

Near Field Summary and Analysis of the Third AIAA Sonic Boom Workshop Shock-Plume Interaction Case

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The Third AIAA Sonic Boom Prediction Workshop was held during January 2020, on the weekend prior to the AIAA SciTech conference. The workshop had 23 participants who represented 6 different countries and 18 unique organizations that included government, industry and academia. The workshop was attended by over 50 individuals. The motivation for the workshop stems from the goal of obtaining supersonic commercial overland flight. In order to replace the current prohibition with a certification standard, an international effort is required to quantify the accuracy and reliability of prediction methods. The workshops also identify deficiencies in existing methods where further research should be focused. The workshop consisted of two days with the first day focused on nearfield computational fluid dynamics (CFD) and the second day on propagation techniques. The nearfield CFD study included two configurations known as the biconvex and the C608. This paper provided a summary and comparison of the results for the shock-plume interaction case, also known as the biconvex case. Overall agreement between the participants was very good with the largest standard deviations due to a slight shift of the shock location, not the predicted strength of the shocks.

Nomenclature

dp/p_{inf}	=	freestream pressure difference normalized by freestream pressure
h	=	characteristic spacing of the grid, nondimensional
L	=	model reference length, 22.4 inches
p	=	pressure
ϕ	=	off-track angle where zero is directly below the model, degrees
r	=	radius, inches
x	=	distance downstream from the model nose, inches
y	=	spanwise distance from the model nose, inches
z	=	distance below the model nose, inches
CFD	=	computational fluid dynamics
HLLC	=	Harten-Lax-van Leer-Contract
HPA	=	high pressure air
HWCNS	=	High-order Hybrid Weighted Compact Nonlinear Scheme
IGES	=	Initial Graphics Exchange Specification
LBFD	=	Low Boom Flight Demonstrator
ME	=	mixed-element
QCR	=	quadratic constitutive relation
RANS	=	Reynolds-averaged Navier-Stokes
RC	=	rotation/curvature correction
SA	=	Spalart Allmaras turbulence model
SBPW	=	Supersonic Boom Prediction Workshop
SST	=	Menter's shear stress transport turbulence model
VL	=	van Leer
WS	=	workshop
WT	=	wind tunnel

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I. Introduction

THE Third AIAA Sonic Boom Prediction Workshop (SBPW3) was held during January 2020 in conjunction with the AIAA SciTech conference in Orlando, Florida. The workshop had 23 participants who represented 6 different countries and 18 unique organizations that included government, industry and academia. The workshop was attended by over 50 individuals. The motivation for the workshop stems from the goal of realizing a rule change to permit supersonic commercial overland flight. In order to replace the current prohibition, forming a certification standard requires an international effort to quantify the accuracy and reliability of prediction methods. The workshops held have helped identify deficiencies in existing methods where further research should be focused. Consequently, the objective of the SBPW3 was to assess the state of the art for predicting nearfield signatures with computational fluid dynamics (CFD) and propagation codes used to propagate nearfield signatures to the ground. The two previous workshops were held in 2014 and 2017, respectively. The results of these workshops are documented in AIAA Journal of Aircraft articles Refs. [1–3].

The combination of nearfield CFD and propagation techniques are necessary to predict the acoustic signature on the ground and how it is perceived by humans. This prediction is the goal of the wider sonic boom community as seen in Fig. 1. Consequently, SBPW3 consisted of two days with the first day focused on nearfield CFD and the second day on propagation techniques. The first day of SBPW3 featured analysis of the nearfield pressure field of a low boom flight demonstrator prototype and a shock-plume interaction wind tunnel model. The second day of the workshop focused on atmospheric propagation as detailed in Ref. [4]. The objective of the first day of this workshop was to assess the state of the art for predicting nearfield pressure signatures needed for accurate and reliable sonic boom prediction. Nearfield pressure signatures, extracted from the CFD solutions, were gathered from the international participants. The participants were required to use a series of uniformly-refined, workshop-provided meshes. Some participants also created meshes with their best practices for computing nearfield pressure signatures on the provided geometries. The submissions to this workshop indicated a number of clear trends as compared to previous sonic boom workshops. The number of adapted mesh solutions increased and there was an influx of participation by commercial CFD vendors.

For the nearfield participants, a solution for an axisymmetric case from SBPW2, was requested as a notice of intent to participate. The early review of participant results on a less complex configuration helped to improve the consistency of submissions to this workshop. Two nearfield CFD cases were required for SBPW3: a shock-plume interaction case and C608 documented in Ref. [5]. The required SBPW3 cases met and exceeded the complexity of optional cases from previous workshops [1–3].

The aft region of supersonic aircraft, including the shock-plume interaction has been a challenge and an area where CFD results diverge. A series of tests were conducted by NASA at the Glenn Research Center and Ames Research Center in order to build up a database for CFD validation [6–9]. Experimental measurements and simulation results of the biconvex configuration were published prior to the workshop. This paper provides a summary and comparison of the results for the shock-plume interaction case.

II. Configuration Detail

The biconvex configuration used for the boom workshop is a modified version of an experimental and computational study conducted by NASA [8]. A photo of the biconvex model is shown in Fig. 2 and the full experimental setup is seen in Fig. 3. The pressure signature was obtained from a rail located underneath the model. In order to get a representative plume flow, high pressure air blew through the blade strut and into the nozzle. Figure 4 shows the internal flow paths of the experimental model (where HPA stands for high pressure air). For the workshop, the internal flow of the configuration was simplified. The pressure taps were left in (instrumentation station) but the flow was modeled as a simple circular engine boundary condition, i.e., the flat plate at the beginning of the cavity, as shown in Fig. 5.

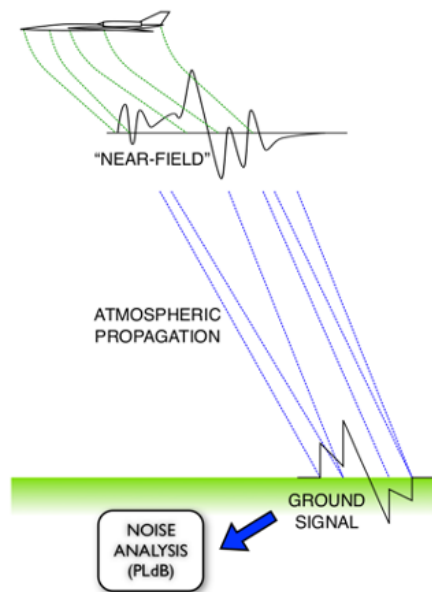


Fig. 1 Sonic boom prediction process.

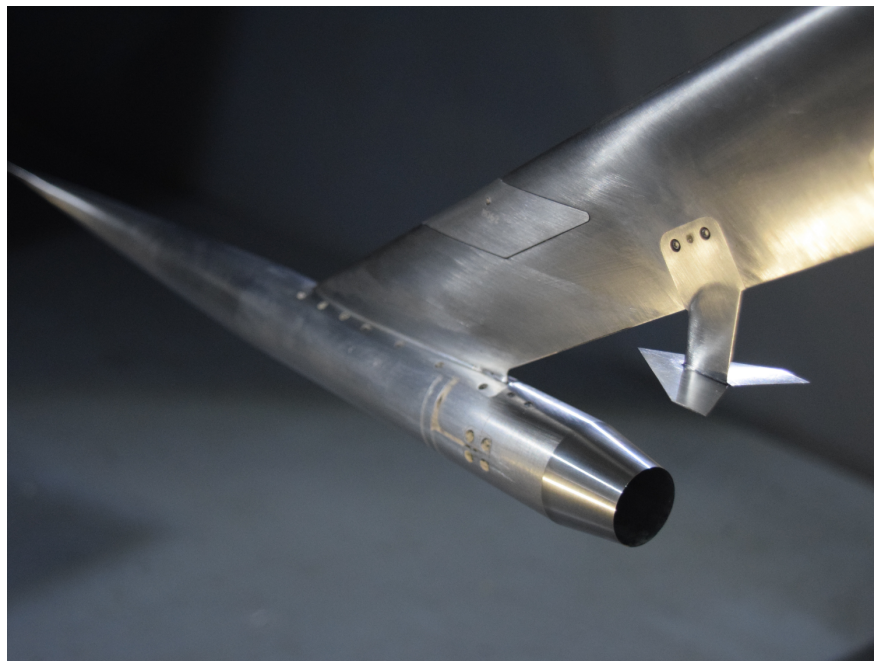


Fig. 2 Experimental biconvex configuration (external photo).

