Sonic boom benchmark cases validation with FASIP

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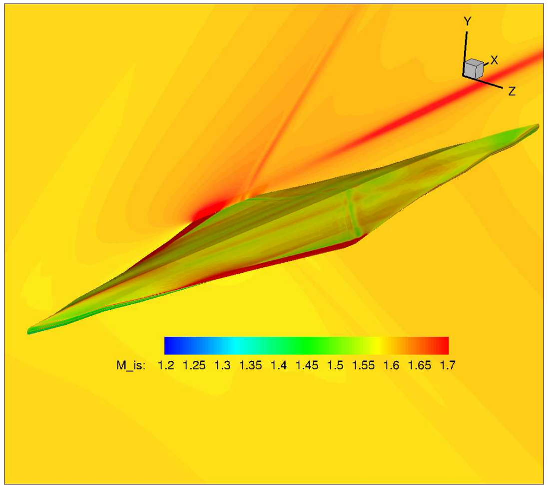
Introduction

- Low boom airplane design

- CFD tools for sonic boom prediction: Cart3d, Fun3d, CFL3d, SU2 and so on

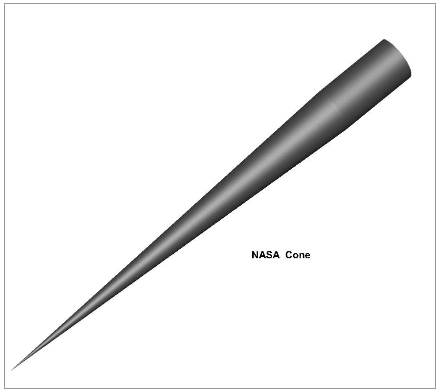
- FASIP for SBiDir-FW desgin

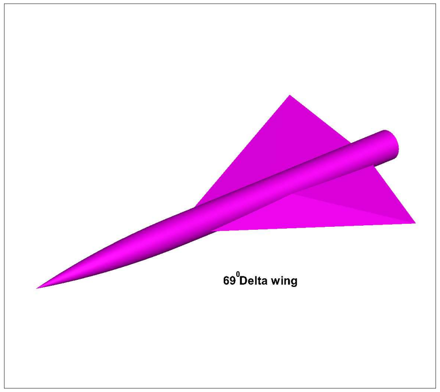
- Assess FASIP code in the prediction of near-field pressure signatures



Summary of cases analyzed

- NASA cone model 1
- SEEB-ALR Body of Revolution
- 69 degree Delta Wing Body





Numerical Strategies

- Euler's equations
- Low Diffusion E-CUSP (LDE) Scheme as an accurate Riemann solver
- The MUSCL, 3rd and 5th Order WENO scheme for the inviscid flux
- High scalability parallel computation*

**Wang et al, Journal of Aerospace Computing, Information, and Communication, V.5, pp.425-447*

Euler's Equations in Generalized Coordinates(ξ, η, ζ)

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{E}}{\partial \xi} + \frac{\partial \mathbf{F}}{\partial \eta} + \frac{\partial \mathbf{G}}{\partial \zeta} = 0$$

where

$$\mathbf{E} = \begin{pmatrix} \bar{\rho} U \\ \bar{\rho}\tilde{u}U + l_x \bar{p} \\ \bar{\rho}\tilde{v}U + l_y \bar{p} \\ \bar{\rho}\tilde{w}U + l_z \bar{p} \\ (\bar{\rho}\tilde{e} + \bar{p})\, U - l_t \bar{p} \\ \bar{\rho}\tilde{\nu}U \end{pmatrix}$$

$$
\begin{aligned}
U &= l_t + \mathbf{l} \bullet \mathbf{V} = l_t + l_x u + l_y v + l_z w \\
V &= m_t + \mathbf{m} \bullet \mathbf{V} = m_t + m_x u + m_y v + m_z w \\
W &= n_t + \mathbf{n} \bullet \mathbf{V} = n_t + n_x u + n_y v + n_z w
\end{aligned}
$$

