USM3D Simulations for Third Sonic Boom Prediction Workshop (SBPW-3)

Alaa Elmiligui, Mohagna Pandya, and Melissa Carter

NASA Langley Research Center, Hampton VA 23681

Boris Diskin

National Institute of Aerospace, Hampton, VA 23666

and

Sudheer Nayani

Analytical Services & Materials, Inc., Hampton, VA 23666

3rd AIAA Sonic Boom Prediction Workshop, January 4-5, 2020

Orlando, Florida

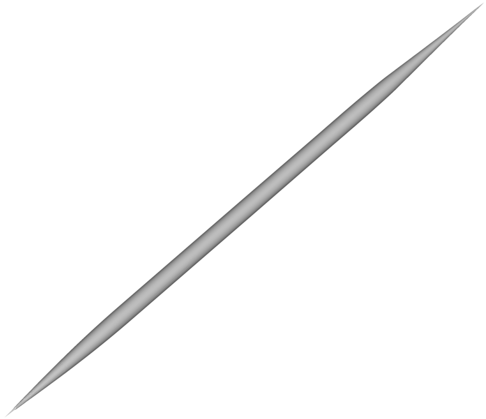
Outline

- Objective
- Workshop Test Cases
- Numerical Tools
- Numerical Results
- Concluding Remarks

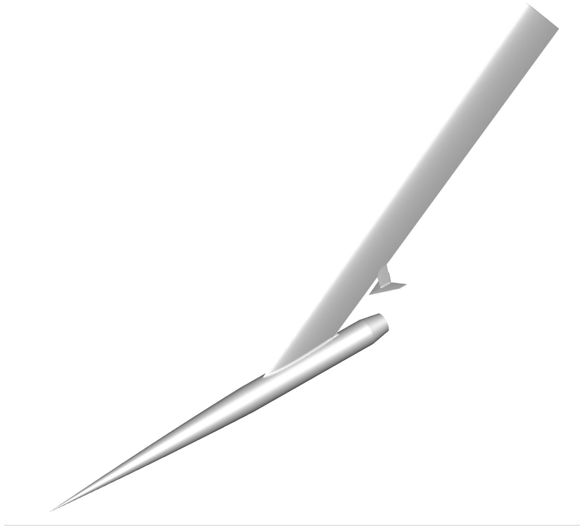
Objective

- Summarize USM3D contributions to the 3rd AIAA Sonic Boom Prediction Workshop (SBPW-3)
- Introduce USM3D mixed-element code to supersonic community
- Compare results from two different methods to solve the nonlinear iterations within USM3D mixed-element code
- Compare results from mixed-element and production versions of USM3D

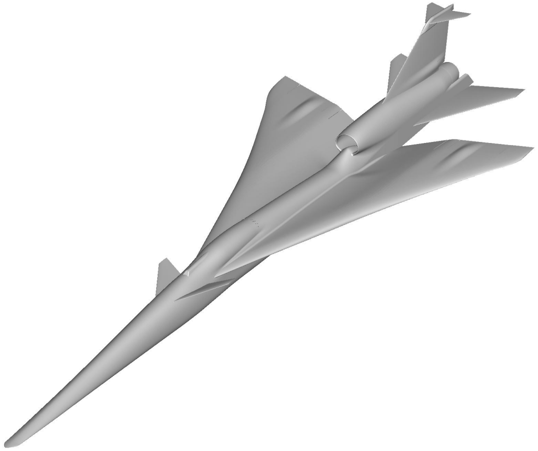
Test Cases for 3rd Sonic Boom Prediction Workshop



Axisymmetric Body of Revolution



Biconvex 9x7 Shock-Plume Interaction Model



C608 Low Boom Flight Demonstrator

Numerical Tools

- Computational Fluid Dynamics Codes
  - USM3D Production code (supports only tetrahedral grids)

    Pandya, M. J., Frink, N. T., Abdol-Hamid, K. S., Samareh, J. A., Parlette, E. B., and Taft, J. R., “Enhancements to TetrUSS for NASA Constellation Program,” Journal of Spacecraft and Rockets, Vol. 49, No. 4, 2012, pp. 617-631

  - USM3D mixed-element code (supports any combination of tetrahedral, pyramidal, prismatic, and hexahedral grids)

    Pandya, M. J., Diskin, B., Thomas, J. L., and Frink, N. T., “Assessment of USM3D Hierarchical Adaptive Nonlinear Iteration Method Preconditioners for Three-Dimensional Cases,” AIAA Journal, Vol. 55, No. 10, 2017, pp 3409-3424

- *Propagation Tools*
  - *sBOOM propagation code*

    Sriram K. Rallabhandi. "Advanced Sonic Boom Prediction Using the Augmented Burgers Equation", Journal of Aircraft, Vol. 48, No. 4 (2011), pp. 1245–1253

  - Loudness code

    Shepherd, K. P., and Sullivan, B. M., “A Loudness Calculation Procedure Applied to Shaped Sonic Booms,” NASA Technical Paper 3134, 1991

USM3D Simulations for SBPW-3

USM3D Production Code	USM3D Mixed-Element Code
Cell-centered, finite volume	
Euler and Navier-Stokes equations	
Upwind spatial discretization	
FDS, AUSM, HLLC, LDFSS, FVS	
LTS and 2nd-order time stepping	
Integration with baseline solver technology	Two different methods for nonlinear iterations
Tetrahedral grids	Combination of tetrahedral, pyramidal, prismatic, and hexahedral grids
Min-mod limiter	Limiters (Barth-Jespersen, Venkat, van Leer, van Albada)
Turbulence models SA-standard, kε, SST	Turbulence Models SA-, standard and negative

USM3D Mixed-Element Code

- **System of nonlinear equations, R(Q) = 0**

- **Two different methods to solve for nonlinear iterations**
  - Preconditioner-Alone **(PA)**
  - Hierarchical Adaptive Nonlinear Iteration**(HANIM)**

- **PA method**
  - baseline technology with improved discretization and preconditioner

- **HANIM**
  - significant improvements over PA in robustness and iterative convergence
  - enhanced solver for the system of nonlinear equations
  - provides two additional hierarchies around the preconditioner of PA
  - CFL adaptation used as a comprehensive tool

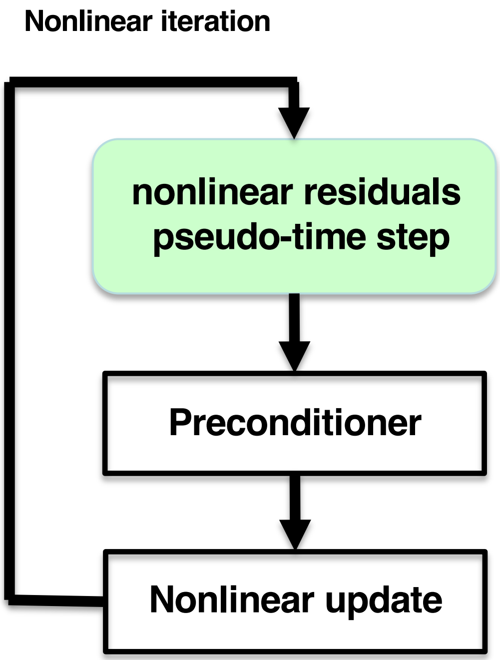
PA Method

➢ **Baseline technology with improved discretization and preconditioner**

- first-order FDS scheme for mean flow approximate Jacobian
- point- or line-implicit scheme for solving preconditoner equations
- residual reduction targets for preconditioner

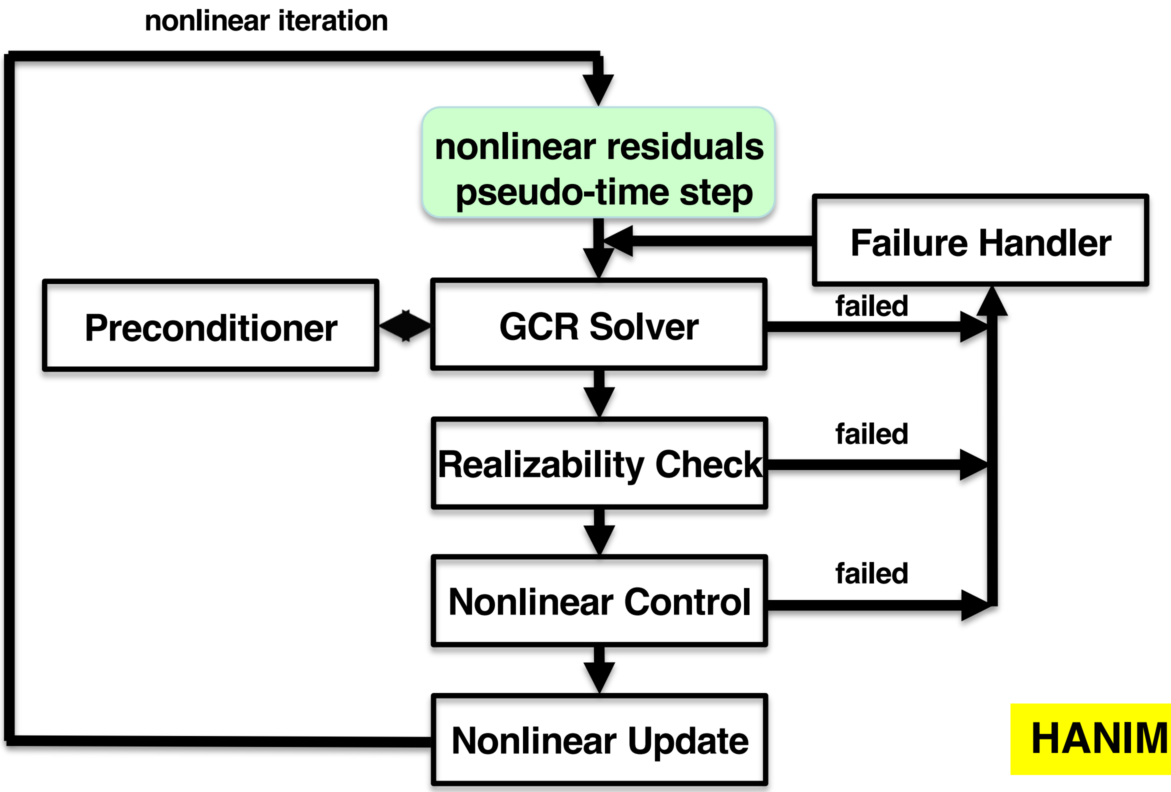
$$\frac{V}{\Delta\tau}\Delta Q + \frac{\partial \hat{R}}{\partial Q}\Delta Q = -R\left(Q^n\right)$$ ← Solved by Preconditioner

$$Q^{n+1} = Q^n + \Delta Q$$ ← Performed inside Nonlinear Update



PA Flowchart

Hierarchical Adaptive Nonlinear Iteration Method (HANIM)



HANIM Flowchart

Numerical Results

Axisymmetric Body of Revolution

Test Conditions:

- Inviscid test case
- Mach 1.6
- Angle of attack 0.0º
- Reference length 32.92 m
- Altitude 15760 m
- Temperature 216.6ºK

Axisymmetric Body of Revolution Grids

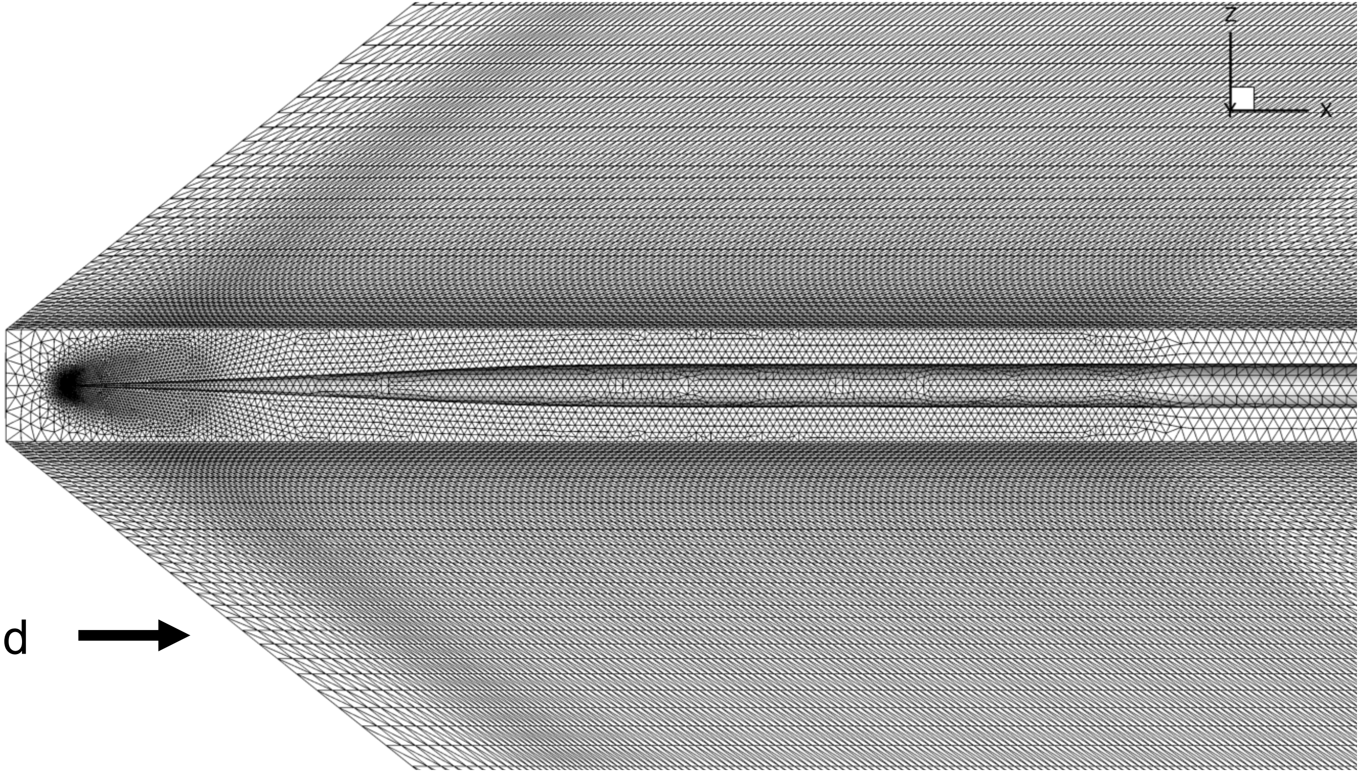
	Grid Level	Scale Factor	Nodes (millions)	Mixed-Element (millions)	Tetrahedral (millions)
Coarsest →	Axi-5	2.56	0.65	1.38	3.71
	Axi-4	2.00	1.60	3.70	9.24
	Axi-3	1.60	5.08	12.31	29.68
	Axi-2	1.28	15.91	40.44	93.75
Finest →	Axi-1	1.00	56.09	151.30	332.14