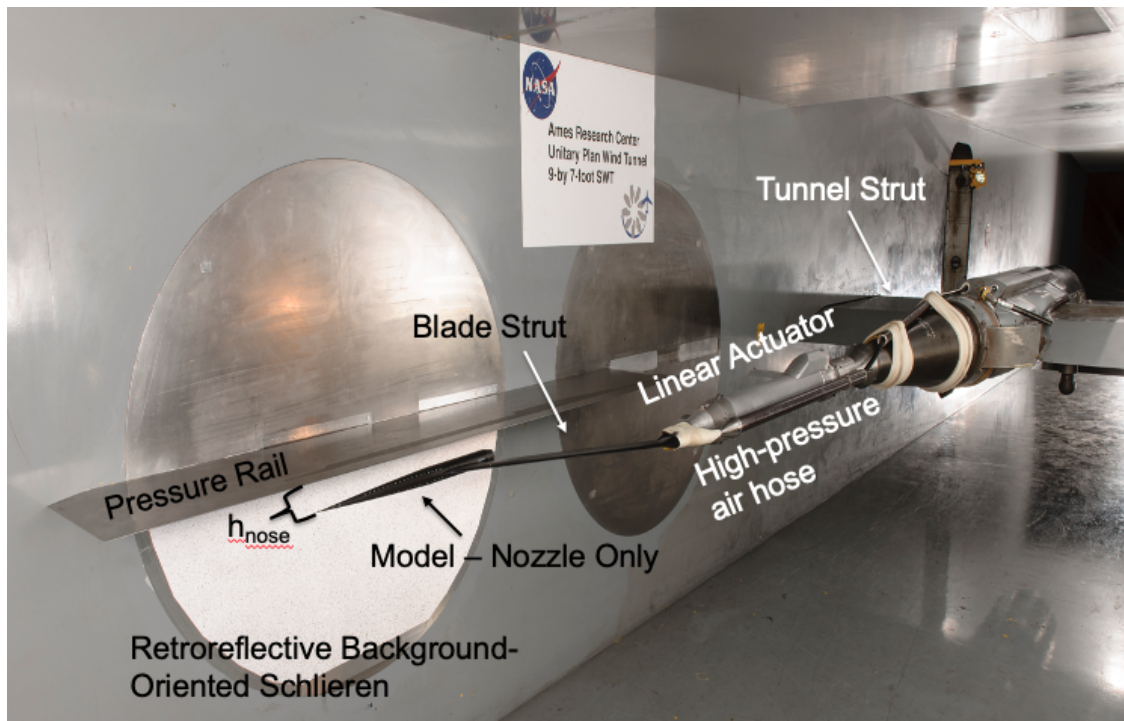


Fig. 3 Experimental setup inside the Ames 9- by 7-foot wind tunnel.

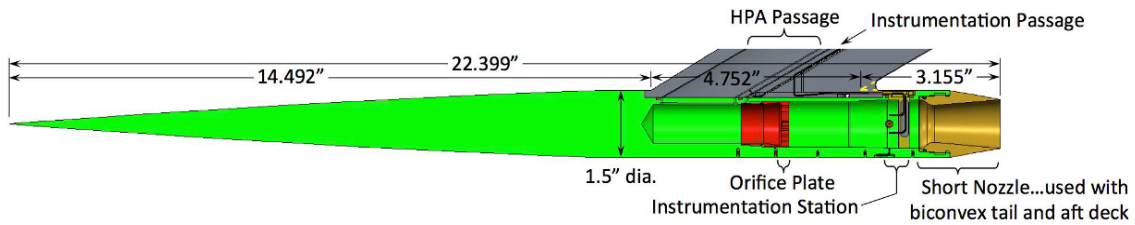


Fig. 4 Experimental biconvex configuration (internal diagram).

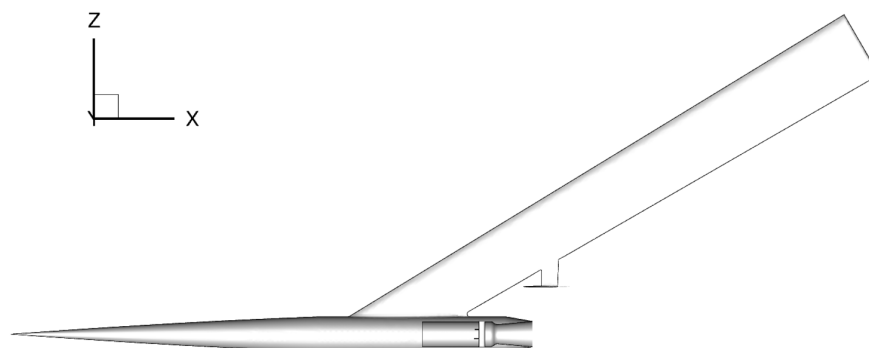


Fig. 5 Computational biconvex configuration.

III. Grid Generation

The following discussion describes the grid software used to create the workshop provided grids as well as the sourcing schemes applied to obtain those grids. The grid refinement strategy and results are also documented.

A. Software

Grid generation for the biconvex configuration was performed using HeldenMesh [10]. HeldenMesh consists of two components: HeldenPatch and HeldenMesh. HeldenMesh was designed to be compatible with TetrUSS [11], including GridTool, for interactive geometry preparation [12].

The grid generation process begins with HeldenPatch that reads an Initial Graphics Exchange Specification (IGES) file, or GridTool restart file. If an IGES file is provided, HeldenPatch can prepare the geometry to create a watertight model suitable for meshing. HeldenPatch outputs a GridTool restart file, which can be read by HeldenMesh. The section below defines the sourcing process used to govern size and resolution of surface and volume meshes prior to the mesh generation process with HeldenMesh. HeldenMesh then uses a new advancing front/advancing layer algorithm that is considerably faster and less computer intensive than VGRID's method [12–14]. Additionally, HeldenMesh creates the surface mesh, volume mesh and closes the grid in a single operation.

B. Sourcing

The configuration was sourced with line and plume sources using best practices documented in Ref. [15] and is shown in Fig. 6. For the shock sourcing, the HeldenMesh shock sourcing was used [12]. Three individual shock sources were used that covered from the tip of the nose of the cone back to the plume exhaust while a fourth shock source was used to capture the shock from the shock generator. Table 1 shows the input used for the four shock sources while Table 2 shows the x, y, and z locations of the four shock sources.

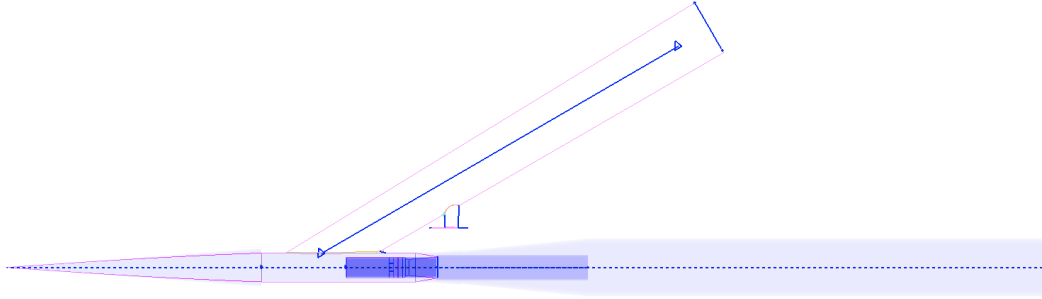


Fig. 6 Configuration sourcing of the biconvex configuration.

