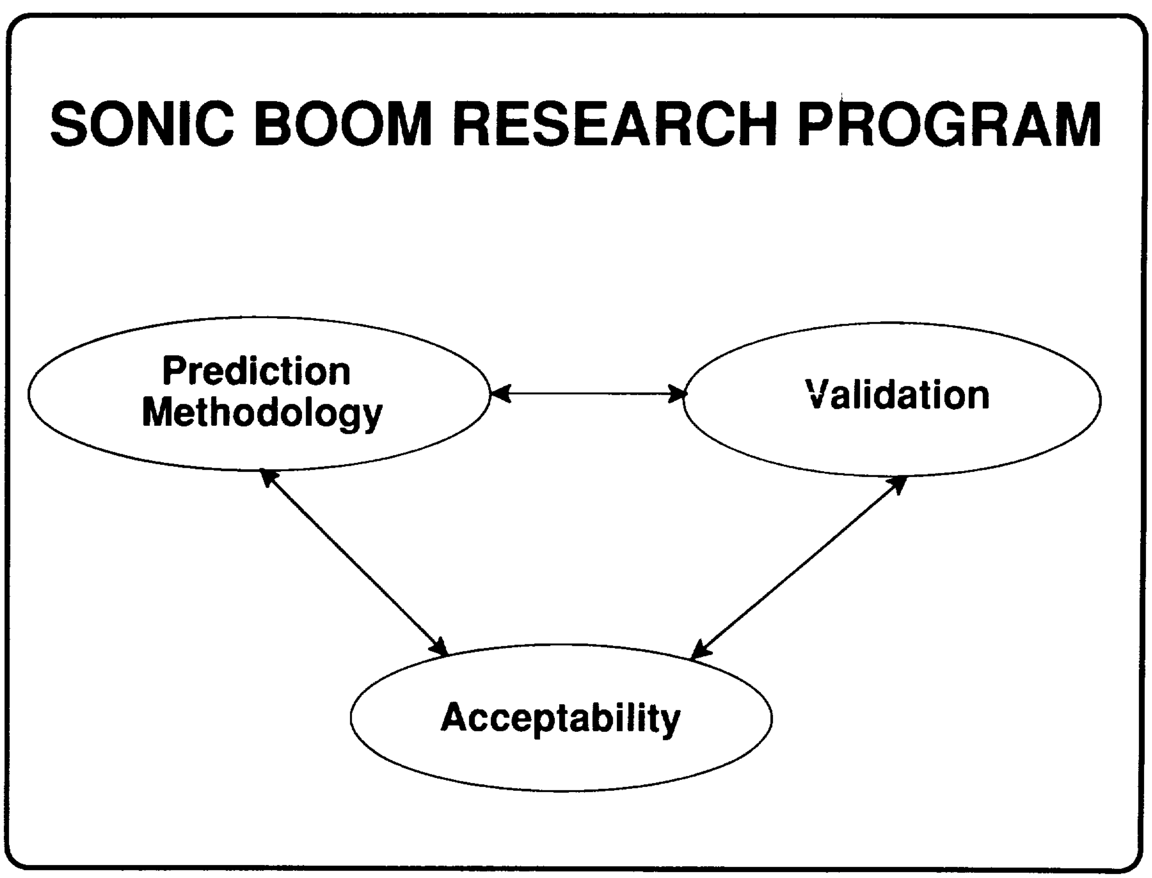
INTRODUCTION

This paper describes the NASA Ames Research Center program in sonic boom prediction methodologies. This activity supports NASA's High Speed Research Program (HSRP). An overview of the program, recent results, conclusions, and current effort will be given. This effort complements research in sonic boom acceptability and validation being conducted at Langley and Ames Research Centers.

The goals of the sonic boom element are: to establish a predictive capability for sonic booms generated by High-Speed Civil Transport (HSCT) concepts; to establish guidelines of acceptability for supersonic overland flight; and to validate these findings with wind tunnel and flight tests. The cumulative result of these efforts will be an assessment of economic viability for supersonic transportation. This determination will ultimately be made by the aerospace industry.



CFD SONIC BOOM PROGRAM

Established approaches to sonic boom prediction and minimization utilize linear supersonic aerodynamics and quasi-linear acoustic propagation theory. However, the accuracy of these methods deteriorates as the Mach number or angle of attack increases, and they have difficulty modeling complex geometries and propulsion system effects. The new generation of proposed HSCTs will be highly optimized in all respects, and hence will require improved accuracy in optimizing the sonic boom.