Axisymmetric Body of Revolution

Symmetry Plane Axi-5 Grid

Inner Grid →

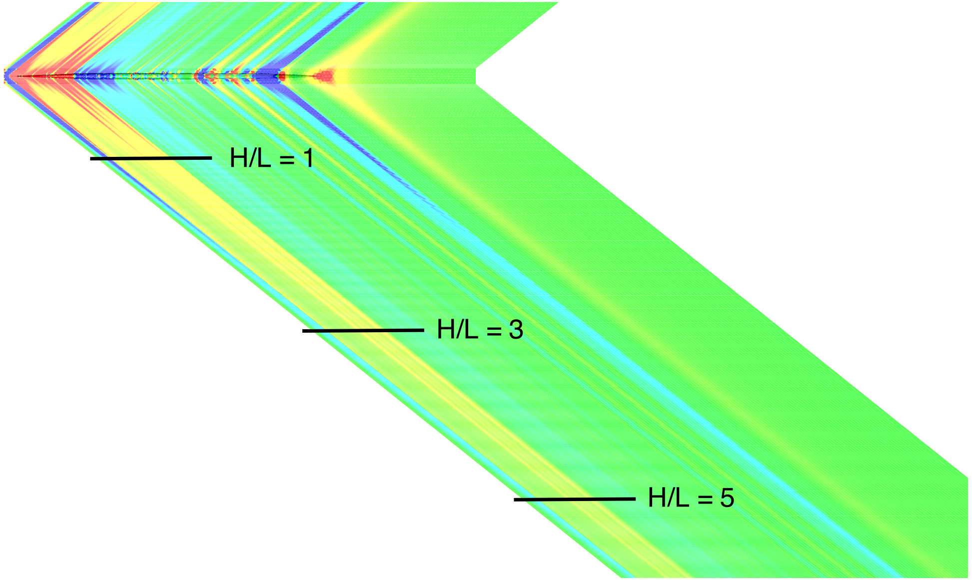
Mach-aligned collar grid →



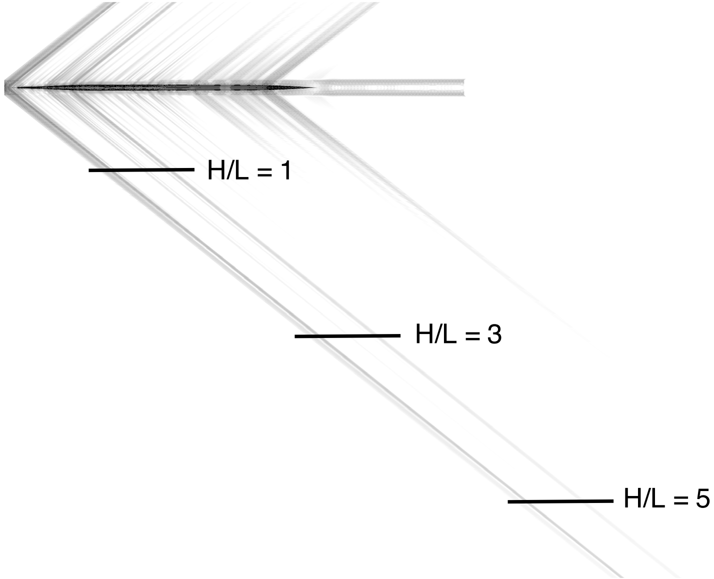
Axisymmetric Body of Revolution

Symmetry Plane

$M_\infty = 1.6$, $\alpha = 0.0°$, Inviscid Flow



Normalized Pressure Contours

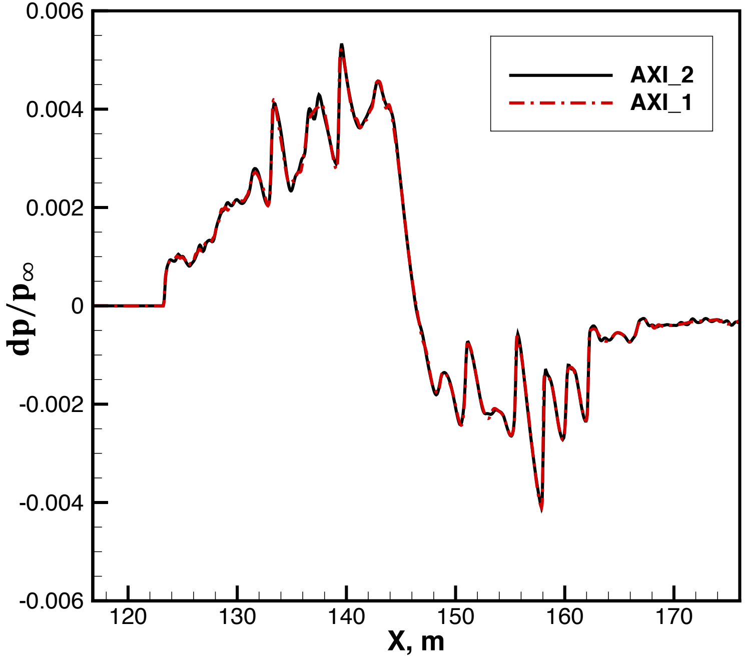


Density Gradient Contours

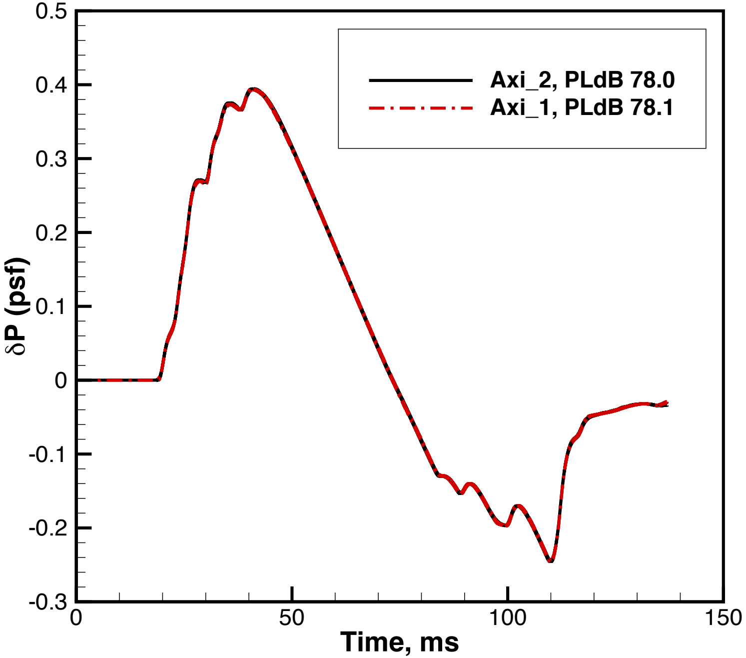
Axisymmetric Body of Revolution

Grid Convergence Mixed-Element USM3D-HANIM

M_∞ = 1.6, α = 0.0º, H/L = 3, Inviscid Flow



Near Field Pressure Signature

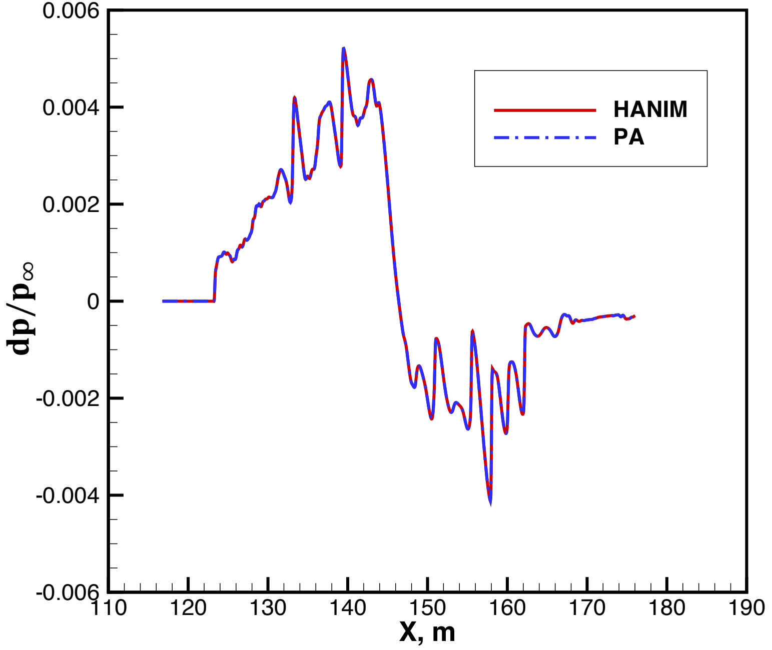


Ground Pressure Signature

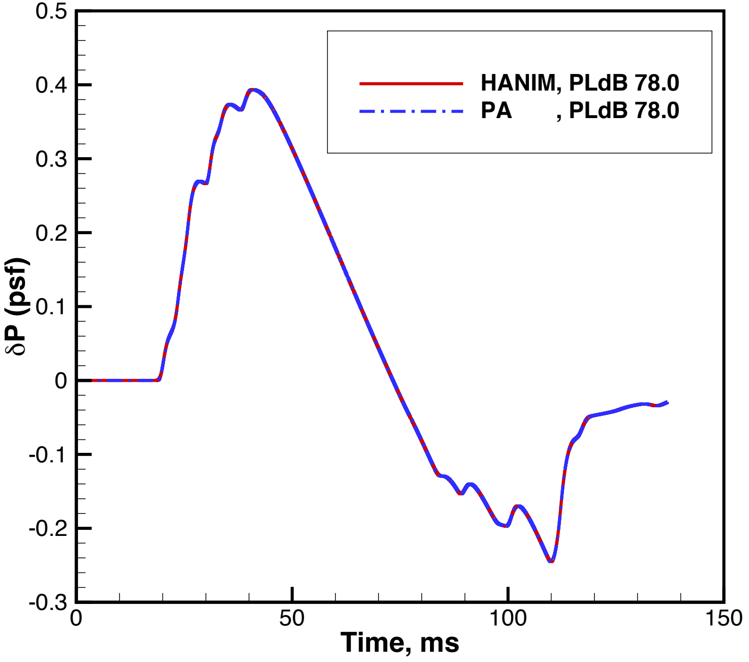
Axisymmetric Body of Revolution

USM3D-(PA vs HANIM) on Finest Mixed-Element Grid

M_{∞} = 1.6, α = 0.0º, H/L = 3, Inviscid Flow



Near Field Pressure Signature

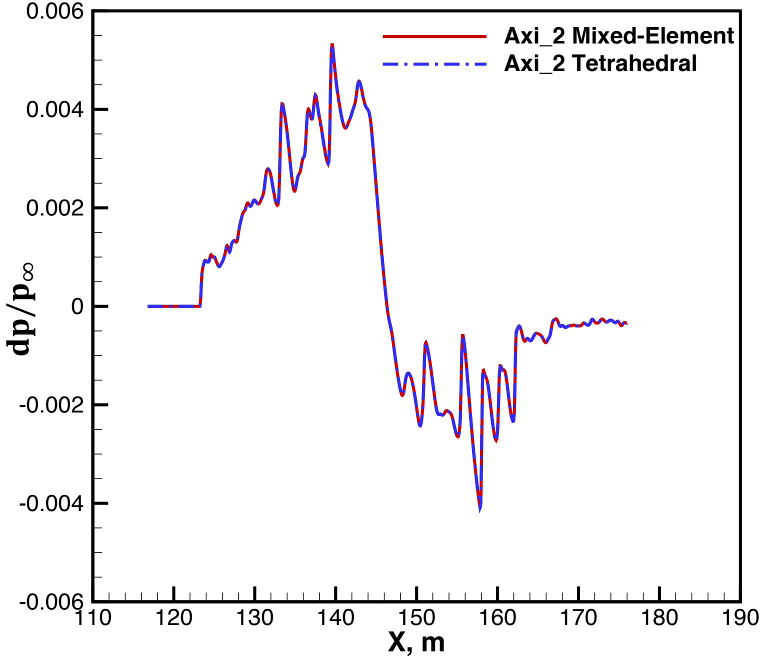


Ground Pressure Signature

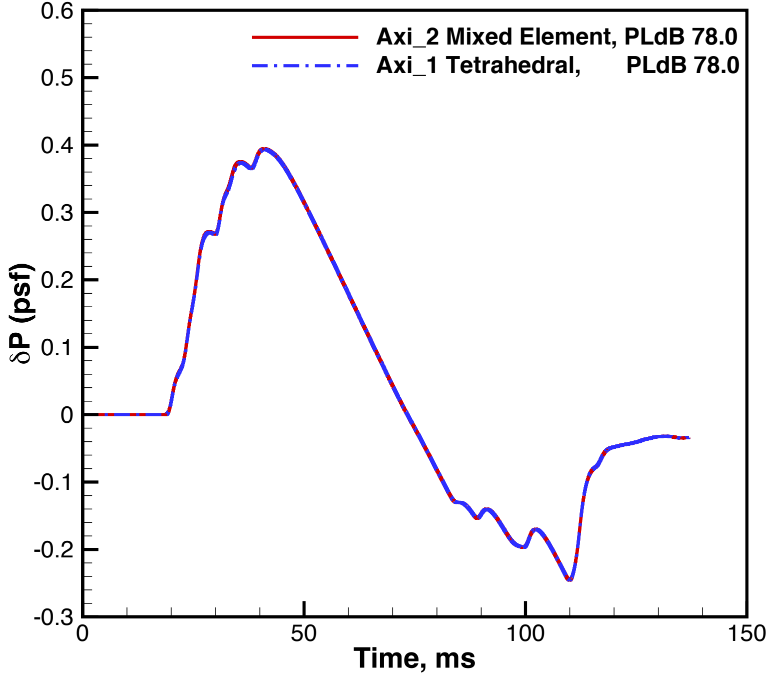
Axisymmetric Body of Revolution

USM3D-PA Mixed-Element and Tetrahedral Grids

$M_\infty = 1.6$, $\alpha = 0.0°$, H/L = 3, Inviscid Flow



Near Field Pressure Signature