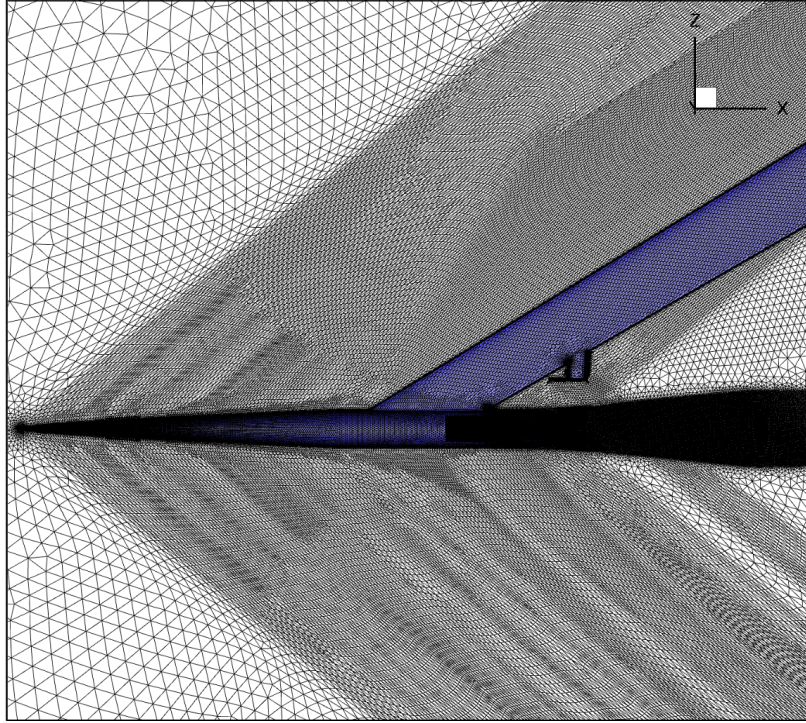
Table 1 Shock source input variables for HeldenMesh.

Strength	Radius	Max Stretch	Curve angle	Angle 1
1	1000.0	1000	20	38.682
Angle 2	S1 inner	S1 outer	S2 inner	S2 outer
38.682	0.1999	0.299	0.2	0.30
Vx	Vy	Vz	Theta 1	Theta 2
0	0	-1	-180	180

Figures 7, 8, and 9 show the finest grid (1.0 scale) close to the model, the entire symmetry plane, and the volume grid, respectively. The grid level details are discussed in the next section.

Table 2 Shock source locations for HeldenMesh.

Sources	1	2	3	4
X1	0.0	5.75	13.3	22.066
Y1	0.0	0.0	0.0	0.0
Z1	0.0	0.0	0.0	2.047
X2	5.75	13.3	22.45	24.029
Y2	0.0	0.0	0.0	0.0
Z2	0.0	0.0	0.0	2.051

**Fig. 7 Fine (1.00 scale) surface and near-symmetry plane grid.**

C. Grid Refinement

The goal of the workshop was to deliver a family of grids where the sourcing was consistent among the grids and the mesh size changed by a constant factor throughout the grid. A series of three grids were generated with the scaling and input variables listed in Table 3. Two sets of grids were generated; tetrahedral and mixed-element. The element counts for the two sets are listed in Tables 4 and 5, respectively.

IV. Simulation Conditions

The specified conditions for the workshop were chosen to match wind tunnel data. Unfortunately, there was a slight error in the calculation of unit Reynolds number where the workshop participants were requested to run with 4.5 million per foot while the experiment was run at approximately 3.5 million per foot. A quick study using the NASA CFD code FUN3D, showed no noticeable difference in the pressure signature (Figs. 10 and 11). The simulation conditions provided to the participants is shown in Table 6.

Data were extracted from the computational solution by means of a workshop provided Tecplot script. Three locations were specified to match where experimental data were obtained. These locations are listed in Table 7. For all the data shown in this paper, the following color scheme will be implemented for plotting: $0^\circ \phi$ is red, $15^\circ \phi$ is green,

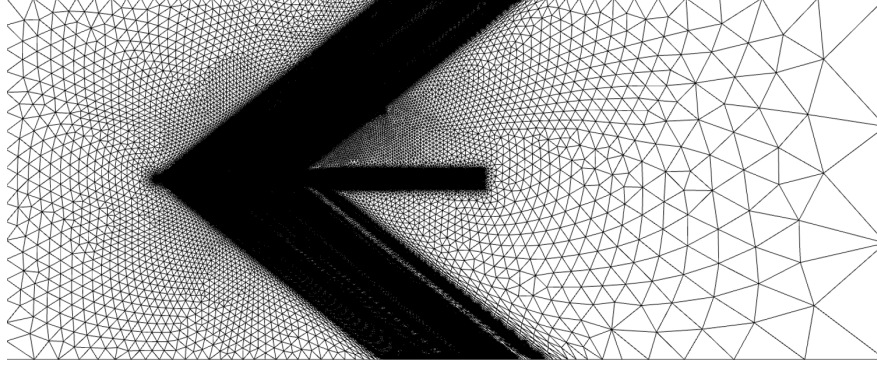


Fig. 8 Fine (1.00 scale) symmetry plane grid.

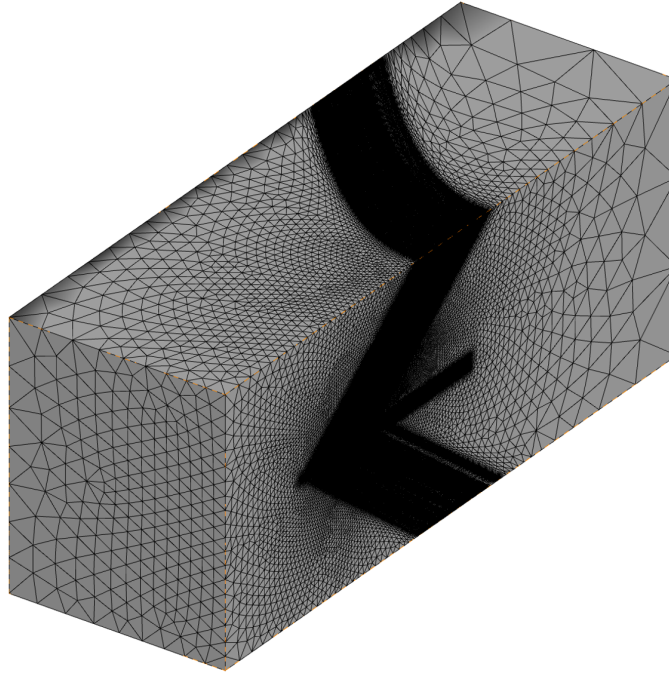


Fig. 9 Fine (1.00 scale) volume grid.

and $30^\circ \phi$ is blue. This can be seen in Figs. 10 and 11.

In order to test the grid quality and the extraction tool, the grid family was run by participants A and C prior to the grids being released to the rest of the participants. Figures 12–17 compare the results from the three grids for the three ϕ angles of 0° , 15° , and 30° . While the results are slightly different, both participants' results showed a sharpening of the shocks as the grid size increased.