It has been proposed to utilize computational fluid dynamics (CFD) to provide the near-field pressure distribution. This approach has several advantages: nonlinear effects and geometric complexities can be fully accounted for, including propulsion system effects; the pressure field can be propagated to a distance sufficiently far from the vehicle that linear propagation theory is valid; a complete aerodynamic description of the vehicle is generated, facilitating simultaneous analysis of the complete system; and a common database can be used for low speed analysis and off-design performance.

The first element of this project was to validate CFD codes for sonic boom prediction. Three test cases of increasing complexity were selected for this purpose, and results of this study will be given later. Other aspects of the CFD activity include predictions of sonic boom for proposed configurations, pre-test analysis of wind tunnel models and post-test diagnostics, and numerical minimization of sonic boom loudness using CFD and optimizer technology.

AMES SONIC BOOM PROGRAM (COMPUTATIONAL)

- **Code validation**
- **CFD near-field prediction**
- **Experiment support**
- **Loudness reduction**

EXPERIMENTAL SONIC BOOM PROGRAM

Wind tunnel testing is another important aspect of the sonic boom effort. The 9x7-foot tunnel at Ames accesses the Mach 1.5 to 2.5 range and allows large models to be tested with measurements at sufficiently large altitudes for code validation and linear extrapolation. This facility was used extensively in the 1970's to test SST concepts. However, "tailored" waveforms are a relatively new concept and a sonic boom database needs to be developed for these configurations. Thus, as low-boom models are produced, the 9x7 will be used to measure sonic boom performance, providing code validation data and benchmarking progress of low-boom designs.

AMES SONIC BOOM PROGRAM (EXPERIMENTAL)

- **Update data base**
- **Verify design methods**
- **Demonstrate performance**

AMES COOPERATIVE RESEARCH

At NASA Ames, the Applied Computational Fluids Branch (RFA) and the Advanced Aerodynamic Concepts Branch (RAC) are contributing to the sonic boom prediction methodology. The Applied Computational Fluids Branch is emphasizing code validation and coupled aerodynamic optimization/sonic boom minimization, while the Advanced Aerodynamic Concepts Branch is performing aerodynamic optimization and complex configuration analysis, and conducting wind tunnel tests with CFD correlation.

Care has been taken to integrate the effort in sonic boom prediction described here with the other elements of sonic boom analysis. Langley-developed low-boom models have been tested in the Ames 9x7 tunnel, and CFD correlation with these tests is in progress. Preliminary results will be presented later. Future models developed by Langley, Ames, and industry will be tested as well.

The acceptability criteria and atmospheric effects will play heavily into the determination of a successful supersonic overland design. Results from this research will be factored into the analysis as they become available. Complementary efforts in sonic boom minimization are also integrated between the centers. Validated CFD codes will be used as numerical wind tunnels to assess sonic-boom-minimized designs. Comprehensive systems analysis using linear methods will, in turn, provide a baseline for subsequent nonlinear analysis using CFD.

AMES SONIC BOOM RESEARCH ORGANIZATIONS

- <u>Applied Computational Fluids (RFA)</u>

  CFD validation, sonic boom prediction and minimization, aerodynamic optimization

- <u>Advanced Aerodynamic Cconcepts (RAC)</u>

  CFD validation, sonic boom prediction, aerodynamic optimization, wind tunnel tests

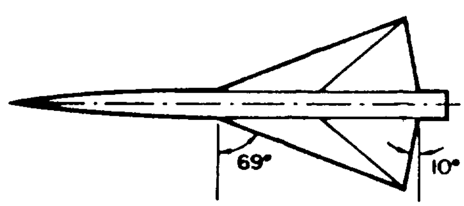
CFD VALIDATION STUDIES

As mentioned earlier, three test cases were chosen to validate CFD codes for sonic boom prediction and to gain experience in the modeling requirements. These configurations were tested in the Ames 9x7-foot tunnel in the 1970's and have experimental data available at a variety of operating conditions and altitudes (see Ref. 1). These geometries represent a progression of geometrical and physical complexity, from a cone-cylinder to a low aspect-ratio wing to a delta-wing body.

In addition, a succession of CFD codes was applied to these test cases. These include TRANAIR, a full-potential code with local mesh refinement capability; TEAM, an Euler/Navier-Stokes code with versatile zonal grid capability; AIRPLANE, an unstructured-grid Euler solver; and UPS, a parabolized Euler/Navier-Stokes code.