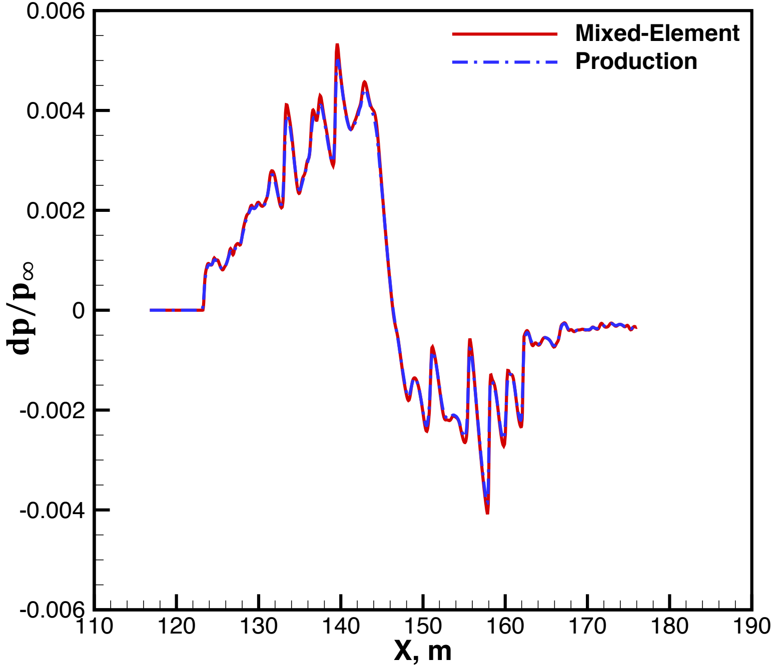


Ground Pressure Signature

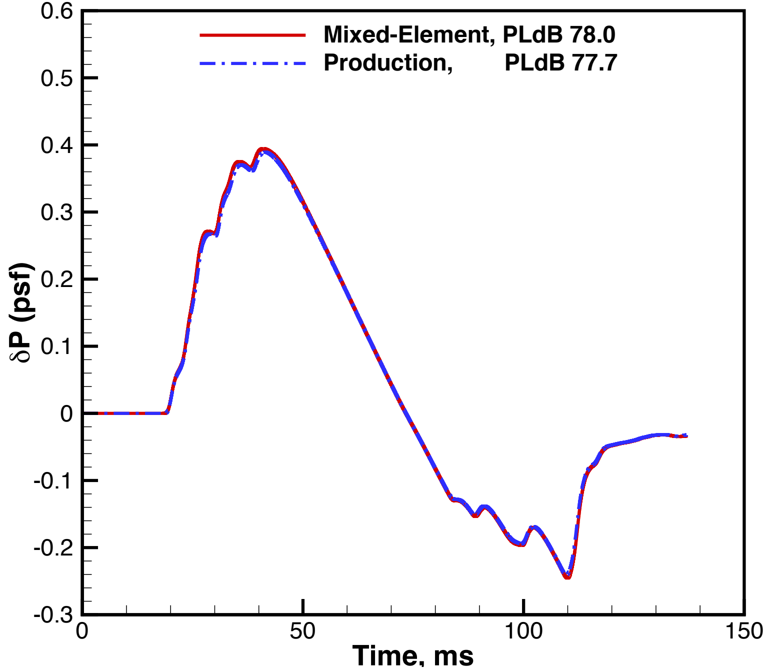
Axisymmetric Body of Revolution

Mixed-Element and Production Versions of USM3D, Axi-2 Grid

$M_\infty = 1.6$, $\alpha = 0.0°$, H/L = 3, Inviscid Flow



Near Field Pressure Signature



Ground Pressure Signature

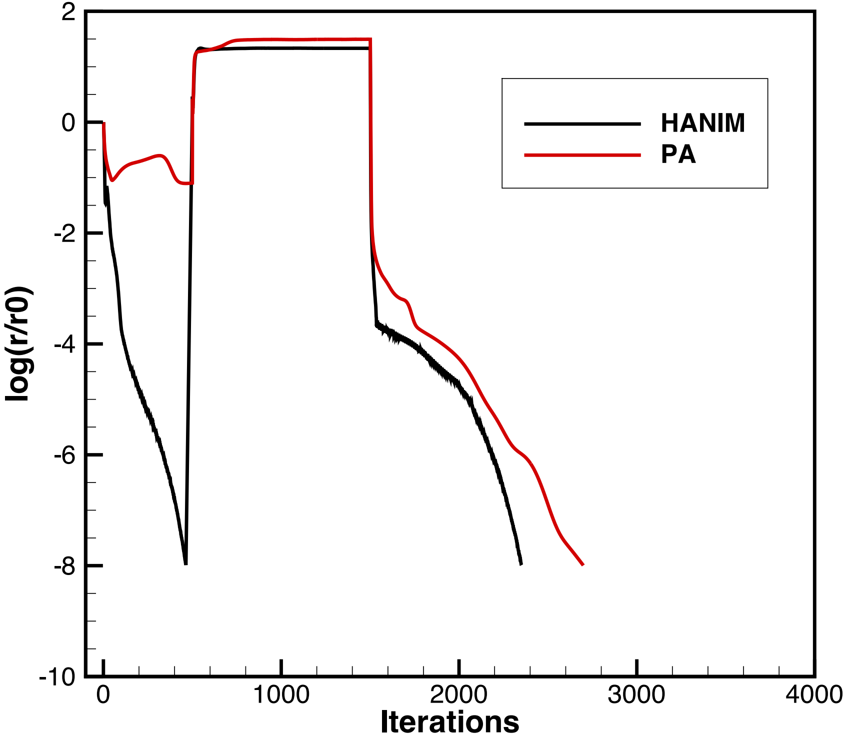
Axisymmetric Body of Revolution

USM3D-(PA vs HANIM) Convergence History

M_∞ = 1.6, α = 0.0º, H/L = 3, Inviscid Flow

Simulations performed on 70 Pleiades Ivy Bridge nodes “1400 cores”

Axi_2 mixed-element grid



Biconvex 9x7 Shock-Plume Interaction Model

Test Conditions:

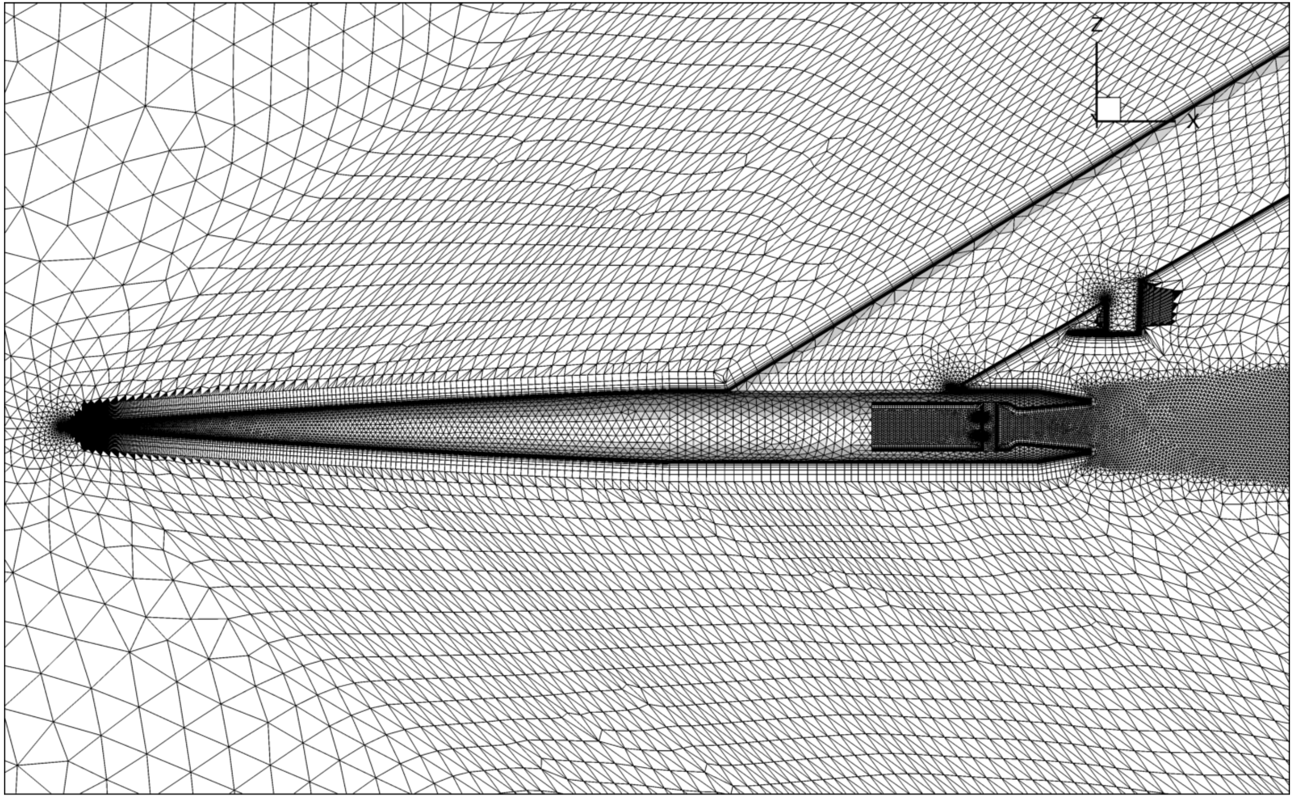
- Mach 1.6
- Angle of attack 0.0º
- Temperature 374ºR
- Unit Reynolds number 376,850 per in
- Engine $P_o/P_\infty = 8$
- Engine $T_o/T_\infty = 1.768$

Biconvex 9x7 Shock-Plume Interaction Model Grids

	Grid Level	Scale Factor	Mixed-Element Grids (millions)		Tetrahedral Grids (millions)	
			Nodes	Cells	Nodes	Cells
Coarsest →	Grid_3	1.57	0.85	2.80	0.85	4.8
	Grid_2	1.28	1.60	6.00	1.60	9.0
Finest →	Grid_1	1.00	3.30	14.60	3.30	18.8