V. Participants

The groups contributing to the workshop are listed in Table 8. The group letter is the first part of the submission label used in the next section and detailed in Table 9. Some groups contain a single contributor, but most contained two or more collaborators. Government agencies, industry, academia, and vendors are represented. Most SBPW3 participants contributed to previous workshops. A number of new first-time participant groups represented commercial CFD vendors. Each group submitted results and prepared a presentation for the workshop. These presentations have been collected in the workshop website (lbpw.larc.nasa.gov). Participant A created a series of adapted grids that were made available to workshop participants. Participant B performed a series of flux and limiter comparisons. Participant C presented an

Table 3 Grid refinement hieldenmesh parameters.

Grids	1.57 (coarse)	1.28 (medium)	1.00 (fine)
Refine Factor	1.0	0.7	0.47
Layer (H1)	0.0006	0.0004	0.0028
Arate	0.109	0.15	0.28
Brate	0.05	0.05	0.05

Table 4 Tetrahedral grids element counts.

Scale	Nodes	Tetrahedral
1.57 (coarse)	846,227	4,785,786
1.28 (medium)	1,576,352	8,988,516
1.00 (fine)	3,286,221	18,815,990

Table 5 Mixed-element grids element counts.

Scale	Nodes	Tetrahedral	Prisms
1.57 (coarse)	846,227	2,825,421	650,469
1.28 (medium)	1,576,352	5,984,989	993,489
1.00 (fine)	3,286,221	14,627,534	1,388,470

Table 6 Computational Simulation Condition.

Mach Number	1.6
Angle of Attack	0.0°
Unit Reynolds Number (million per foot)	4.522
Temperature (Rankine)	374°
Engine Plenum Pressure Ratio	8.0
Engine Plenum Temperature Ratio	1.768

Table 7 Data Extraction Locations.

y (in)	z (in)	r (in)	ϕ (deg)
0.069	-15.108	15.108	0.260
3.915	-14.496	15.015	15.115
7.592	-13.070	15.115	30.152

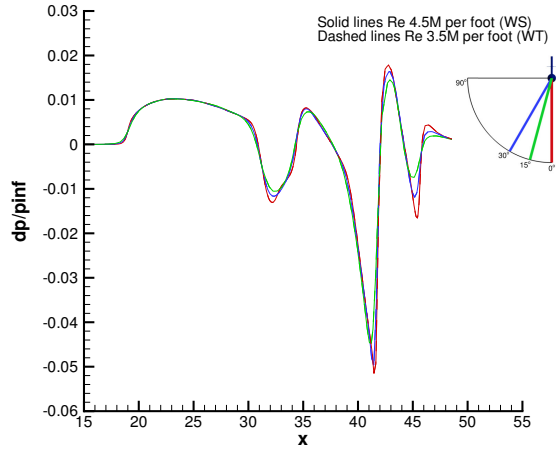


Fig. 10 Reynolds number effect on FUN3D fine grid pressure signature.

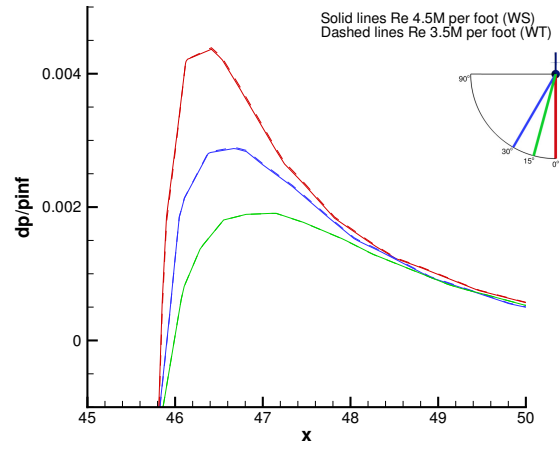


Fig. 11 Reynolds number effect on FUN3D fine grid pressure signature, zoom of shock plume interaction.

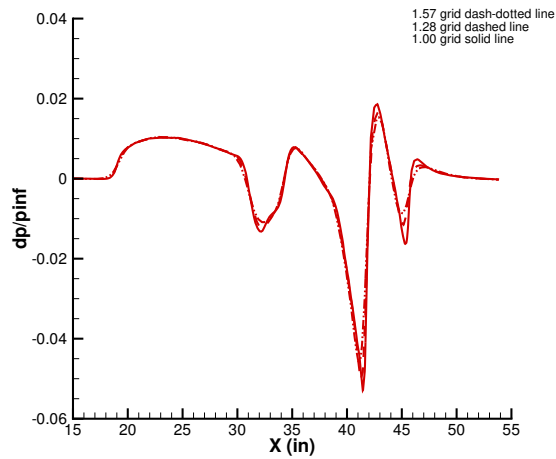


Fig. 12 Participant A grid study at $\phi=0^\circ$.

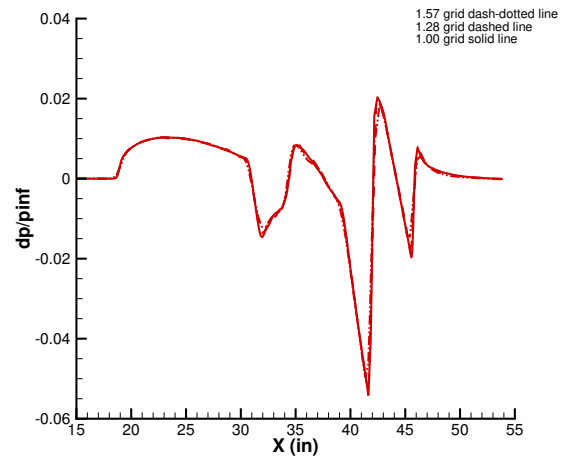


Fig. 13 Participant C grid study at $\phi=0^\circ$.

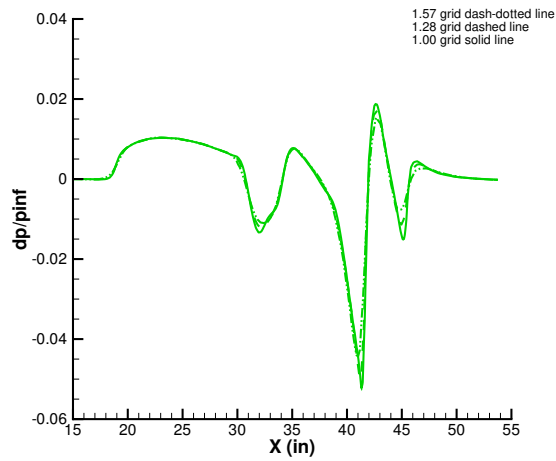


Fig. 14 Participant A grid study at $\phi=15^\circ$.

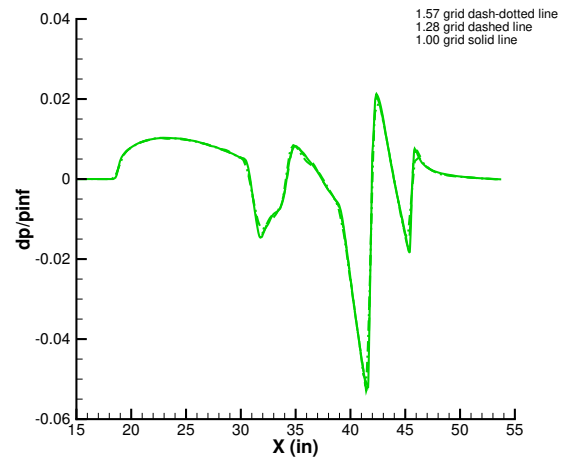


Fig. 15 Participant C grid study at $\phi=15^\circ$.