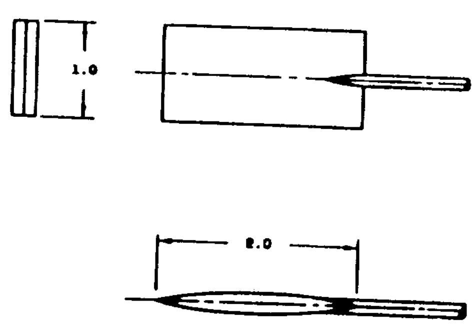
Initially, the CFD codes were used to generate a solution in the near-field, about one-quarter to one body length vertically below the vehicle. The pressure on the centerline was then extracted from the solution and used to initialize a quasi-linear extrapolation code to propagate the signal to the desired altitude. Other methods of incorporating CFD into the sonic boom analysis were subsequently investigated have been reported in Ref. 2.

CFD VALIDATION MODELS



Delta Wing/Body

Cone Cylinder

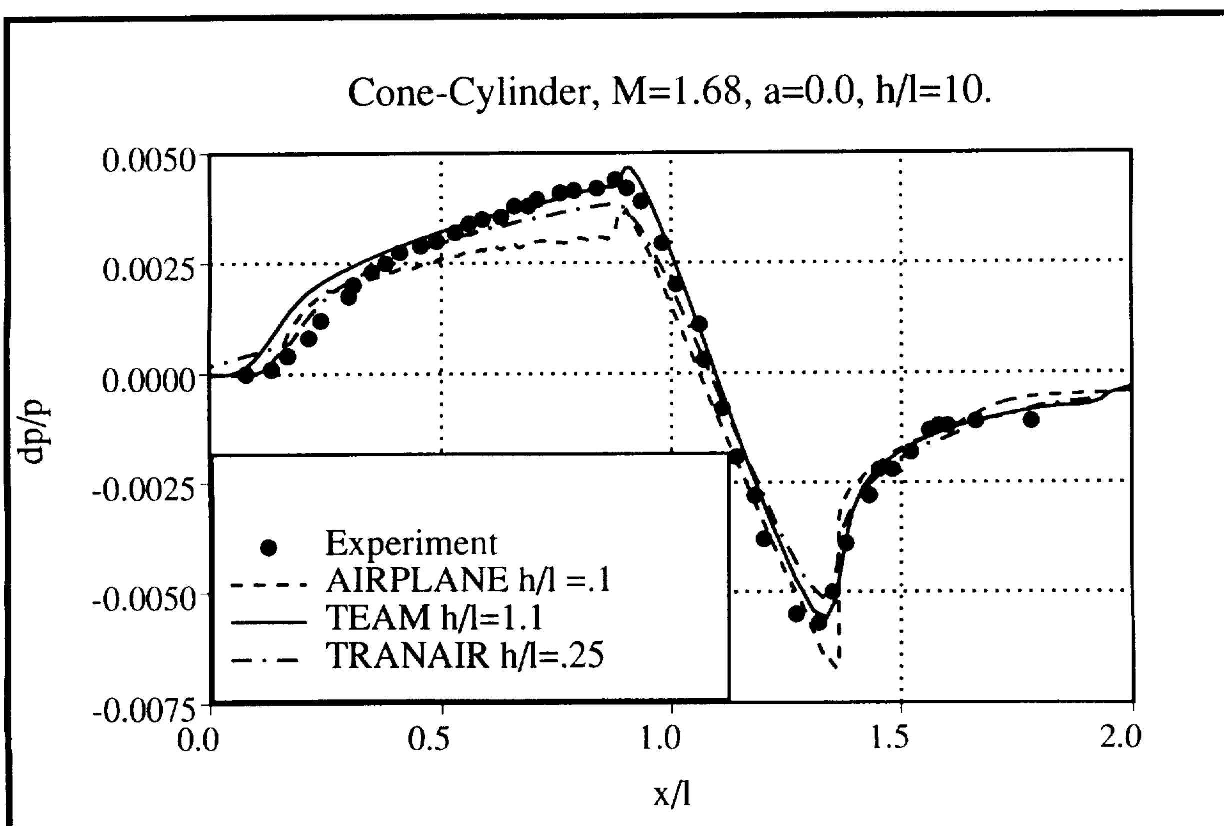


Low-Aspect-Ratio Wing

CONE-CYLINDER VALIDATION

A cone-cylinder geometry was the first test case, where the cone angle is 6.48 deg. and the test Mach number was 1.68. The overpressure signature for this model was measured at altitudes of 10 and 20 cone lengths. Because of the large altitude and very weak shock generated by the geometry, this case was a good test of dissipative errors present in the computations.