$$
\mathbf{l} = \frac{\nabla \xi}{J} \mathrm{d}\eta \mathrm{d}\zeta, \ \mathbf{m} = \frac{\nabla \eta}{J} \mathrm{d}\xi \mathrm{d}\zeta, \ \mathbf{n} = \frac{\nabla \zeta}{J} \mathrm{d}\xi \mathrm{d}\eta
$$

$$
l_t = \frac{\xi_t}{J} \mathrm{d}\eta \mathrm{d}\zeta, \ m_t = \frac{\eta_t}{J} \mathrm{d}\xi \mathrm{d}\zeta, \ n_t = \frac{\zeta_t}{J} \mathrm{d}\xi \mathrm{d}\eta
$$

$$
J = \frac{\partial(\xi, \eta, \zeta)}{\partial(x, y, z)} = \frac{1}{x_\xi (y_\eta z_\zeta - y_\zeta z_\eta) - x_\eta (y_\xi z_\zeta - y_\zeta z_\xi) + x_\zeta (y_\xi z_\eta - y_\eta z_\xi)}
$$

The Low Diffusion E-CUSP* (LDE) Scheme†

• The basic idea of the LDE scheme is to split the inviscid flux into the convective flux E^c and the pressure flux E^p

$$\mathbf{E} = E^c + E^p = \begin{pmatrix} \rho U \\ \rho u U \\ \rho v U \\ \rho w U \\ \rho e U \\ \rho \tilde{\nu} U \end{pmatrix} + \begin{pmatrix} 0 \\ l_x p \\ l_y p \\ l_z p \\ p\overline{U} \\ 0 \end{pmatrix}$$

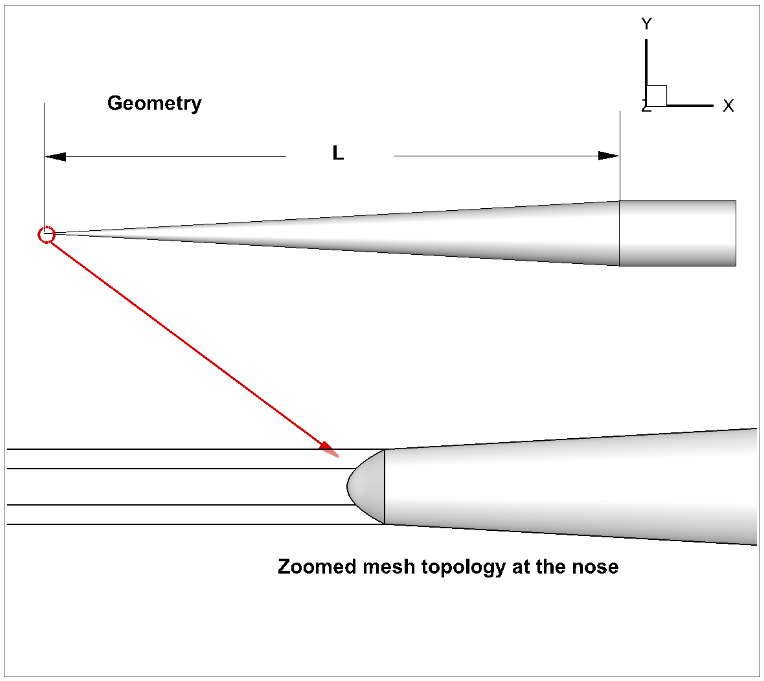
• Ability to capture crisp shock and contact discontinuities

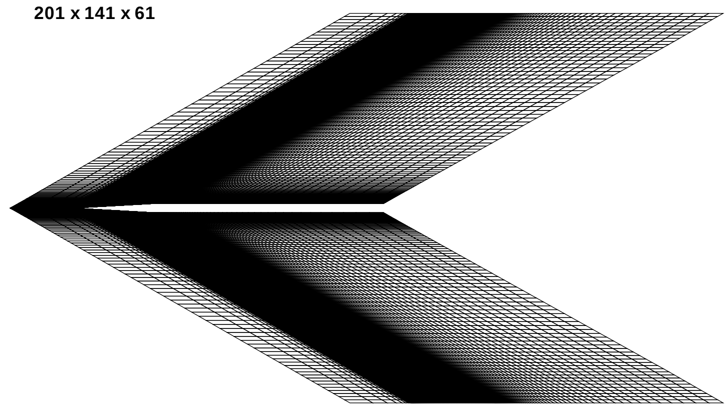
• Simpler and more CPU efficient than Roe scheme