Biconvex 9x7 Shock-Plume Interaction Model

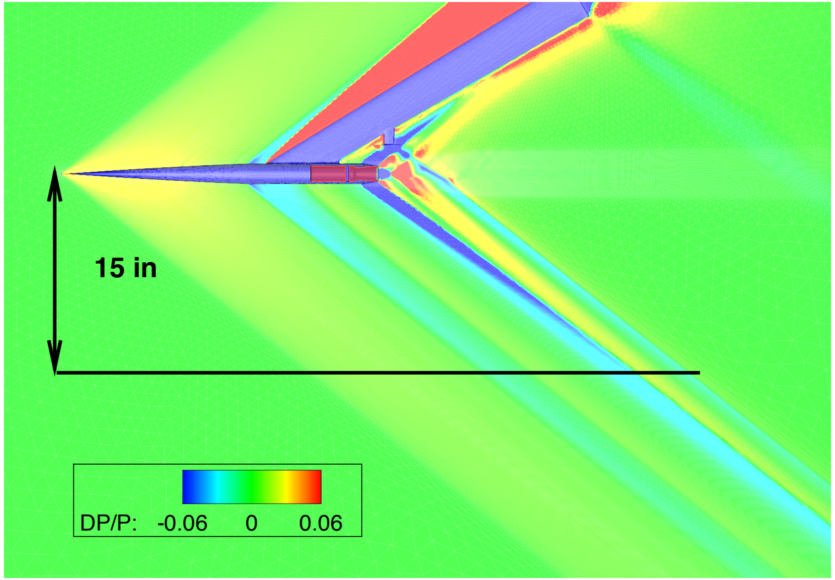
Symmetry Plane Grid_3



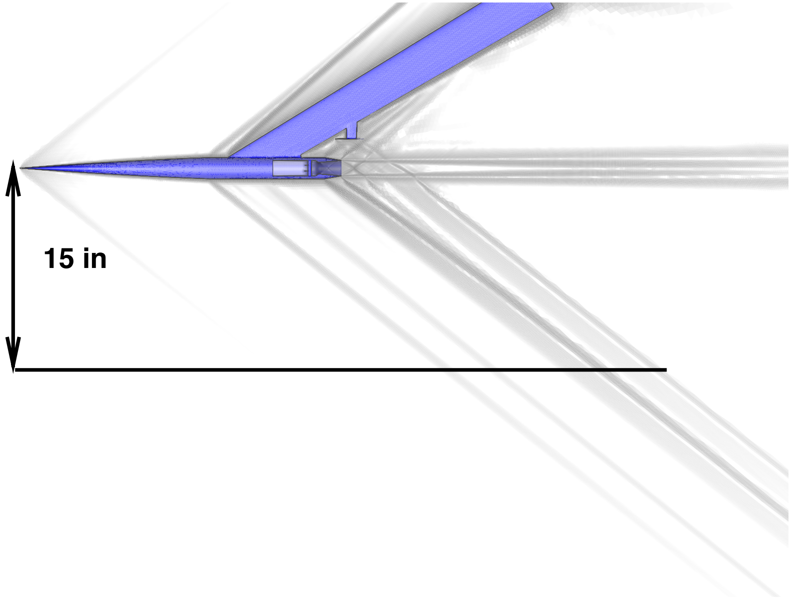
Biconvex 9x7 Shock-Plume Interaction Model

Symmetry Plane

$M_\infty = 1.6$, $\alpha = 0.0^o$, Re = 376,850 per in



Normalized Pressure Contours

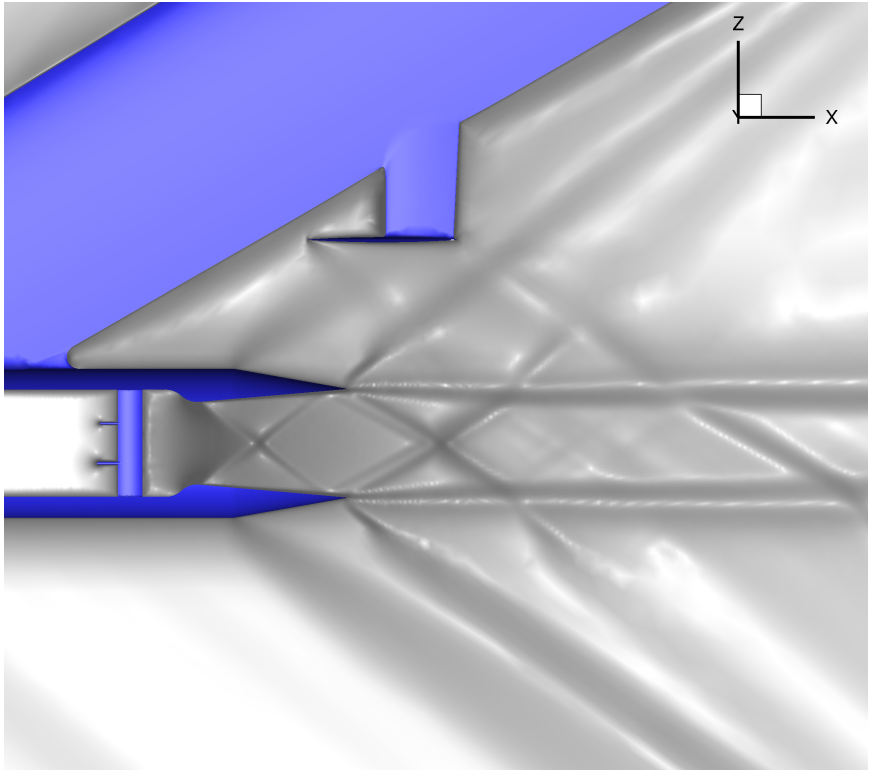


Density Gradient Contours

Biconvex 9x7 Shock-Plume Interaction Model

Symmetry Plane Density Gradient Contours

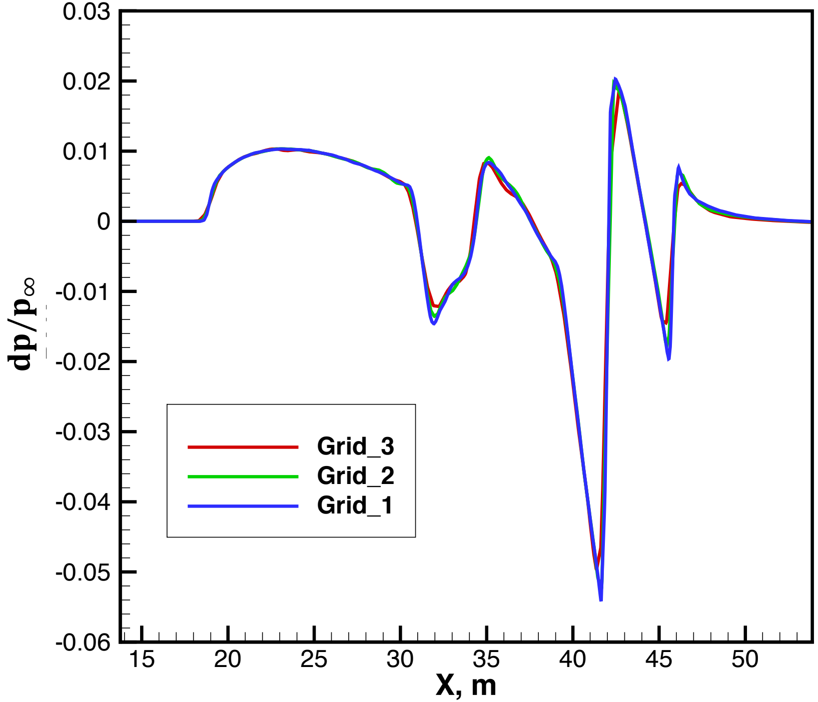
$M_\infty = 1.6$, $\alpha = 0.0^o$, $Re = 376{,}850$ per in

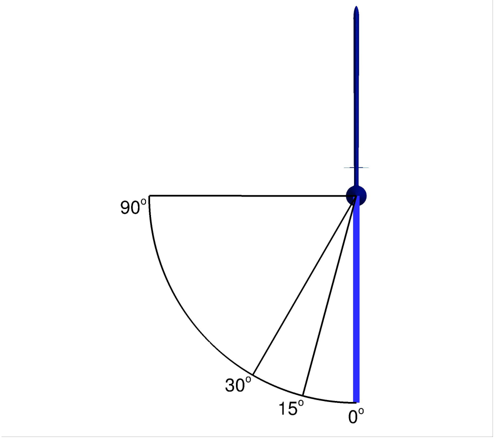


Biconvex 9x7 Shock-Plume Interaction Model

Grid Convergence on Tetrahedral Grids USM3D-PA

M_∞ = 1.6, α = 0.0°, Re = 376,850 per in



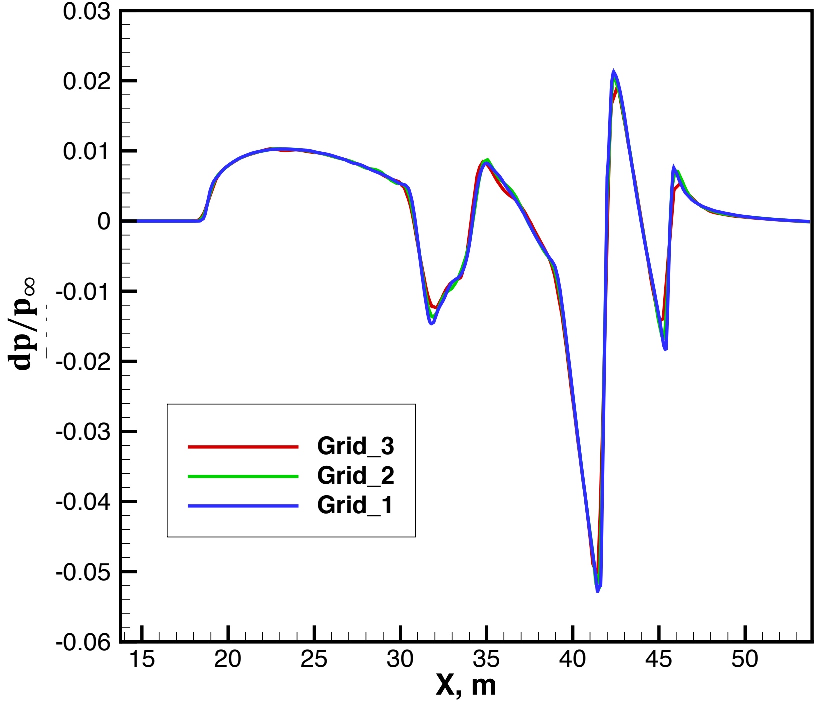


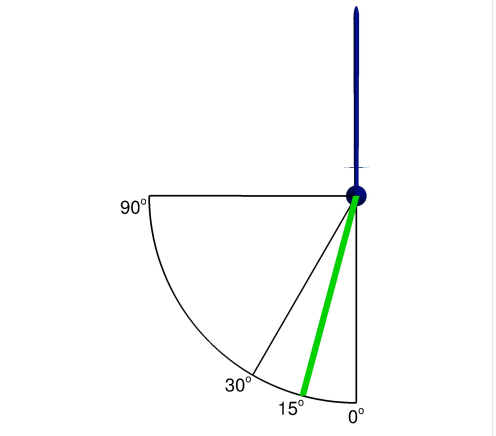
Near Field Pressure Signature, ϕ = 0°

Biconvex 9x7 Shock-Plume Interaction Model

Grid Convergence on Tetrahedral Grids USM3D-PA

$M_\infty = 1.6$, $\alpha = 0.0^o$, Re = 376,850 per in



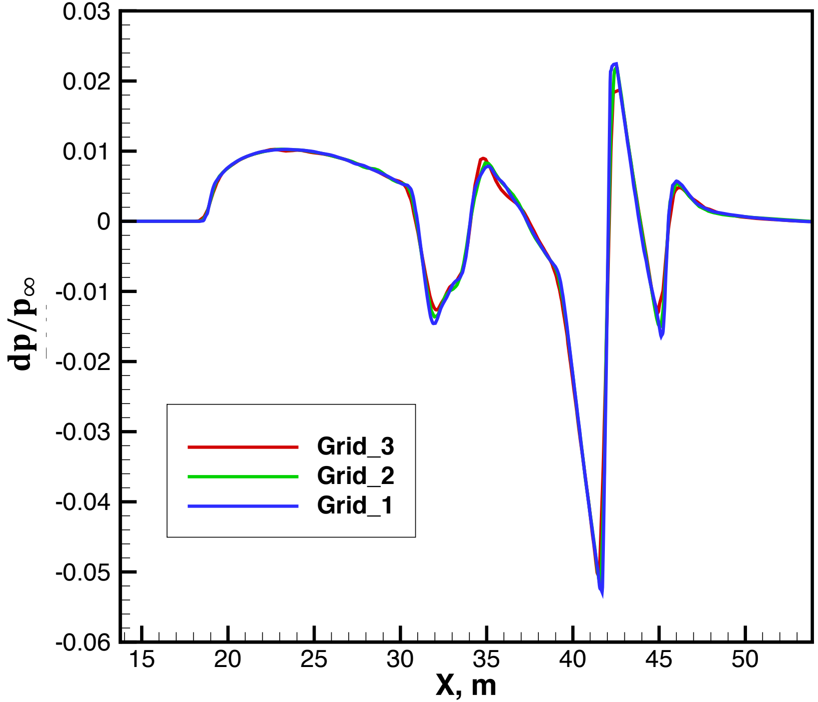


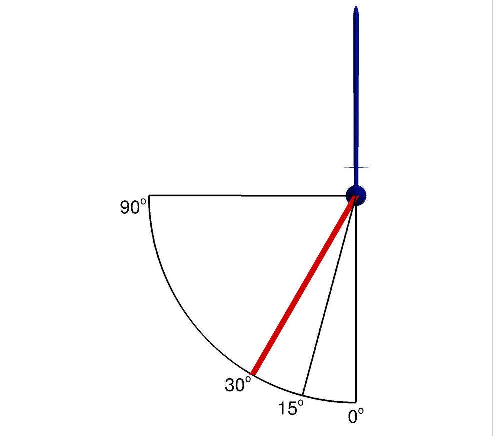
Near Field Pressure Signature, $\phi = 15^\circ$