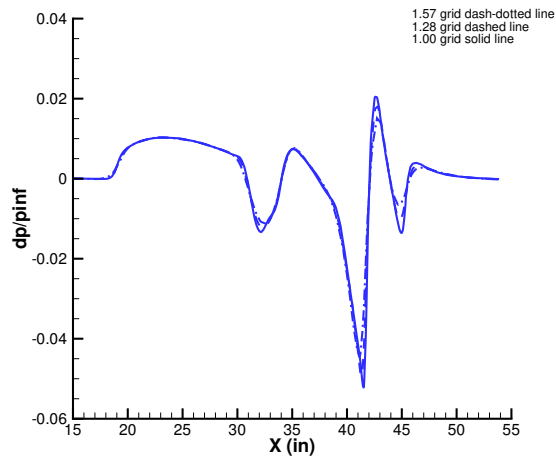


Fig. 16 Participant A grid study at $\phi=30^\circ$.

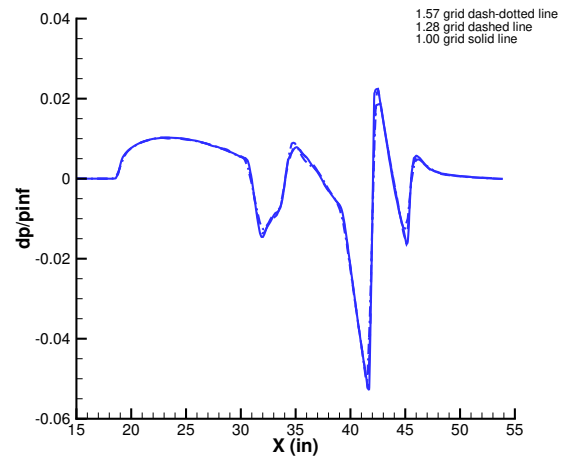


Fig. 17 Participant C grid study at $\phi=30^\circ$.

improved nonlinear solution technique and its potential to reduce simulation wall clock time. Participant E compared multiple mesh adaptation metrics. Participant F showed density contours showing all of the interactions between the support structure, the biconvex, the nozzle and jet flow. Participant G compared structured versus unstructured results. Participant H showed the effect of the model support on the solution by performing additional studies without it. Participant I showed pressure contours showing the progression of the solution through grid levels. Participant J showed comparisons between their custom grids to those provided by the workshop. Participant K compared a not yet commercially available code to their established released code. Participant L examined the sensitivity due to turbulence models. Participant M compared the mixed-element grid solutions to the all tetrahedral grid solutions. Participant N applied anisotropic mesh adaption to control solution interpolation error and errors in the pressure signature. Participant O compared different codes as well as compared the difference between the mixed-element, all tetrahedral, and adapted grids.

Table 8 Participant groups.

Group	Organizations	Contributors
A	DLR	J. Kirz and R. Rudnik
B	Texas A&M	F. Carpenter and P. Cizmas
C	NASA	A. Elmilgui, M. Pandya, M. Carter, B. Diskin, and S. Nayani
D	ONERA	O. Atinault
E	Boeing	T. Michal, T. Maggee, J. Krakos, and D. Lazzara
F	STC and NASA	W. Spurlock, A. Aftosmis, and M. Nemec
G	NASA	J. Jensen, J. Duensing, M. Piotrowski, J. Housman, and C. Kiris
H	Northwestern Polytechnical University	Z. Han, J. Qiao, Y. Ding, L. Zhang, and K. Song
I	Siemens Digital Industry Software	C. Nelson, O. Tong, and M. Castillo
J	Boom Technology	E. Fabiano
K	ANSYS Canada	I. Ozcer, J. Stokes, L. Munholand, and K. Zore
L	Metacomp Technologies	A. Potturi
M	NASA	M. Park
N	INRIA	A. Loseille and F. Alauzet
O	JAXA	H. Ishikawa, S. Koganezawa, and Y. Makino
P	Lockheed Martin	M. Buonanno

Table 9 Biconvex submissions.

Case	Code	Model	Mesh	Additional Details
AA	TAU	SA	WS-Mixed	
AB	TAU	SA	WS-Tet	
AC	TAU	SA	Centaur-Mixed	
AD	TAU	SA	WS-Adapted	
BA	UNS3D	SST	WS-Mixed	Roe w/Harten Flux
BB	UNS3D	SST	WS-Mixed	Roe w/Harten Flux, Modified limiter
BC	UNS3D	SST	WS-Mixed	Roe Flux, Modified limiter
BD	UNS3D	SST	WS-Mixed	Roe w/Harten Flux, Modified limiter with Green-Gaus gradients
CA	USM3D-ME	SA	WS-Mixed	
CB	USM3D	SA	WS-Tet	
DA	SU2	SA	WS-Tet	
EB	BCFD	SA	Adapted	Adapted to Goal Oriented Error Estimate
EC	BCFD	SA	Adapted	Adapted to L2 Multiscale Error Estimate
ED	FUN3D	SA	Adapted	Grad-Mixed
EE	FUN3D	SA	Adapted	Goal-Mixed
FA	Cart3D	Inviscid	Cartesian	Adapted to Goal Oriented Error Estimate
GA	LAVA Structured	SA	Pointwise/CGT	Roe Scheme
GB	LAVA Structured	SA	Pointwise/CGT	HWCNS
GC	LAVA Unstructured	SA	StarCCM+	
HA	PMNS3DR	Inviscid	Structured	
IA	STAR-CCM+	SST	WS-Mixed	
JA	CFD++	SA-RC	WS-Mixed	
KA	HALO3D	SA	WS-Mixed	
KB	Fluent	SST	WS-Mixed	
LA	CFD++	SST	WS-Mixed	
LB	CFD++	SA	WS-Mixed	
LC	CFD++	SA-RC-QCR	WS-Mixed	
MB	FUN3D	SA	WS-Tet	Roe, VL
MD	FUN3D	SA	Adapted	Roe, VL, Adapted to L2 Multiscale Error Estimate
NA	Wolf	SA	WS-Tet	HLLC
NB	Wolf	SA	Adapted	HLLC, Adapted to L2 Multiscale Error Estimate
NC	Wolf	SA	Adapted	HLLC, Adapted to L4 Multiscale Error Estimate
ND	Wolf	SA	Adapted	Adapted to Goal Oriented Error Estimate
OA	FaSTAR	SA	WS-Mixed	
OB	TAS	SA	WS-Mixed	
OC	TAS	SA	WS-Tet	
OE	TAS	SA	WS-Adapted	

VI. Results

This section will discuss and compare the results received from the 3rd AIAA Boom Workshop participants. Figures 18 and 19 show solutions from the USM3D code for the fine grid. In Fig. 18, the signature at 15 inches below the nose has been superimposed so that the signature characteristics are easily traceable to the model configuration for later discussions. Figure 19 plots density gradient (a numerical schlieren) showing the complexity of the flow in the region of the plume and biconvex interaction. For this condition, the leading-edge shock off the biconvex configuration lines up with the reflecting internal structure within the nozzle flow.