*Convective Upwind and Split Pressure

†*G. Zha, A Low Diffusion Efficient Upwind Scheme, AIAA J. V.43, pp.1137-1140, 2005*

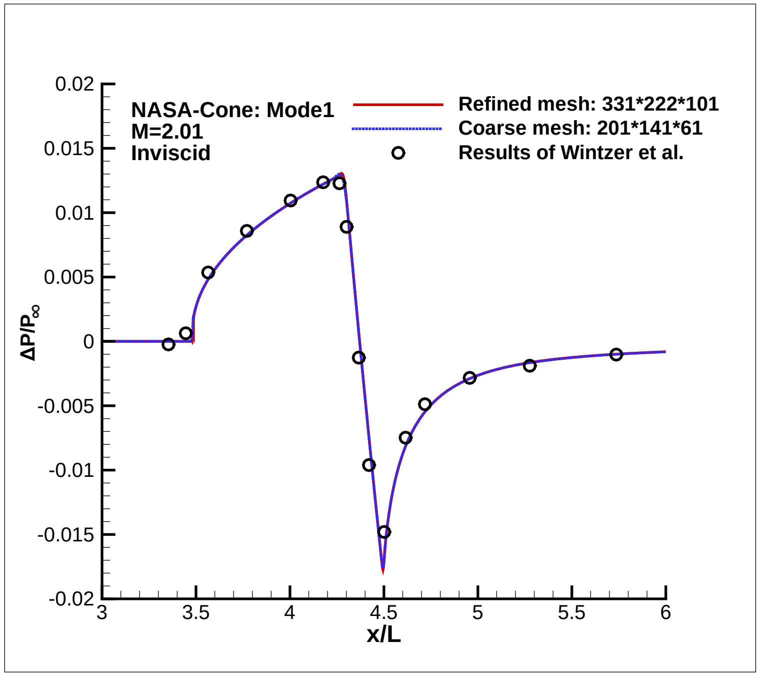
NASA cone: Model 1





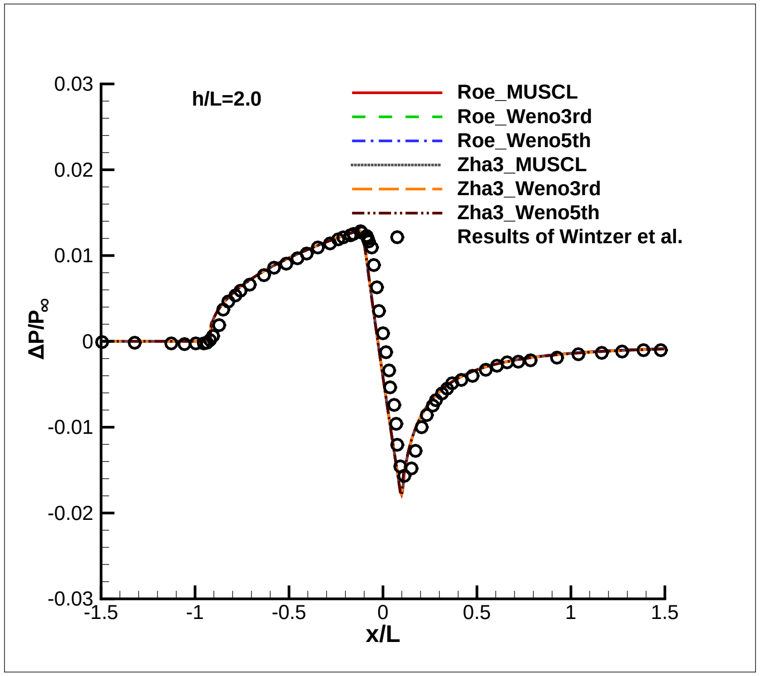
Sharp tip is replaced with a tiny semi-sphere
O-type mesh topology
Grid alignment with mach angle
Coarse mesh size: 1.72 million; Refined mesh size: 7.42 million