Biconvex 9x7 Shock-Plume Interaction Model

Grid Convergence on Tetrahedral Grids USM3D-PA

$M_\infty = 1.6$, $\alpha = 0.0^o$, Re = 376,850 per in



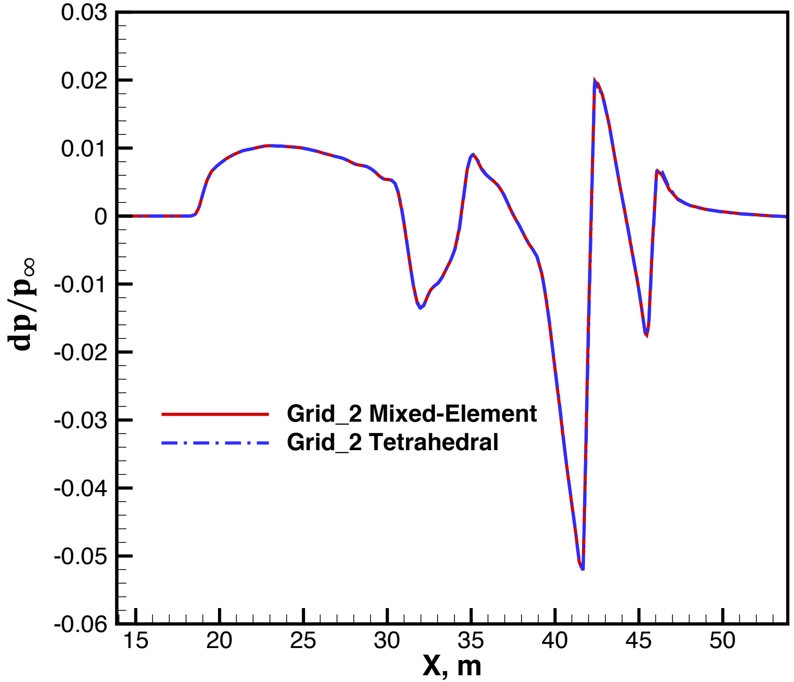


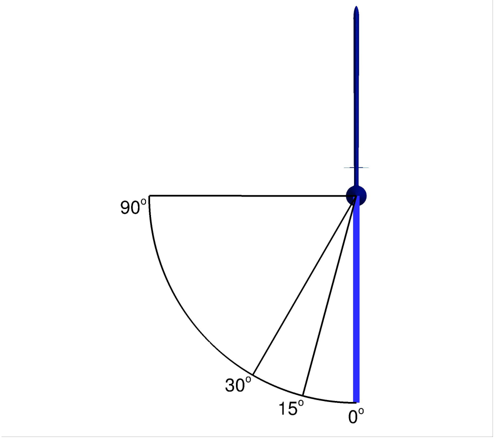
Near Field Pressure Signature, ϕ = 30°

Biconvex 9x7 Shock-Plume Interaction Model

USM3D-PA Solutions on Mixed-Element and Tetrahedral Grids

M_∞ = 1.6, α = 0.0°, Re = 376,850 per in



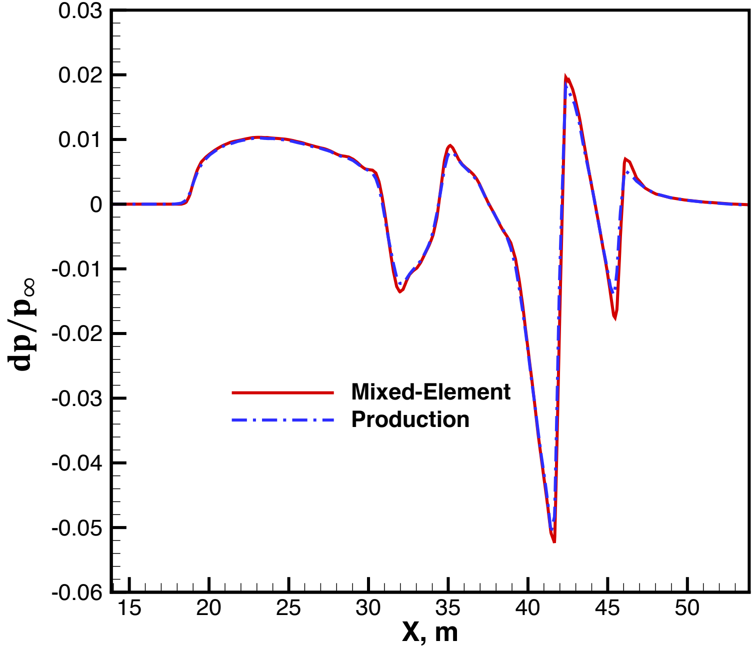


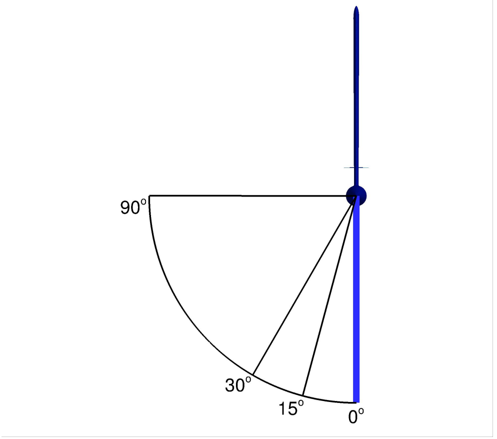
Near Field Pressure Signature, ϕ = 0°

Biconvex 9x7 Shock-Plume Interaction Model

Mixed-Element and Production Versions of USM3D on Tetrahedral Grid_2

M_∞ = 1.6, α = 0.0°, Re = 376,850 per in





Near Field Pressure Signature, ϕ = 0°

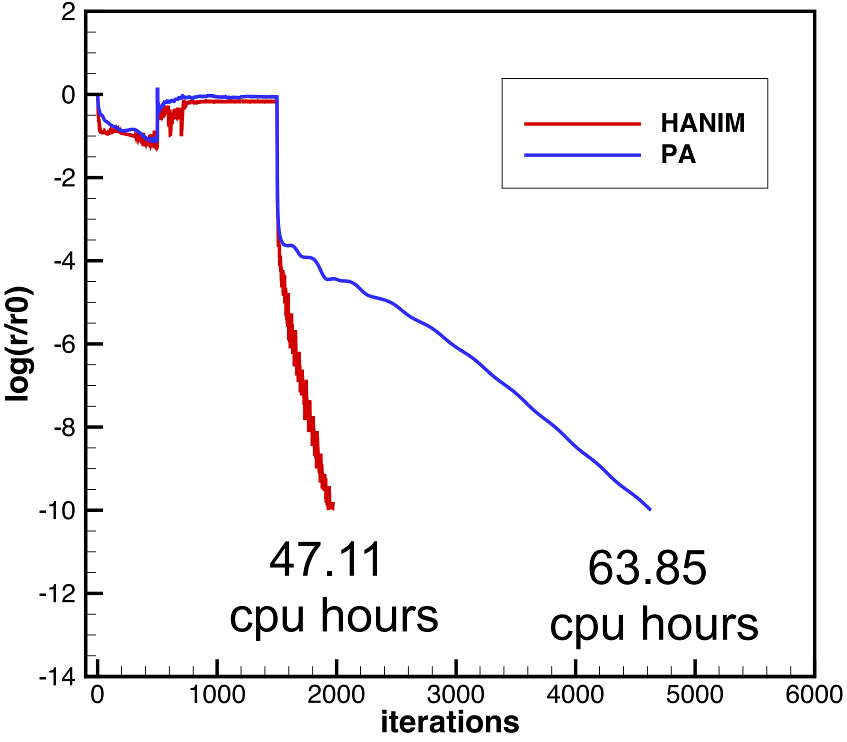
Biconvex 9x7 Shock-Plume Interaction Model

USM3D-(PA vs HANIM) Convergence History

M_∞ = 1.6, α = 0.0º, Re = 376,850 per in

Simulations performed on 8 Pleiades Ivy Bridge Nodes “160 cores”

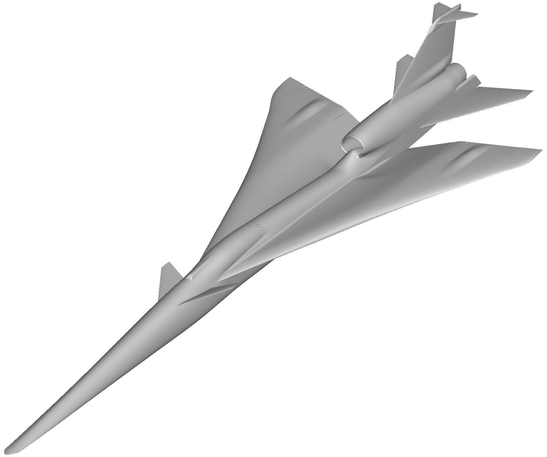
Grid_2 mixed-element



C608 Low Boom Flight Demonstrator

Test Conditions:

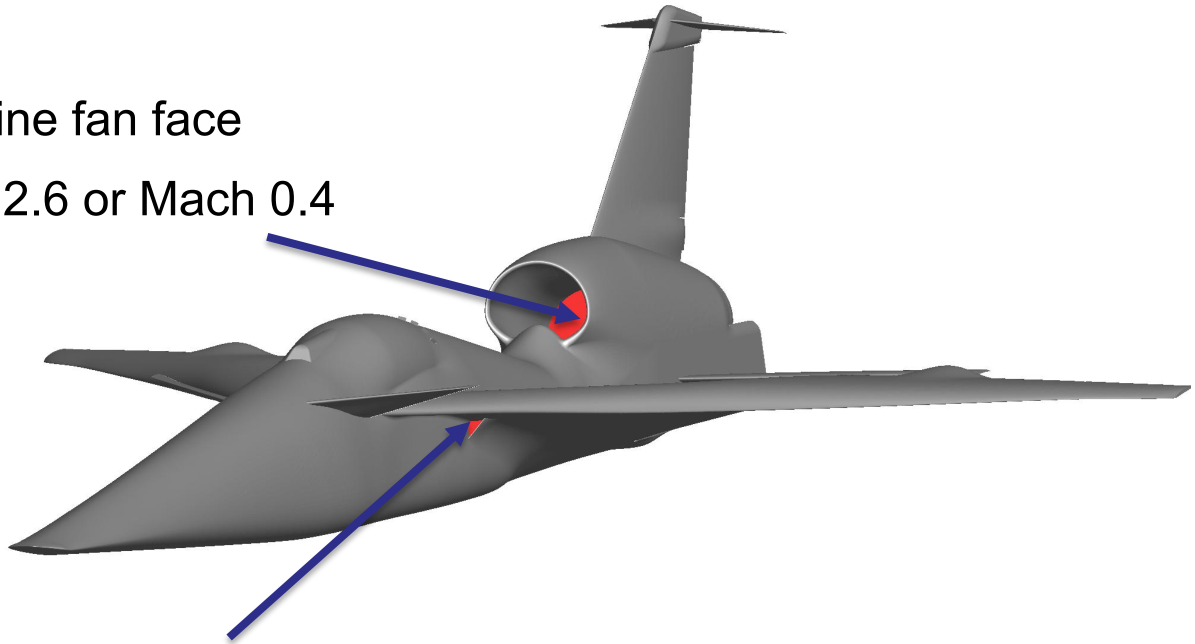
- Mach 1.4
- Angle of attack 2.15° built into the grids
- Body length 1080 in
- Temperature 389.9°R
- Unit Reynolds Number 109,776 per inch
- Altitude 53,200 ft