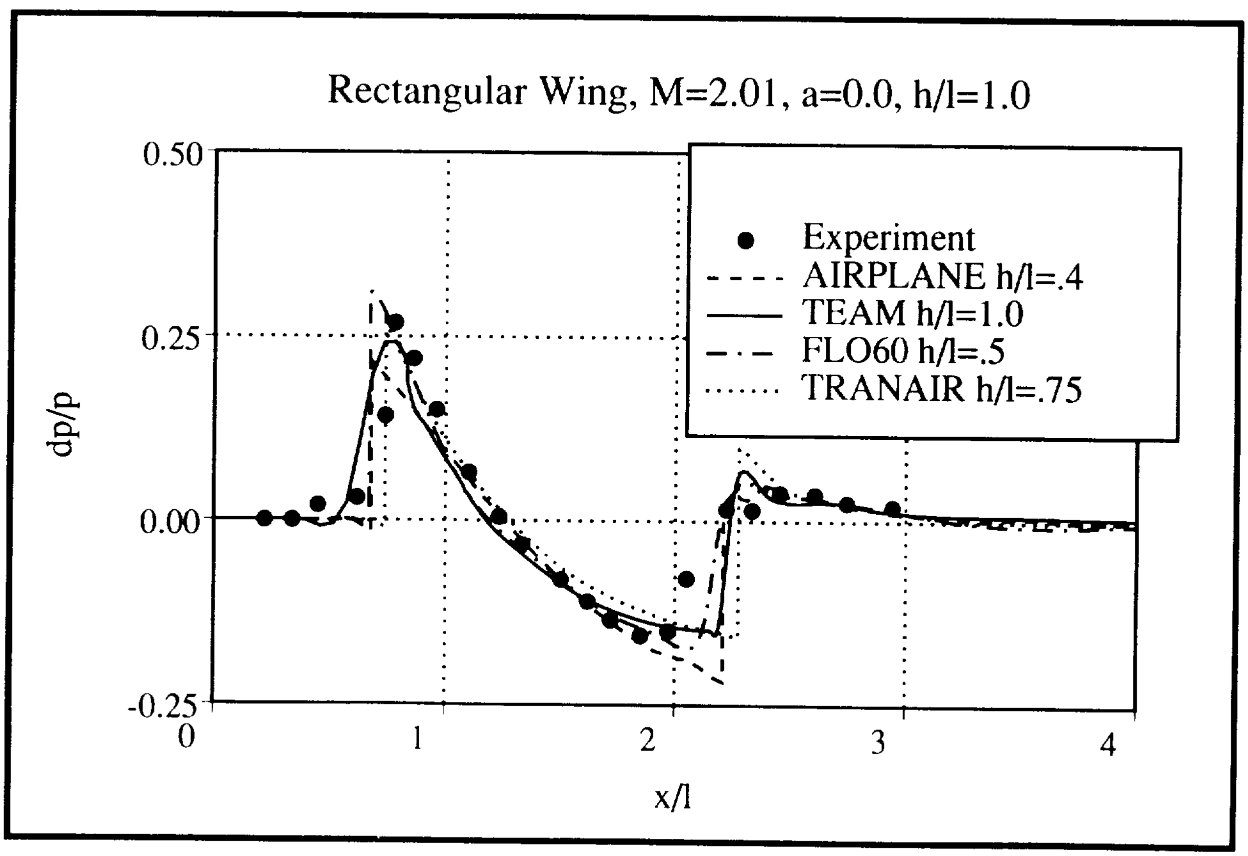
Results for this case using the UPS code have been reported previously in Ref. 2, and further results will be reported in Refs. 3 and 4. The figure below shows the results for the AIRPLANE, TEAM, and TRANAIR codes at an altitude of ten cone lengths. All three codes show very good correlation with the data. Previous studies with the UPS code indicated that grid resolution at the expansion was critical to capture the weak disturbance generated by this shape. Note that the correlation with the data improves as the altitude at which the linear extrapolation commences is increased, as indicated in the legend.