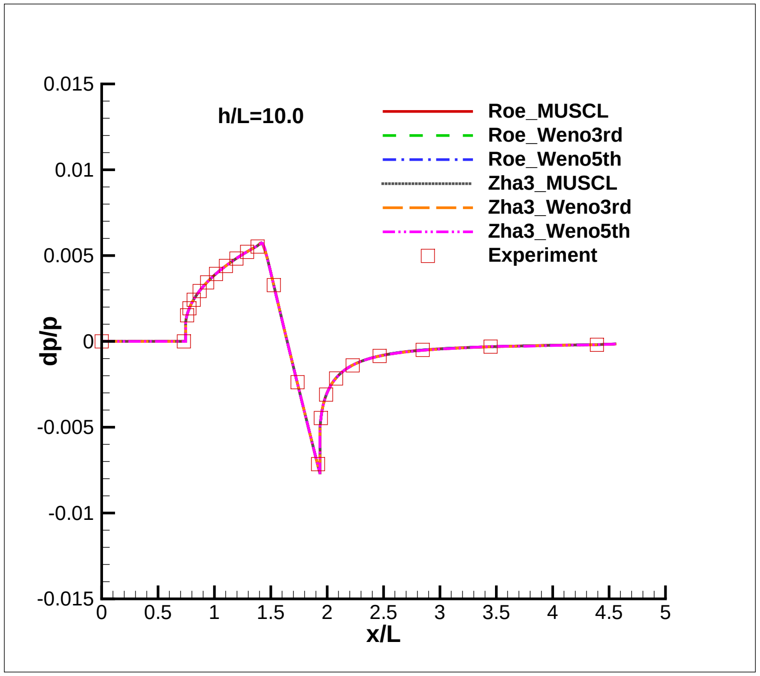
NASA cone *



*Extracted near field signatures at 2 body length below.
Coarse mesh: 1.72 million; Refined mesh: 7.42 million

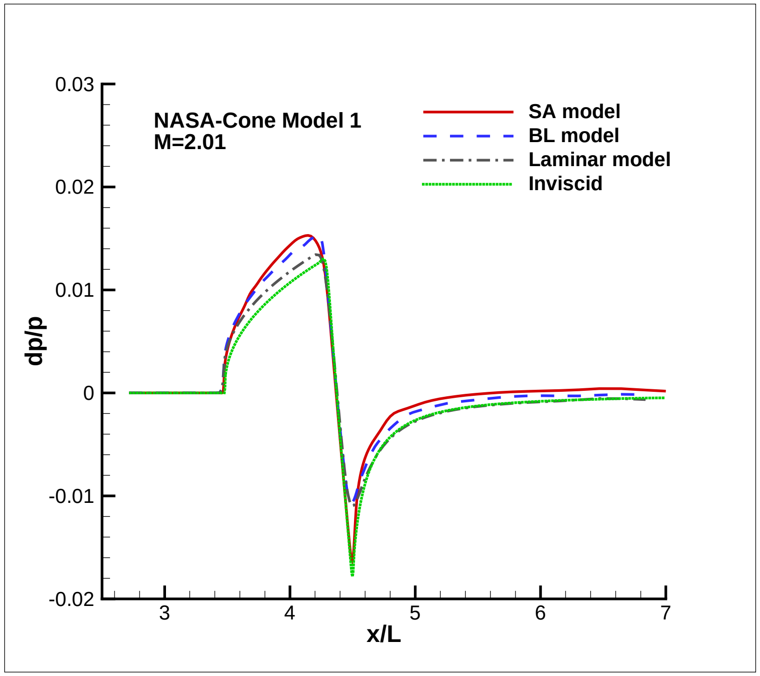
NASA cone *





*Extracted near field signatures with different schemes, left: 2 body below; right: 10 body below