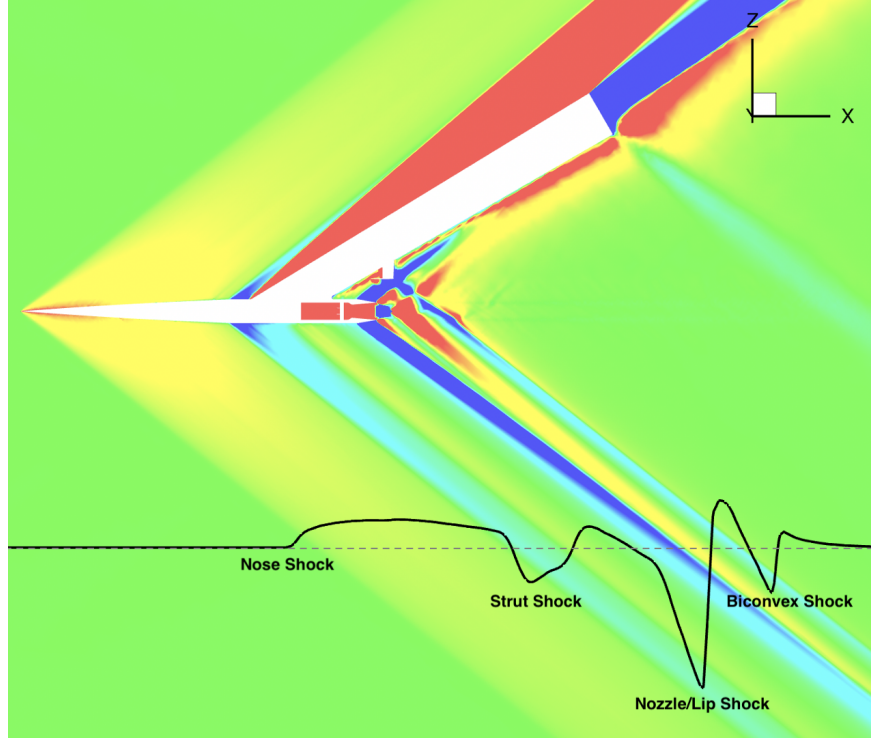


Fig. 18 USM3D production code fine grid symmetry solution with dp/p_{inf} cut.

Before discussing the results, the authors would like to reiterate from the workshop goals that we are not identifying whether a submission is right or wrong. The goal is to look at the trends and try to determine what might be causing outliers. Additionally, the agreement in the results for this workshop was exceptionally good and the scales in plots had to be tightened to highlight any differences.

Figure 20 shows the results from all of the participants on the fine grid at $\phi=0^\circ$. Overall there is good agreement among the participants. Figure 21 adds the experimental data, along with its standard deviation, to the workshop results. It is important to note that the walls of the test section were not modeled during the workshop and the blade/cone intersection surfaces were simplified for ease of grid generation. Again, the agreement between the participants results and experimental data is good although the experimental data do not return to zero which indicates that tunnel or support structure interference may be occurring.

Figure 22 adds the participant result standard deviations to the fine grid solutions at $\phi=0^\circ$. Figures 23 and 24 show just the standard deviation with the second figure, Figure 24, zoomed into the aft region of the signature. Comparing the two figures, the largest difference is located at the shock from the nozzle-lip area. The deviation is so large in part due to a slight shift in the predicted shock location of some of the codes. The biconvex/plume interaction region also shows an increased standard deviation that is partly due to the shift in the shock location. Both of these items will be discussed in more detail later in the paper.

The following paragraphs will discuss and compare results from the participants beginning at the cone/strut interface, proceeding aft to the nozzle-lip shock and finally the plume/biconvex shock. Figure 25 shows the participants' results for the fine grid at $\phi=0^\circ$ zoomed into the cone-strut interface shock. The results are close together prior to the shock where a few of the solutions begin to separate from the rest. Four participant submissions that differ from the majority

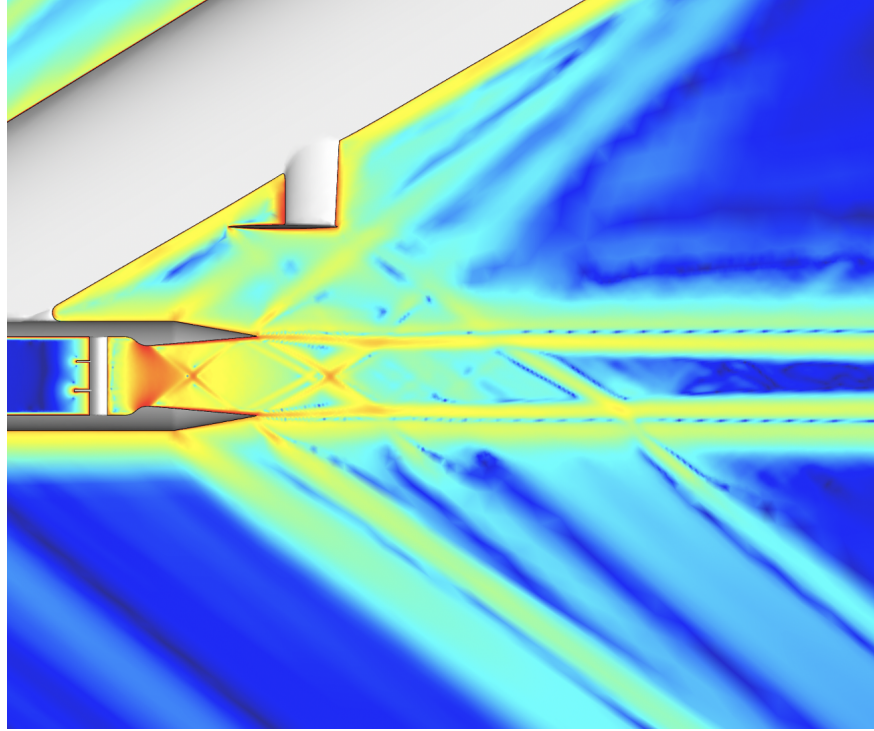


Fig. 19 USM3D production code fine grid symmetry solution showing density gradient (numerical schlieren).

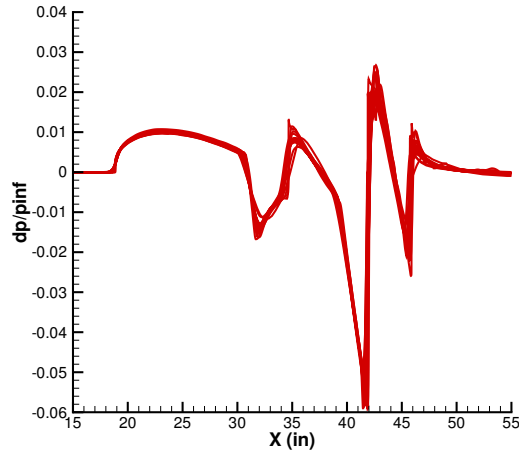


Fig. 20 Fine grid results from all participants at $\phi=0^\circ$.

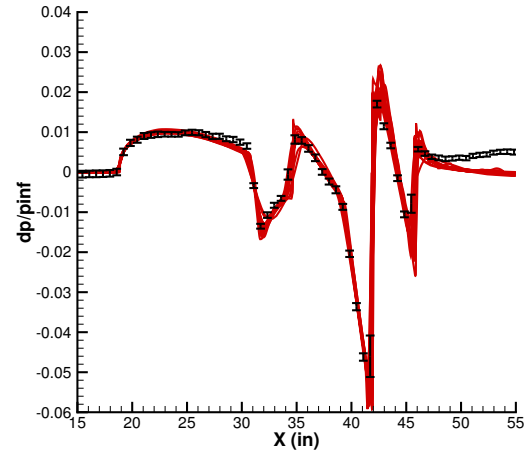


Fig. 21 Fine grid results from all participants at $\phi=0^\circ$ with experimental data (symbols).

of the solutions are isolated and shown in Fig. 26. The solid line submissions were from participant created grids. The dotted line results are a submission using the tetrahedral grids as compared to the mixed-element grids, where for their code, the mixed-elements grids matched the rest of the participant submissions.