LOW ASPECT-RATIO WING VALIDATION

The second test case was a low aspect-ratio (AR=0.5) rectangular-planform wing. The airfoil was a 12.5%-thick biconvex section. The test Mach number was 2.01 and overpressure data were taken at altitudes of 1 and 8 chord-lengths. This geometry generated a non-axisymmetric flow field near the body, requiring a 3-D calculation for the near-field. Also, the sting was large relative to the body, and contributed significantly to the strength and location of the tail shock.

Again, the computational results show good correlation with the data taken at one body length. The error in tail shock location arises mainly from sting interference not modeled in the computations.



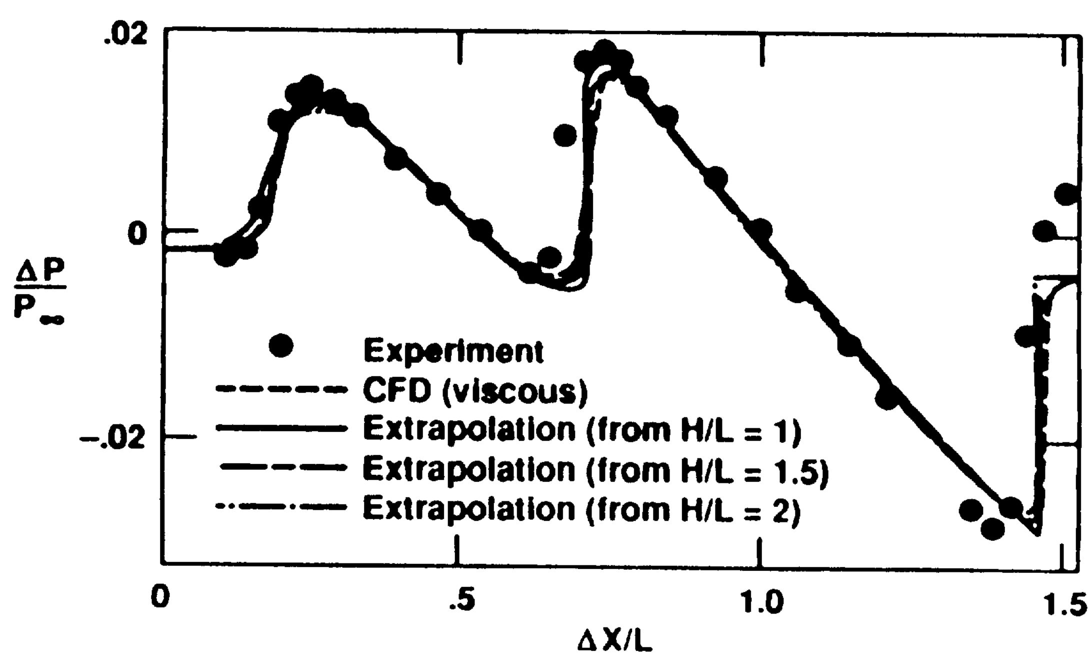
DELTA-WING BODY VALIDATION

The final test case was a delta wing mounted on an ogive-cylinder fuselage. The airfoil section was a 5%-thick double-wedge; the wing leading edge sweep was 69 deg. and the trailing edge was swept forward 10 deg. This model was tested at Mach numbers of 1.68 and 2.7, and at lift coefficients of 0, 0.08, and 0.15. The higher Mach number swept the Mach lines further back and substantially increased the size of the domain required to propagate the shock structure to a given altitude from the body. Furthermore, the higher angles of attack generated strong shocks that necessitated good grid resolution in the far field. Also, the sting on this model ramped down from the fuselage diameter to about half its thickness, and this effect required accurate modeling in the computations to match the expansion and tail shock correctly.

The figure shows correlations at an altitude of 3.1 body lengths. The extrapolation interface was varied to determine if near-field effects were still present, and it is clear that at one body length, the flow is sufficiently linear and axisymmetric for sonic boom extrapolation purposes. Subsequent studies have shown this to be valid as close as one-half body length altitude. The wing span may be a better metric for sensitivity to non-axisymmetric features, and so it is worth noting that for this case, the altitude of one-half body length corresponds to one full wing span.