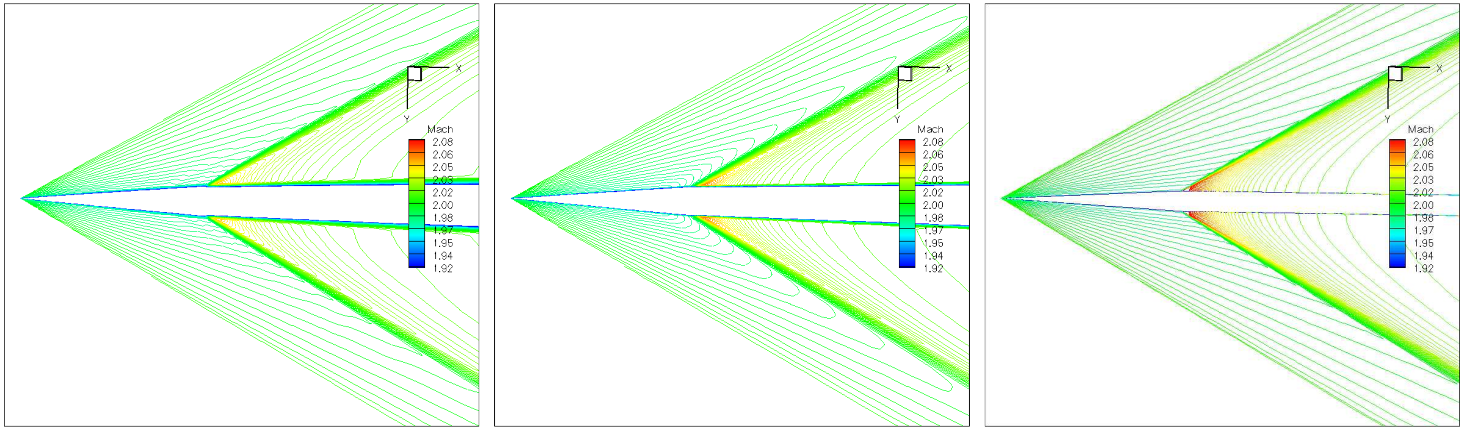
NASA cone *



*Extracted near field signatures with different turbulent modeling

NASA cone *

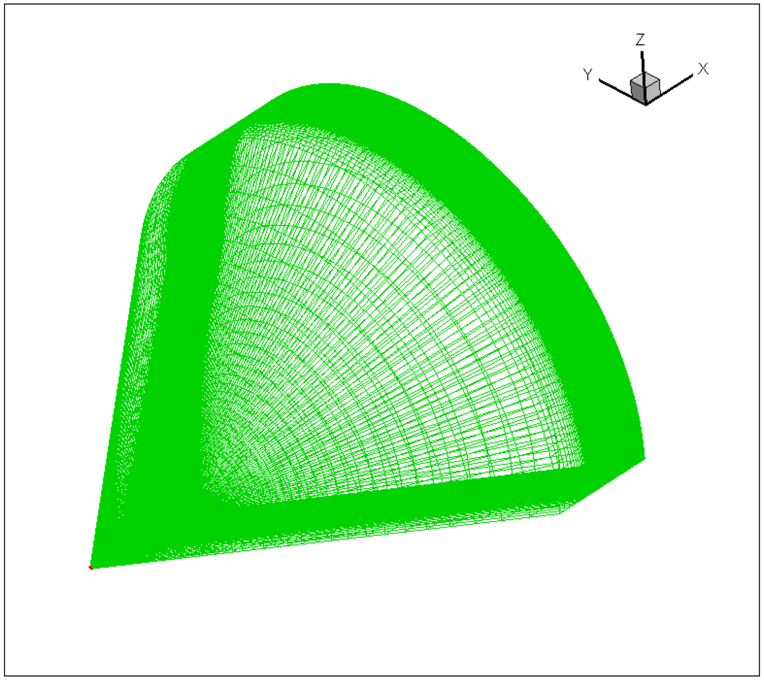
Left: Baldwin-Lomax model; Middle: Spalart-Allmaras model; Right: Inviscid