C608 Low Boom Flight Demonstrator

Engine fan face

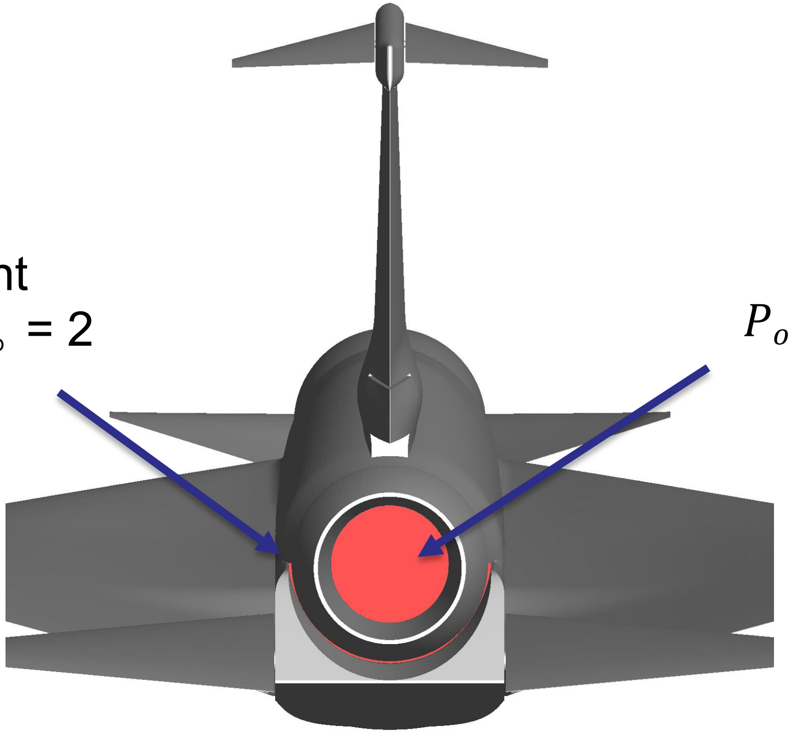
$P/P_\infty = 2.6$ or Mach 0.4



Environmental Control System (ECS) Intake face

$P/P_\infty = 1.4$ or Mach 0.35

C608 Low Boom Flight Demonstrator



Engine Bypass Vent
$P_o/P_\infty = 2.4$ & $T_o/T_\infty = 2$

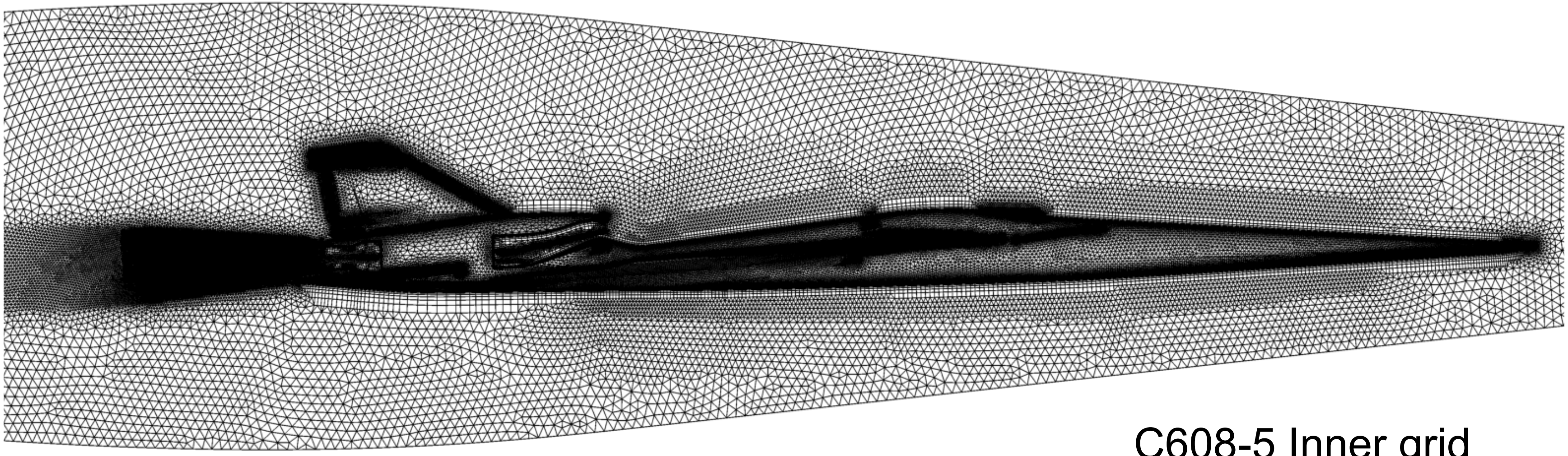
Engine plenum
$P_o/P_\infty = 10$ & $T_o/T_\infty = 7$

C608 Low Boom Flight Demonstrator Grids

	Grid Level	Scale Factor	Nodes (millions)	Mixed-Element (millions)	Tetrahedral (millions)
Coarsest →	C608-5	1.28	11.78	29.82	68.49
	C608-4	1	20.70	50.03	121.01
	C608-3	0.8	34.88	82.27	204.71
	C608-2	0.64	50.22	122.65	295.28
Finest →	C608-1	0.5	89.46	220.53	527.86

C608 Low Boom Flight Demonstrator

Symmetry Plane Inner Grid

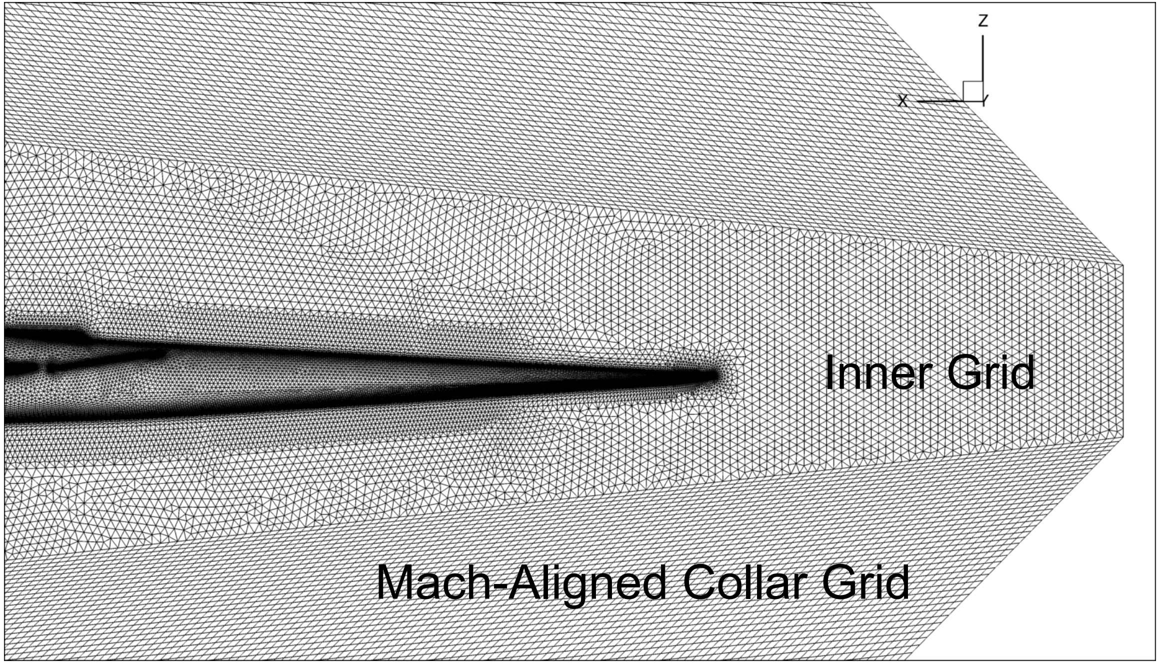


C608-5 Inner grid

C608 Low Boom Flight Demonstrator

Schematic Symmetry Plane Grid

C608-5 grid

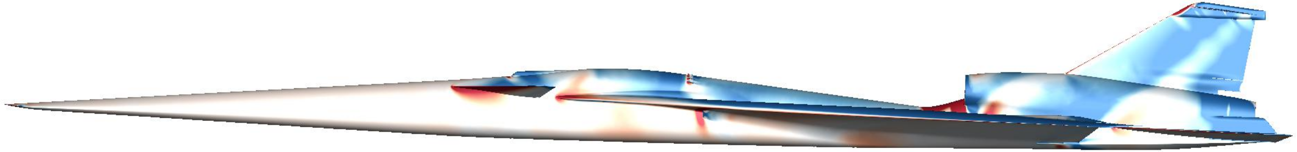


C608 Low Boom Flight Demonstrator

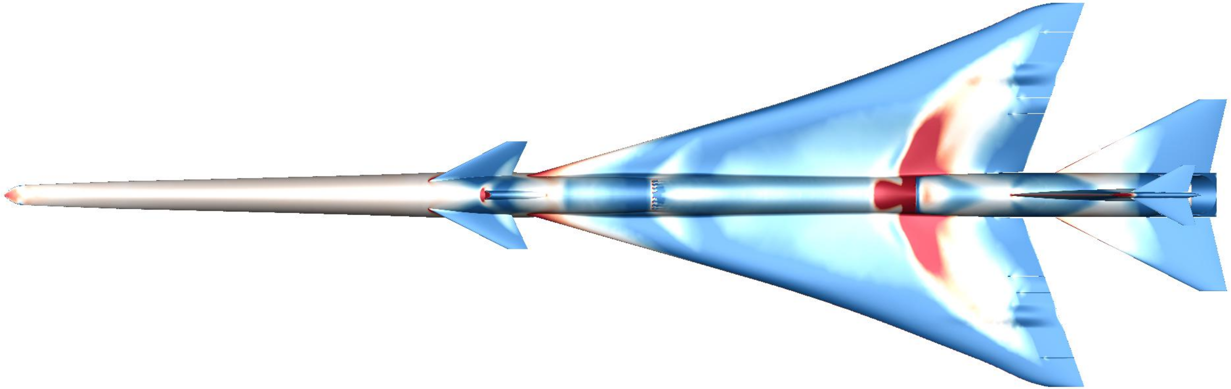
Pressure Coefficient Contours

M_∞ = 1.6, α = 2.15º, Re = 109,776 per in.

Side view

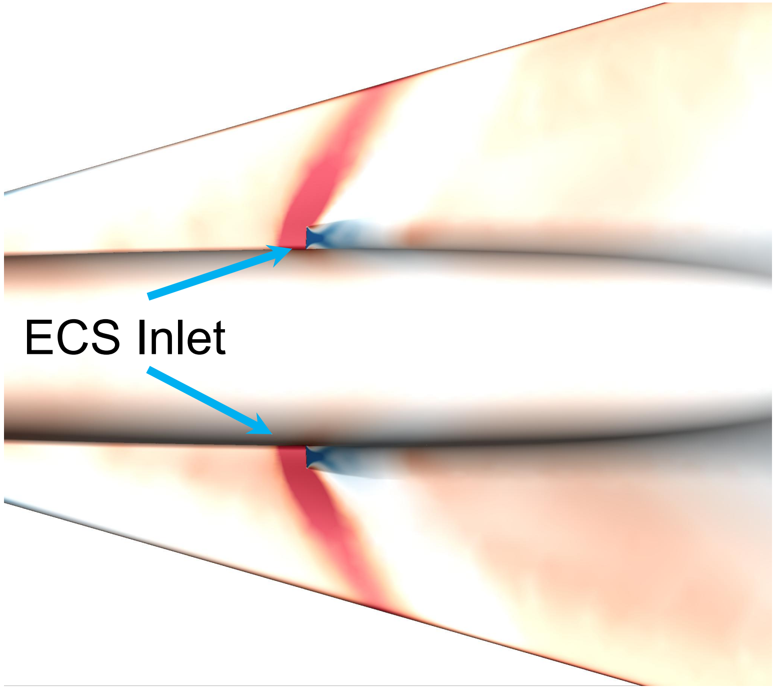


Top view

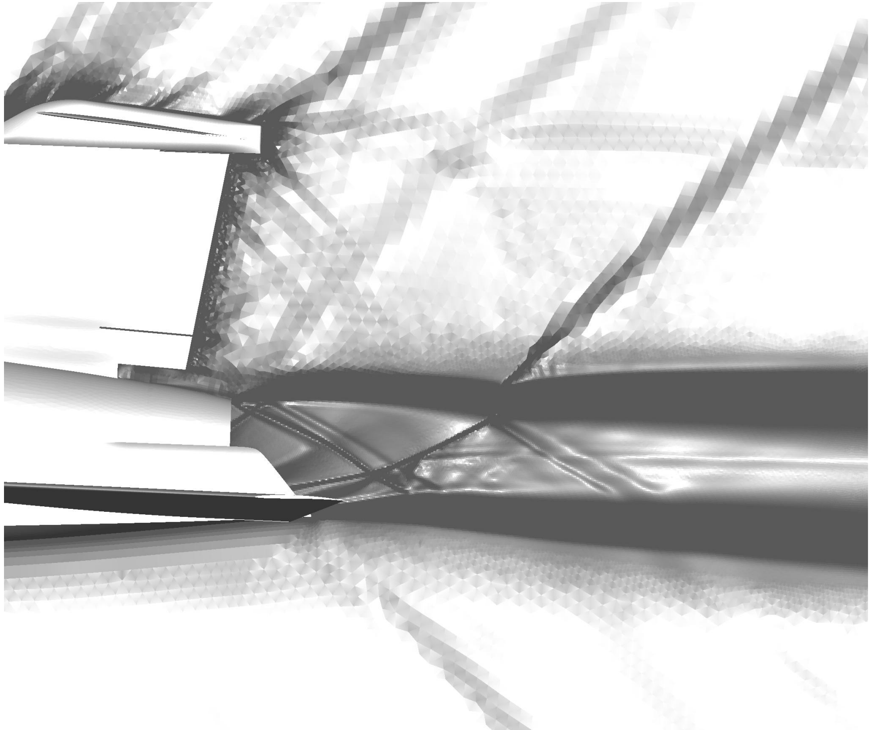


C608 Low Boom Flight Demonstrator

$M_\infty = 1.6$, $\alpha = 2.15^o$, Re = 109,776 per in.