SENSITIVITY TO EXTRAPOLATION ALTITUDE

Pressure signal at H/L = 3.1



CONCLUSIONS FROM PRIOR RESEARCH

The code calibration studies to date have provided great insight into the applicability of CFD to sonic boom prediction. At this point, it can be said without reservation that CFD can be used in conjunction with quasi-linear extrapolation methods to predict sonic booms in the near and far flow field accurately. In many ways, CFD paves the way to much more rapid progress in sonic boom minimization. Errors in wind tunnel data may arise from flow quality, intrusive probes, and model geometry, none of which are present in a good computational discretization. Furthermore, CFD offers fast turnaround and low cost, so high-risk concepts and perturbations to existing geometries can be investigated quickly. It is clear that at this time, the role of the wind tunnel in low-boom model design is to benchmark progress at significant intermediate stages and at the final design point of numerical model development.

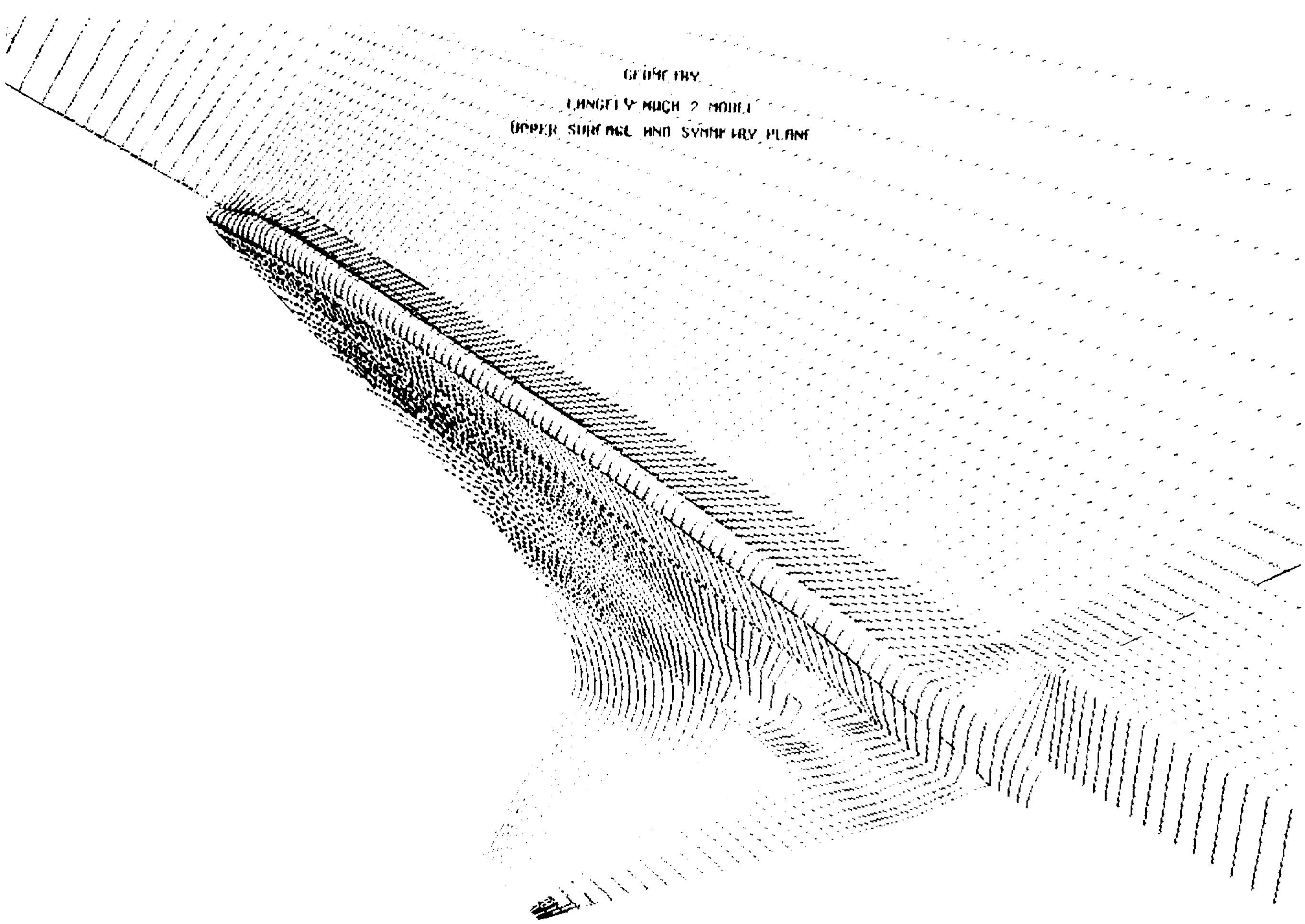
Our studies have demonstrated that for HSCT concepts, Euler (inviscid) flow analysis is sufficient for accurate sonic boom predictions. The most critical aspect is resolving the geometry and flow field. This requires fine surface grids and solution-adaptive grid procedures to keep the computational expense down. The computational domain needs to extend beyond the range of nonlinearities and non-axisymmetric (at least in a local sense) flow; as rules of thumb, an overpressure ratio (dp/p) of less than one-half and an altitude of at least on wing span are required to employ linear methods to propagate the pressure to the far-field.