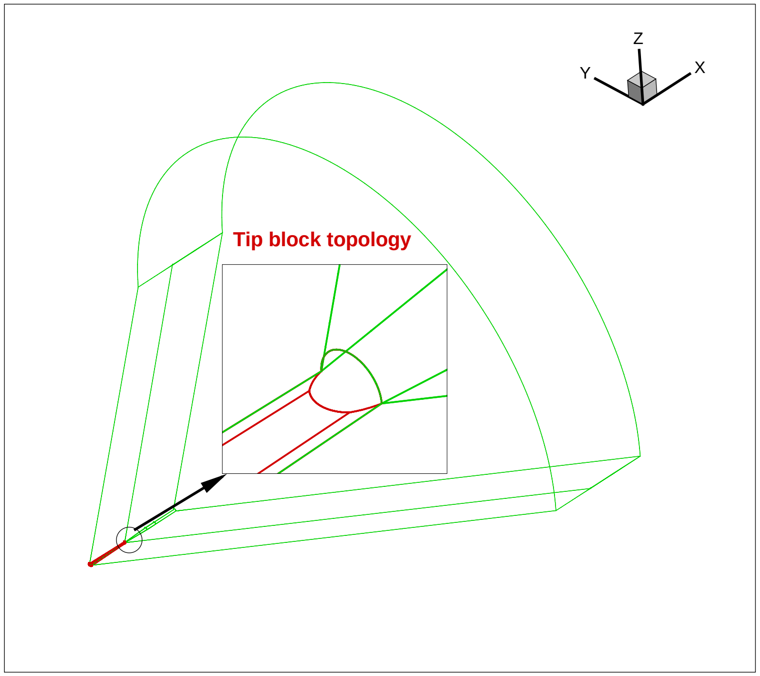


*Mach number contours compared with different turbulent modeling method

SEEB-ALR Body of Revolution

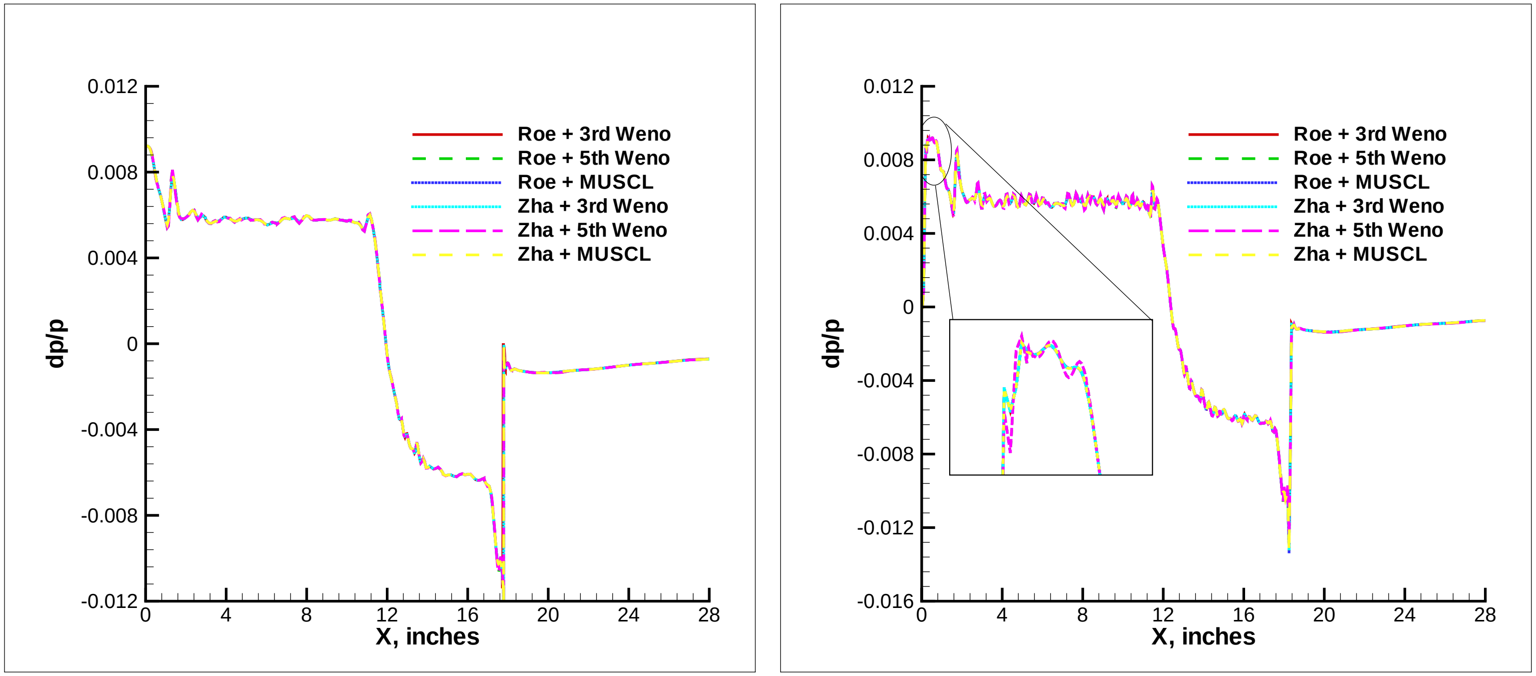
Axisymmetric body designed by Lockheed Martin and features of a flat-top signature
Free stream M=1.6, Gama=1.4