Figure 27 zooms into the participant results in the region of the nozzle-lip shock. It is evident that there are 2 different groups of solutions for this area. The first group has a more gradual shock with curved solutions into a slight angle to the shock. The second group predicts a considerably sharper shock with sharp turns into a straight up and down shock line. This leads to the larger standard deviation seen in Fig. 24. Figure 28 contains the largest outliers for this part,

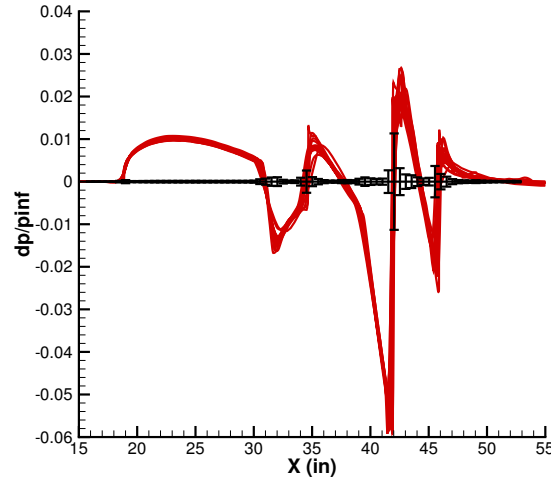


Fig. 22 Standard deviation from the mean of the fine grid results along with the fine grid results.

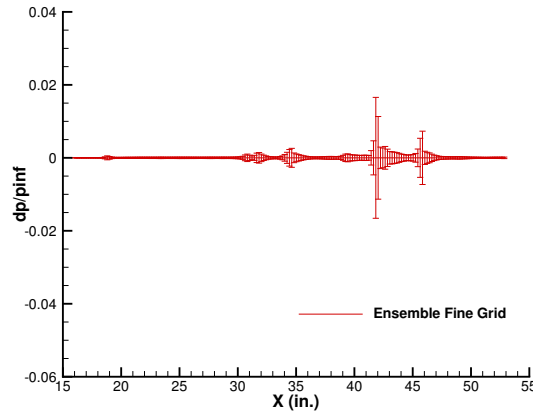


Fig. 23 Standard deviation from the mean of the fine grid results.

four submissions. The solid line solutions are from participant created grids. The dashed line is a workshop provided grid submission, however, while the majority of the submissions used the SA turbulence model, it was one that utilized SST.

Figure 29 shows the results in the plume-biconvex shock iteration region with the six outliers shown separately in Fig. 30. Here the participant submissions have a further vertical spread than in previous plots. Since this area is influenced by not only how the CFD code is modeling the flow out of the nozzle, the jet flow shock structure, as well as the interaction of the shock from the biconvex configuration, it is a challenging region. Overall though, the agreement is better than expected with most of the shocks occurring in the same location. However, there is again two different prediction groups concerning the shocks, the more gradual curve versus the sharp definition. This leads to the larger standard deviation seen in Fig. 24. Where the six outliers are shown, the solid lines are both participant created grids with Euler solutions, which would miss the viscous effects of the jet flow shear layer. The dashed, as discussed earlier, is an SST solution. The dash-dotted lines are solutions created on a workshop provided grid by two different participants, while the dotted line, is a participant created grid with a viscous solution.

The participants were also asked to look at off-angles. Up until now, all of the results were shown at $\phi=0^\circ$ (directly under the model). Figures 31 and 32 show the participant results for their finest grids at $\phi=15^\circ$ with and without the

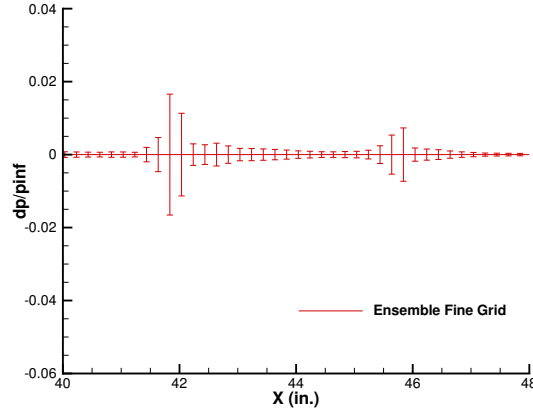


Fig. 24 Standard deviation from the mean of the fine grid results zoomed into the plume shock interaction.

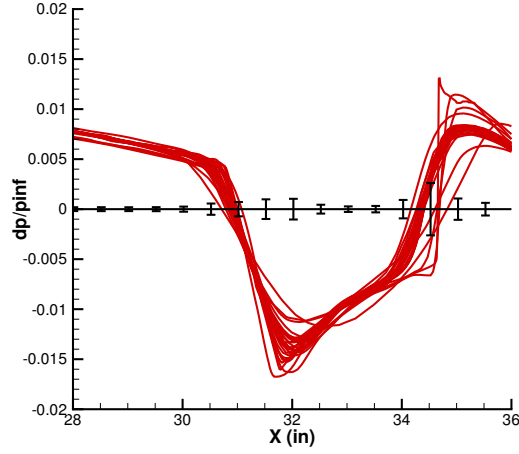


Fig. 25 Fine grid results from all participants at $\phi=0^\circ$ zoomed into cone-strut interface shock.

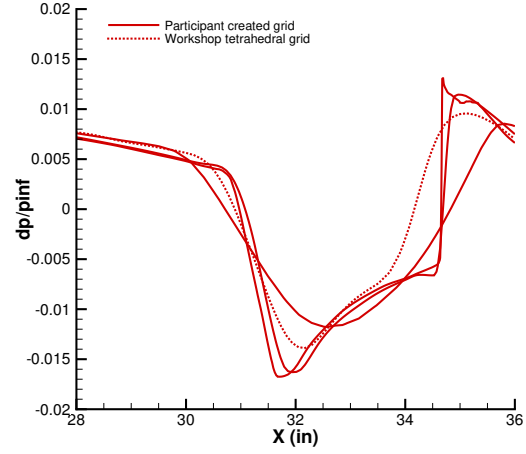


Fig. 26 Fine grid results from four participants at $\phi=0^\circ$ zoomed into cone-strut interface shock.

experimental results, respectively. When compared to the $\phi=0^\circ$ results, Fig. 20, the overall agreement is very similar including the slight separation of results at the strut shock and the two prediction groups for the nozzle-lip shock. There are slight differences including the participant results clustered closer together for the plume-biconvex shock interaction while there is one code that separates from the group at the nozzle-lip shock. The experimental data compare similarly as they did with $\phi=0^\circ$ results except that the simplification for the nozzle/strut interface structure can be seen clearer ($x=25-30$ inches) when comparing results. Finally, at $\phi=30^\circ$, Figs. 33 and 34 compared the fine grid results with and without the experimental data, respectively. The same trends seen with the $\phi=15^\circ$ results can be seen except instead of an outlier at the nozzle-lip shock, there is one in the downstream nozzle flow.

VII. Concluding Remarks

A summary and analysis is provided for the nearfield Computational Fluid Dynamics (CFD) submissions to the Third AIAA Sonic Boom Workshop with a focus on the shock-plume interaction case (biconvex). This case was chosen for SPBPW3 because the aft region of supersonic aircraft, including the shock-plume interaction has been a challenge and an area where CFD results diverge. The results from the participants for this configuration were in excellent

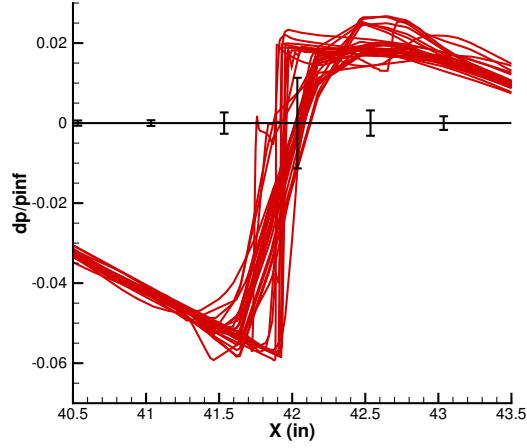


Fig. 27 Fine grid results from all participants at $\phi=0^\circ$ zoomed into nozzle-lip shock.