CONCLUSIONS FROM PRIOR RESEARCH

- **Euler equations simplest sufficient flow model**
- **Geometry and grid resolution are critical**
- **Solution domain must extend beyond nonlinear and nonaxisymmetric range of flow (dp/p<.5, z>L/2,b)**

LOW-BOOM MODEL INVESTIGATION

The next phase of developing sonic boom prediction methodologies focuses on low-boom vehicle concepts. NASA Langley-developed low-boom models for cruise Mach numbers of 2 and 3 were tested in the 9x7-foot tunnel. The geometry of the Mach 2 model included flow-through nacelles, which increased the complexity of the computational model significantly. A multi-block grid, shown below, was generated for this body and solutions are being run to correlate with the wind tunnel data.



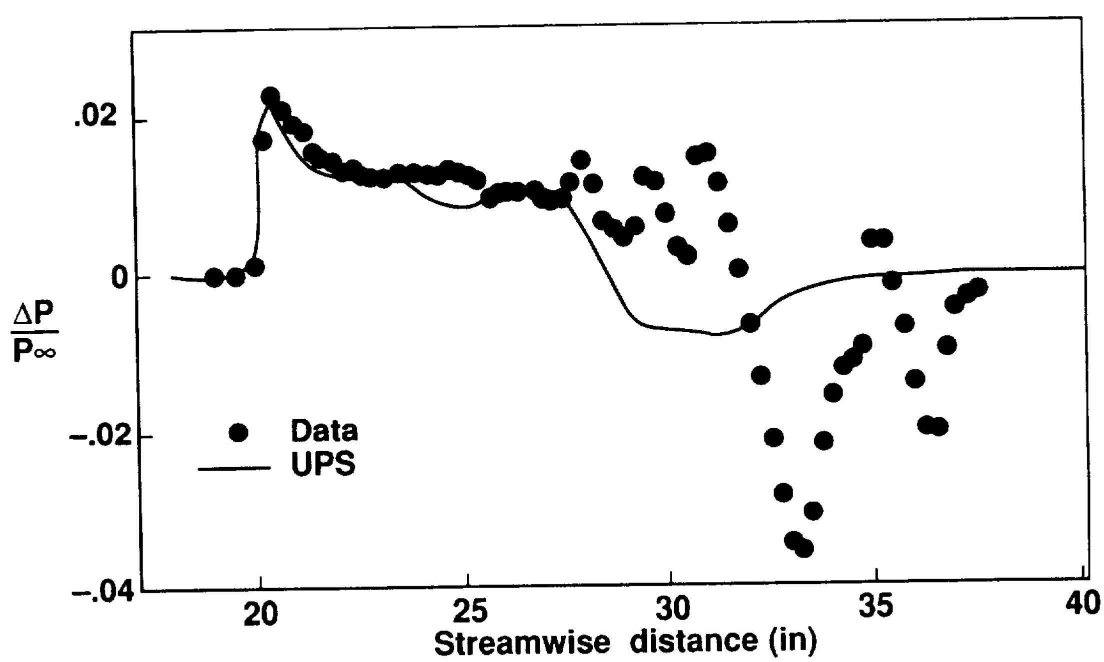
LOW-BOOM MODEL INVESTIGATION

A preliminary result has been obtained for the Mach 2 cruise condition on a geometry that included only the wing and fuselage. The front half of the signature is seen to correlate fairly well with the data, but significant discrepancies are apparent on the rear half. The large expansion and trailing shocks in the data are thought to be due to the sting and strain gauge disturbances, which were not modeled computationally. Further investigations are in progress to understand this result fully. Solutions will be obtained with blocked, flow-through, and power-on nacelles also.