Pressure Coefficient Contours

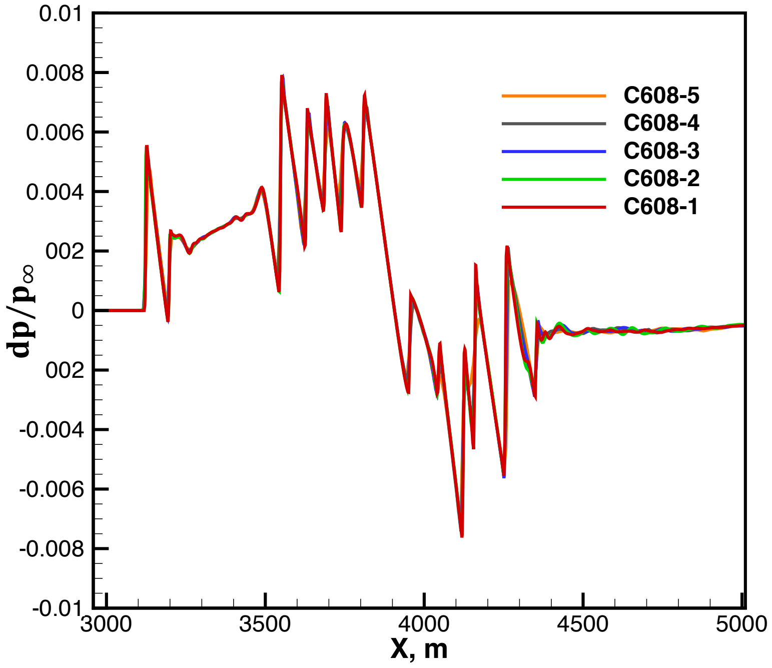


Density Gradient Contours

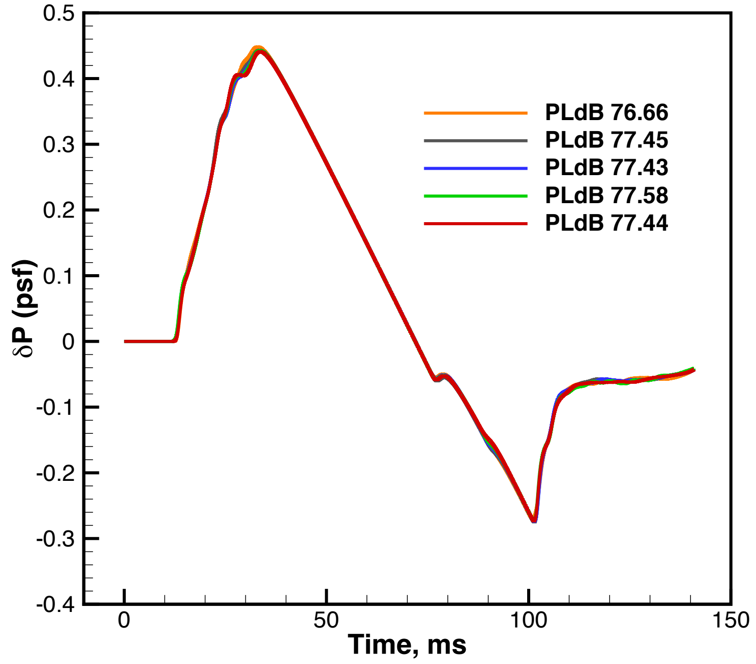
C608 Low Boom Flight Demonstrator

Grid Convergence on Mixed-Element Grids USM3D-HANIM

M_∞ = 1.6, α = 2.15º, H/L = 3, Re = 109,776 per in, ϕ = 0˚



Near Field Pressure Signature

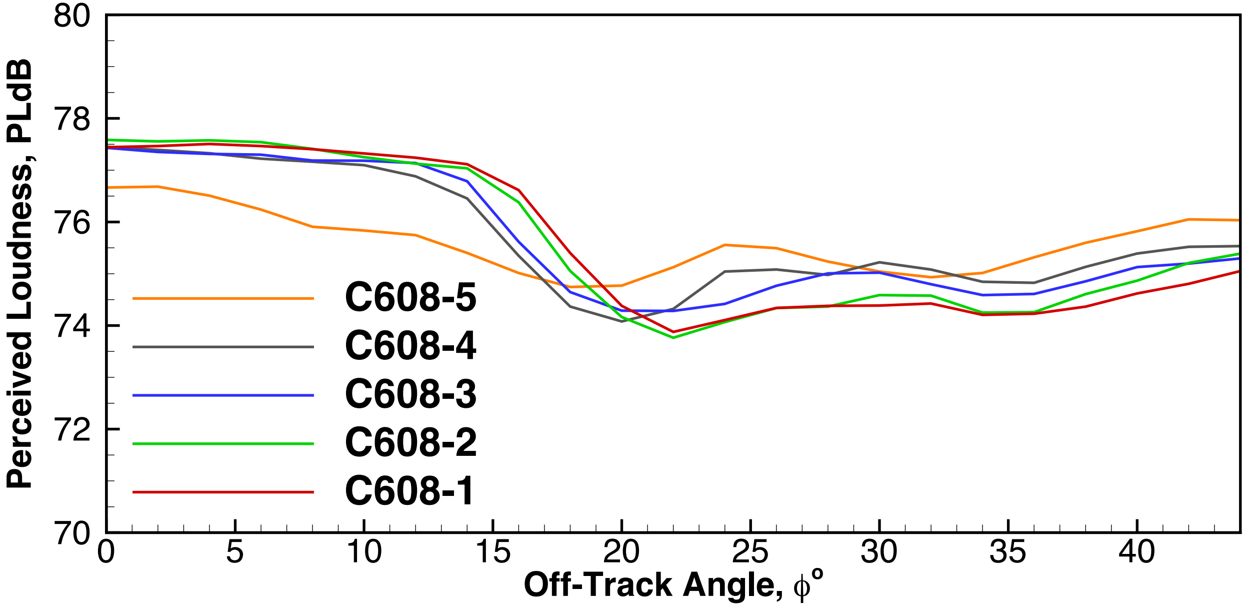


Ground Pressure Signature

C608 Low Boom Flight Demonstrator

Grid Convergence on Mixed-Element Grids USM3D-HANIM

M_∞ = 1.6, α = 2.15º, H/L = 3, Re = 109,776 per in

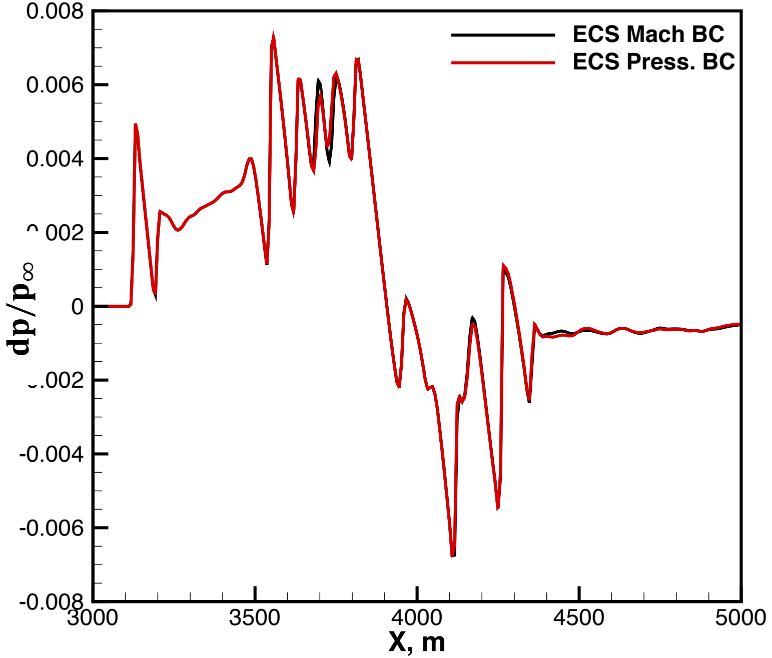


Carpet of Perceived Loudness Levels

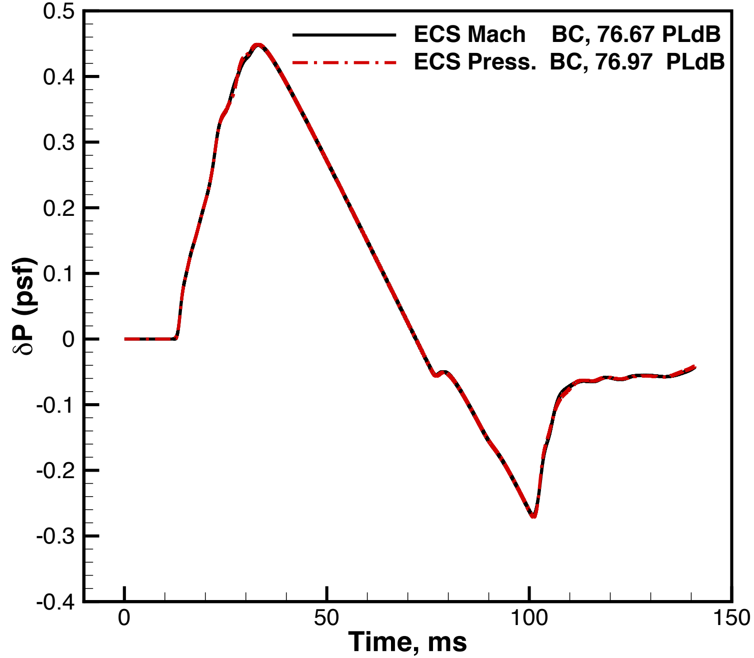
C608 Low Boom Flight Demonstrator

Effect of ECS BC Type USM3D-HANIM C608-5

$M_\infty = 1.6$, $\alpha = 2.15°$, $H/L = 3$, $Re = 109,776$ per in, $\phi = 0°$