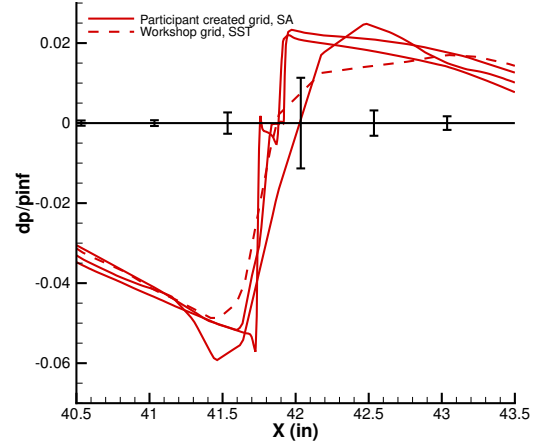


Fig. 28 Fine grid results from four participants at $\phi=0^\circ$ zoomed into nozzle-lip shock.

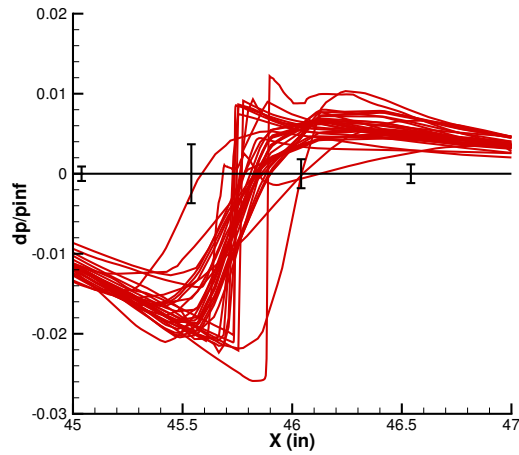


Fig. 29 Fine grid results from all participants at $\phi=0^\circ$ zoomed into plume-biconvex shock interaction.

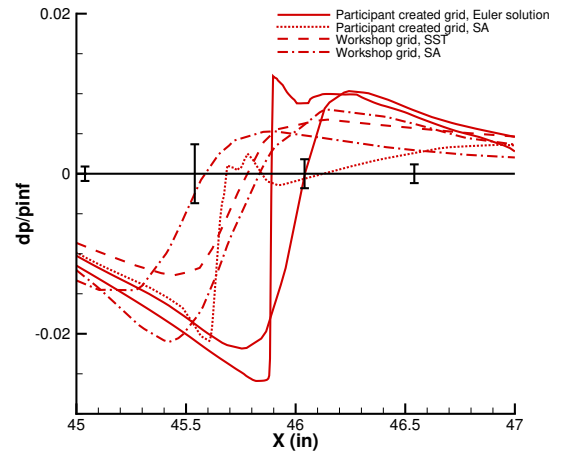


Fig. 30 Fine grid results from six participants at $\phi=0^\circ$ zoomed into plume-biconvex shock interaction.

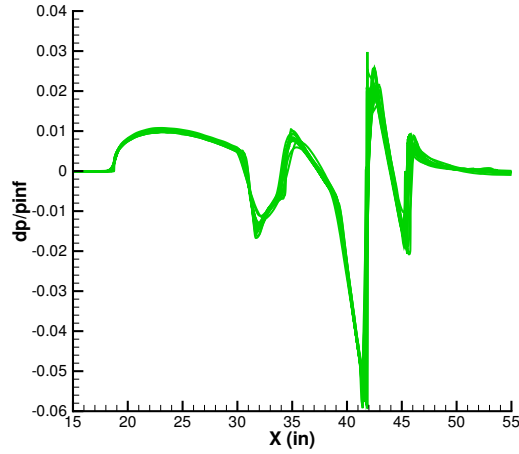


Fig. 31 Fine grid results from all participants at $\phi=15^\circ$.

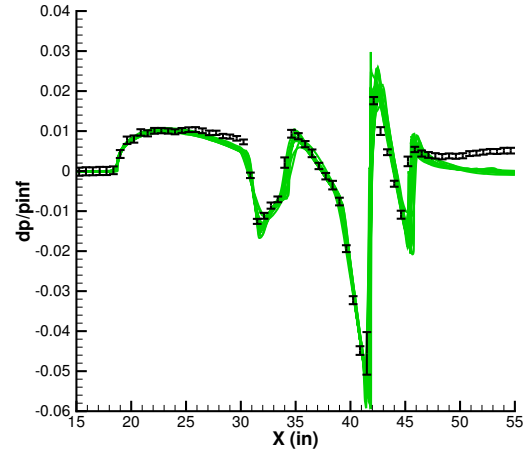


Fig. 32 Fine grid results from all participants at $\phi=15^\circ$ with experimental data (symbols).

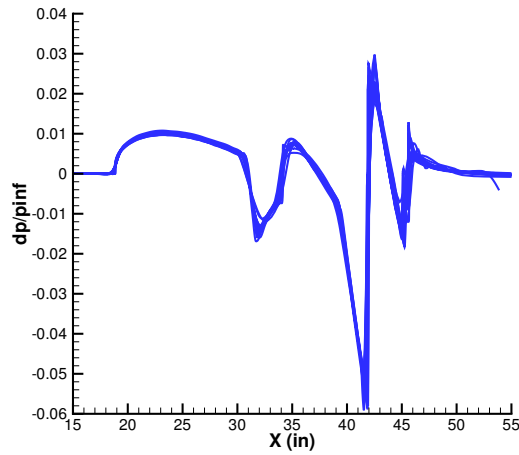


Fig. 33 Fine grid results from all participants at $\phi=30^\circ$.

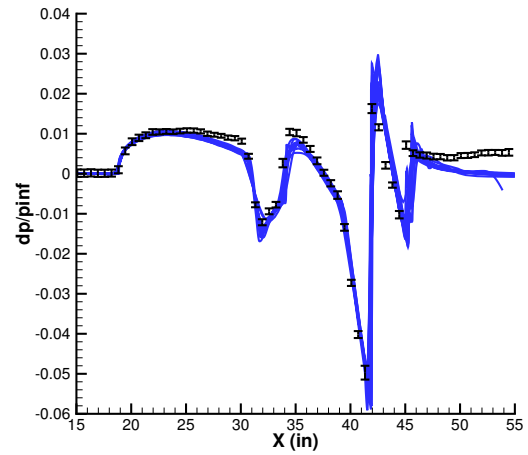


Fig. 34 Fine grid results from all participants at $\phi=30^\circ$ with experimental data (symbols).

agreement, especially when comparing results on workshop provided grids.

Before summarizing the results, the authors would like to reiterate from the workshop goals that we are not identifying whether a submission is right or wrong. The goal is to look at the trends and try to determine what might be causing outliers. Additionally, the agreement in the results for this workshop was exceptionally good and the scales in plots had to be tightened to highlight any differences.

The largest standard deviation from the participant submissions are of the nozzle-lip shock and the plume-biconvex shock interaction. Examination of those results show two groups of solutions that either predict a sharp shock or a somewhat curved shock, hence shifting the shock location slightly causing the discrepancy. The cone-strut interface shock had 4 outliers, 3 of which were from participant created grids while the last one had the participant matching well when using the mixed-element grid (the outlier was from the tetrahedral grid). Next, the nozzle-lip shock had 4 outliers, where 3 were from participant created grids while the fourth outlier, was from an SST submission. Although the majority of the submissions were using the SA turbulence model, there were several SST submissions that did match well, so further examination into the submission may be warranted. Last, the plume-biconvex shock interaction area had 6 outliers. Since this area is influenced by not only how the CFD code is modeling the flow out of the nozzle, the jet flow shock structure, as well as the interaction of the shock from the biconvex configuration, it is a challenging region. Two of the outliers were from inviscid codes, which cannot capture the viscous shear layer effects of the plume region. One was from a participant provided grid while the other three were on workshop provided grids. The remaining three solutions provide an opportunity to further investigate the cause of the slight differences and hopefully gain additional insight to the aft region modeling of supersonic aircraft.

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