MACH 2 LOW-BOOM MODEL

Sonic Boom at H/L = 1

M = 2 α = 0.69



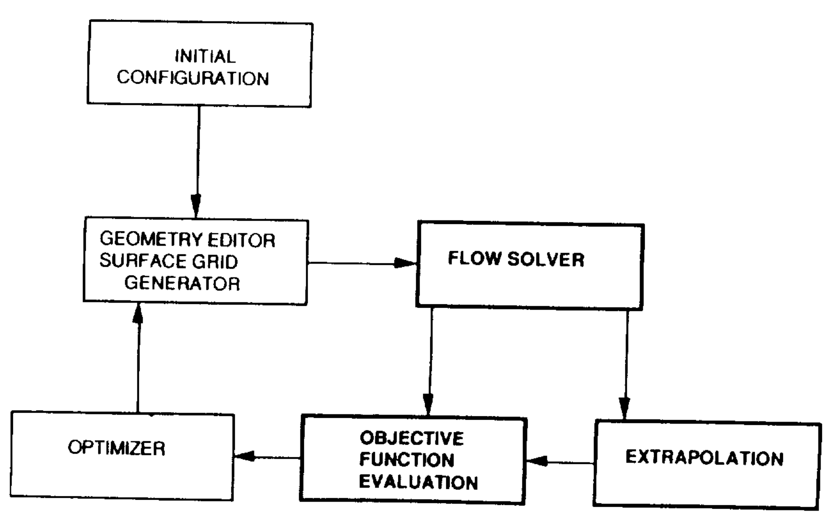
CURRENT RESEARCH OBJECTIVES

As mentioned earlier, attention is now being turned to higher-order effects on sonic boom. This research includes the effect of the propulsion system, which impacts the sonic boom through flow blockage from the pylons and nacelles, inlet spillage, and the exhaust plume. The SA-1150 model will be used to investigate the effect of nacelle placement, while computational studies are underway at NASA Langley to assess the plume effects.

Economic viability is another major thrust now being addressed. This is being pursued through simultaneous aerodynamic optimization and sonic boom minimization. Recognizing that supersonic flight over land is useful only if the resulting vehicle is efficient, these two disciplines need to be linked during the design. The flow chart below demonstrates conceptually how to proceed toward a design that derives the highest aerodynamic efficiency from a vehicle that also achieves desired sonic boom levels. The CFD solution is used both to predict the aerodynamics and sonic boom. Then, a gradient-type optimizer perturbs a parameter space defining the vehicle geometry to reduce the objective function (for example, a combination of sonic boom loudness and drag-to-lift ratio). The new geometry is generated and the iteration loop continues. A good baseline configuration is desirable because of the computational expense involved in this procedure.

The successful conclusion of this effort will yield several valuable products. First, a proof-of-concept configuration will be obtained which demonstrates good aerodynamic efficiency and achieves target sonic boom levels. Also, a base of knowledge about propulsion system effects and integration will be developed. Finally, validated codes will be produced that will be available to impact the HSCT design.

SONIC BOOM MINIMIZATION LOOP



SUMMARY

To summarize the sonic boom prediction effort thus far, we can state that code validation studies are complete and the numerical/physical modeling requirements are well understood. Currently, efforts are being focused on low-boom model development and verification, along with an investigation of propulsion system effects on optimized models. A major milestone in the upcoming year will review progress toward a low-boom design that has good aerodynamic efficiency.

It should also be noted that both NASA Ames and NASA Langley Research Centers will be using the HSCT as a demonstration problem for multidisciplinary numerical analysis on massively parallel computers under the High Performance Computing and Communications Program (HPCCP). The advances in design methodology sought in this program will be of significant and direct benefit to the HSRP effort.

SUMMARY

- CFD validation complete
- Follow-on research In progress:
  - Complex geometry
  - Propulsion effects
  - Optimization
- Major milestone to meet in early CY92
- HPCCP to contribute

FUTURE RESEARCH

Several avenues merit further exploration. Regardless of low-boom designs, many operational issues for supersonic aircraft must be addressed. Some of these are the prediction of off-track booms, which generally receive little attention but may be significant. Also, superbooms generated during acceleration and climbout may endanger structures in their path, and atmospheric focusing and refraction may affect the availability of supersonic corridors. Nonlinear analysis can be brought to bear upon these phenomena.

Looking beyond the current HSCT development cycle opens up the possibility of advanced concepts in supersonic vehicles that are best investigated computationally until a promising design emerges. The use of oblique wings, canards, and unconventional nacelle installations may offer improved sonic boom performance with superior aerodynamics as well.

POTENTIAL FUTURE RESEARCH

- **Off-track boom prediction**
- **Maneuvering booms**
- **Caustics**
- **Advanced concepts**

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