Near Field Pressure Signature

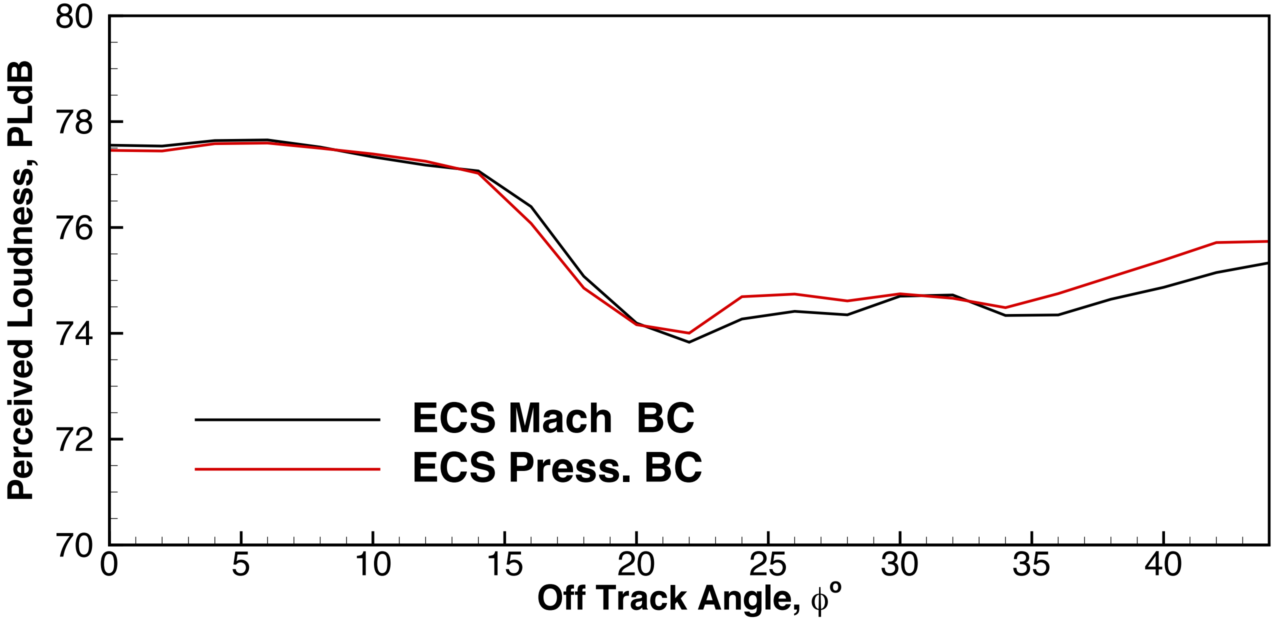


Ground Pressure Signature

C608 Low Boom Flight Demonstrator

Effect of ECS BC Type USM3D-HANIM C608-5

M_∞ = 1.6, α = 2.15º, H/L = 3, Re = 109,776 per in

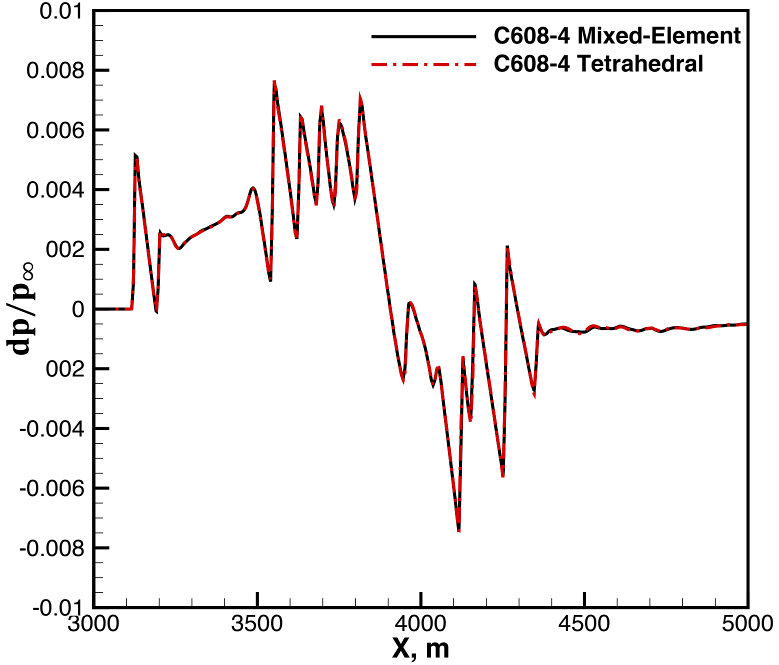


Carpet of Perceived Loudness Levels

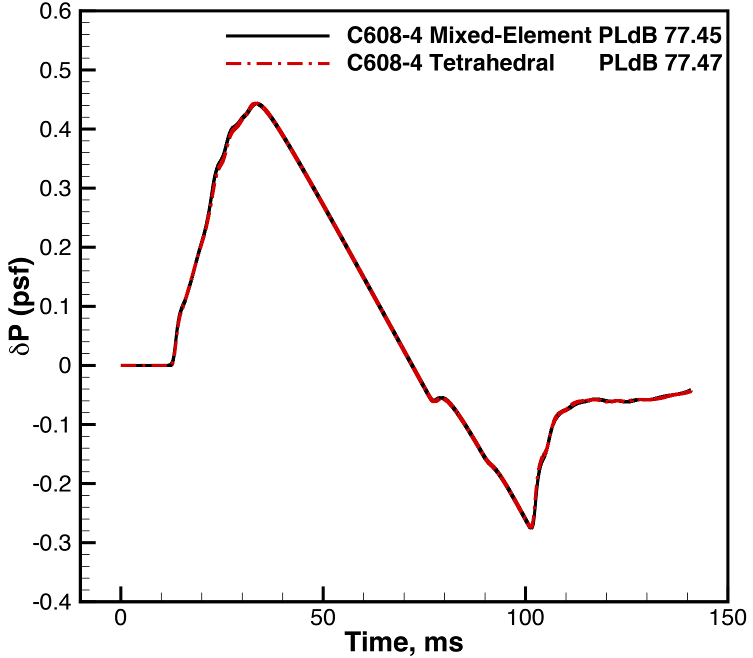
C608 Low Boom Flight Demonstrator

USM3D-HANIM Solutions on Mixed-Element and Tetrahedral Grids

M_∞ = 1.6, α = 2.15º, H/L = 3, Re = 109,776 per in, ϕ = 0°



Near Field Pressure Signature

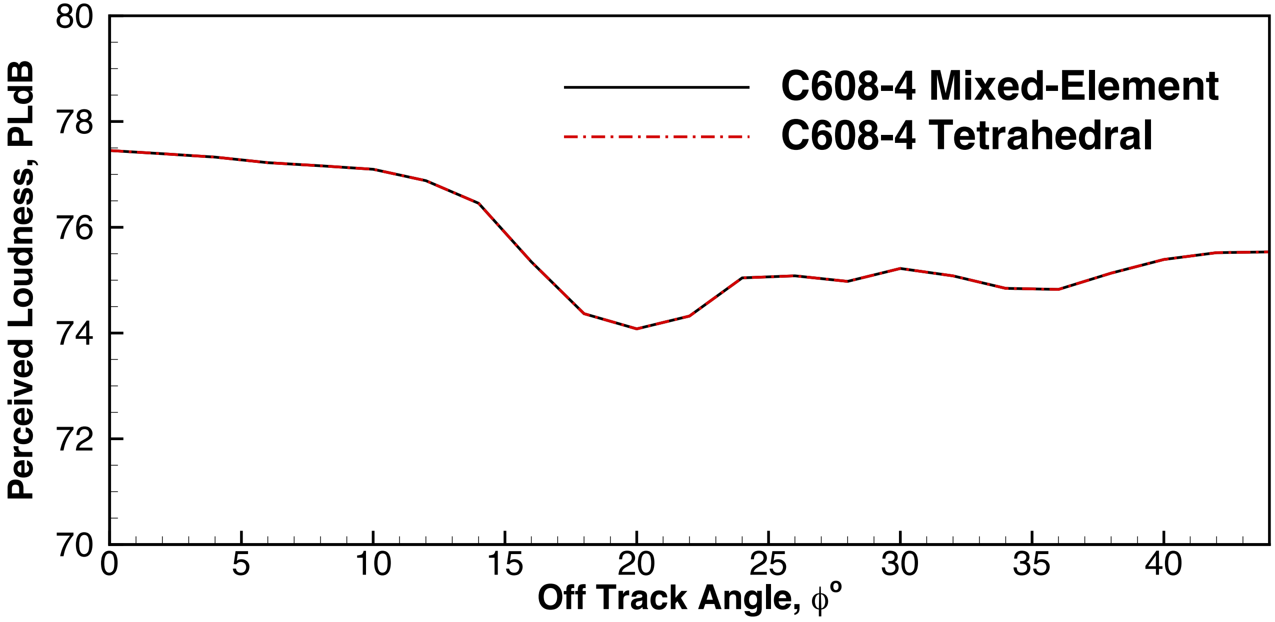


Ground Pressure Signature

C608 Low Boom Flight Demonstrator

USM3D-HANIM Solutions on Mixed-Element and Tetrahedral Grids

$M_\infty = 1.6$, $\alpha = 2.15^o$, $H/L = 3$, $Re = 109{,}776$ per in

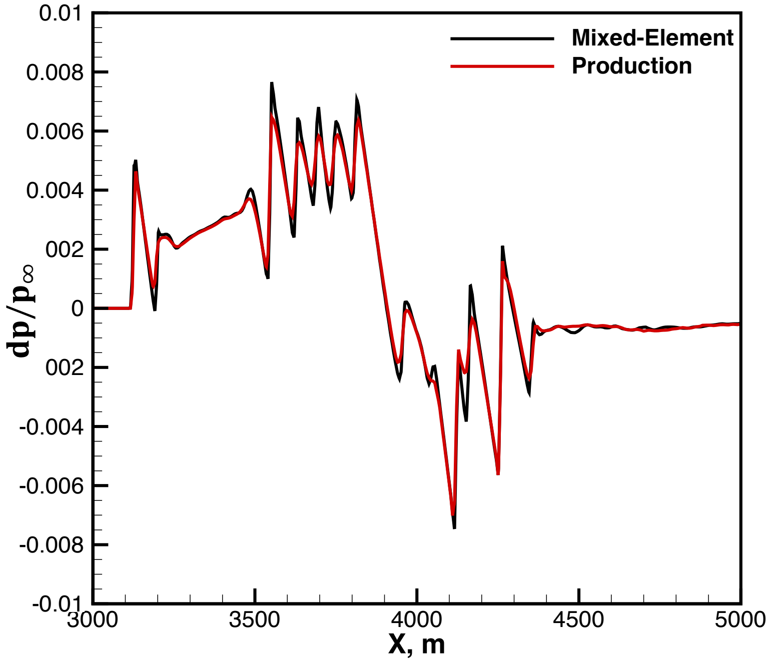


Carpet of Perceived Loudness Levels

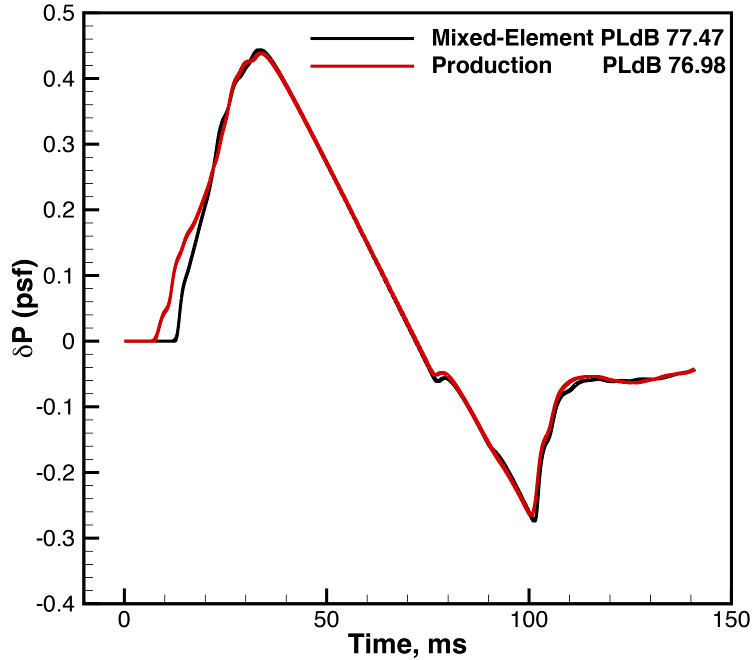
C608 Low Boom Flight Demonstrator

Mixed-Element and Production Versions of USM3D, C608-4 Tetrahedral Grid

$M_\infty = 1.6$, $\alpha = 2.15°$, $H/L = 3$, $Re = 109{,}776$ per in, $\phi = 0°$



Near Field Pressure Signature

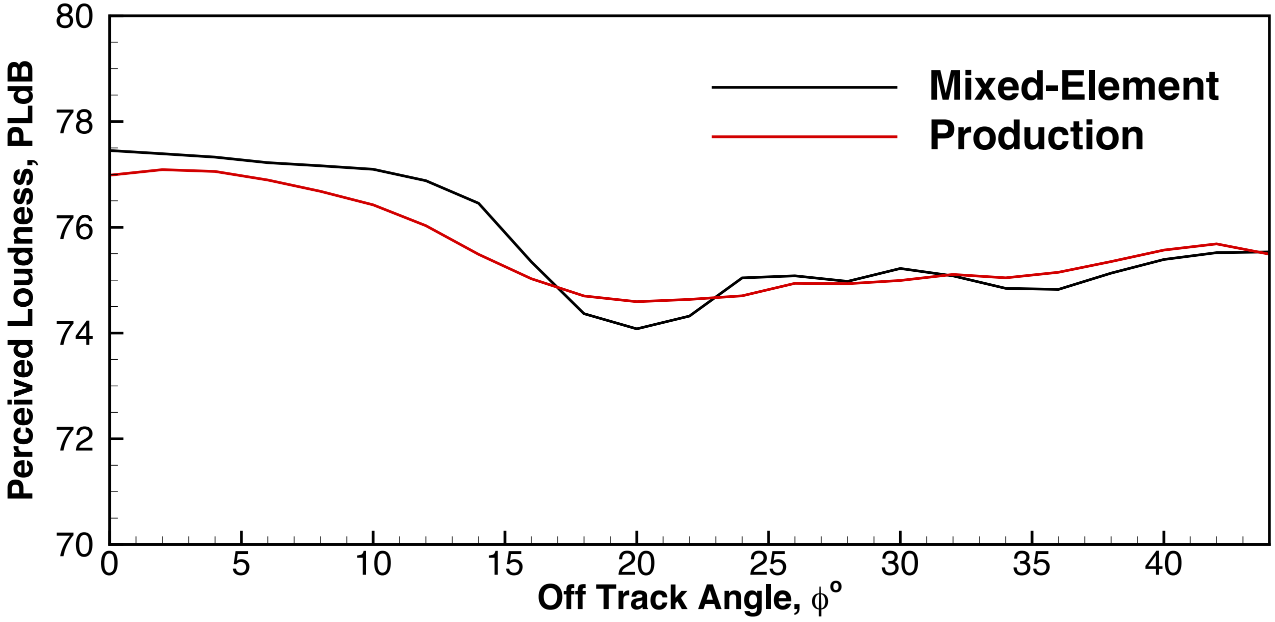


Ground Pressure Signature

C608 Low Boom Flight Demonstrator

Mixed-Element and Production Versions of USM3D, C608-4 Tetrahedral Grid

$M_\infty = 1.6$, $\alpha = 2.15^o$, H/L = 3, Re = 109,776 per in



Carpet of Perceived Loudness Levels

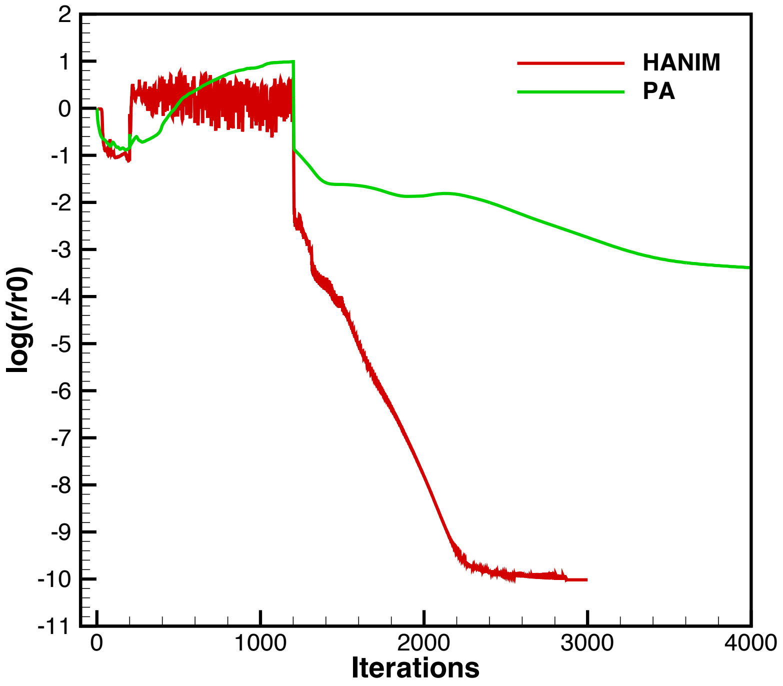
C608 Low Boom Flight Demonstrator

USM3D-(PA vs HANIM) Convergence History

M_∞ = 1.6, α = 0.0º, H/L = 3, Re = 109,776 per in

Simulations performed on 8 Pleiades Ivy Bridge Nodes “160 cores”

C608-4 Tetrahedral grid



Concluding Remarks

- Mixed-element USM3D simulations were conducted on all three SBPW-3 configurations
- sBOOM was used to propagate the nearfield signature to the ground and the loudness levels on the ground were computed
- Results uploaded to sonic boom workshop page
- For all three configurations, USM3D results show:
  - grid convergence on both the mixed-element and tetrahedral family of grids
  - mixed-element grids and the tetrahedral grids are in excellent agreement
  - grid topology has no effect on accuracy of solution
  - PA and HANIM yield identical results

Questions?