O-type mesh topology; Grid alignment with mach angle
Coarse mesh size: 65*97*353=2225665; Refined mesh size: 97*129*593=7420209

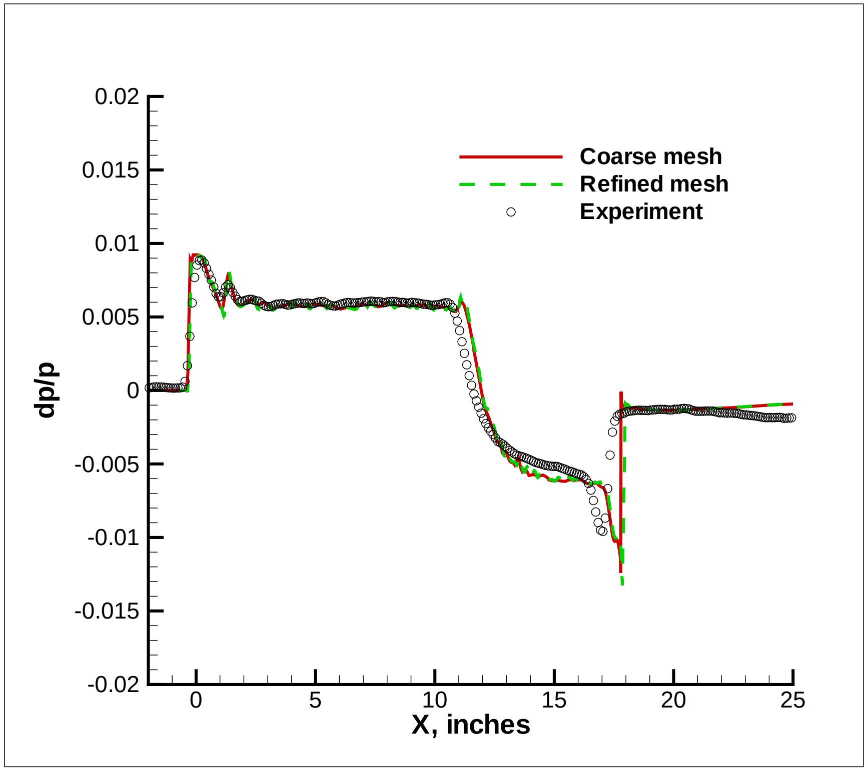
SEEB-ALR *



*Extracted near field signatures at h=21.2 inches with different schemes, left: coarse mesh; right: refined mesh

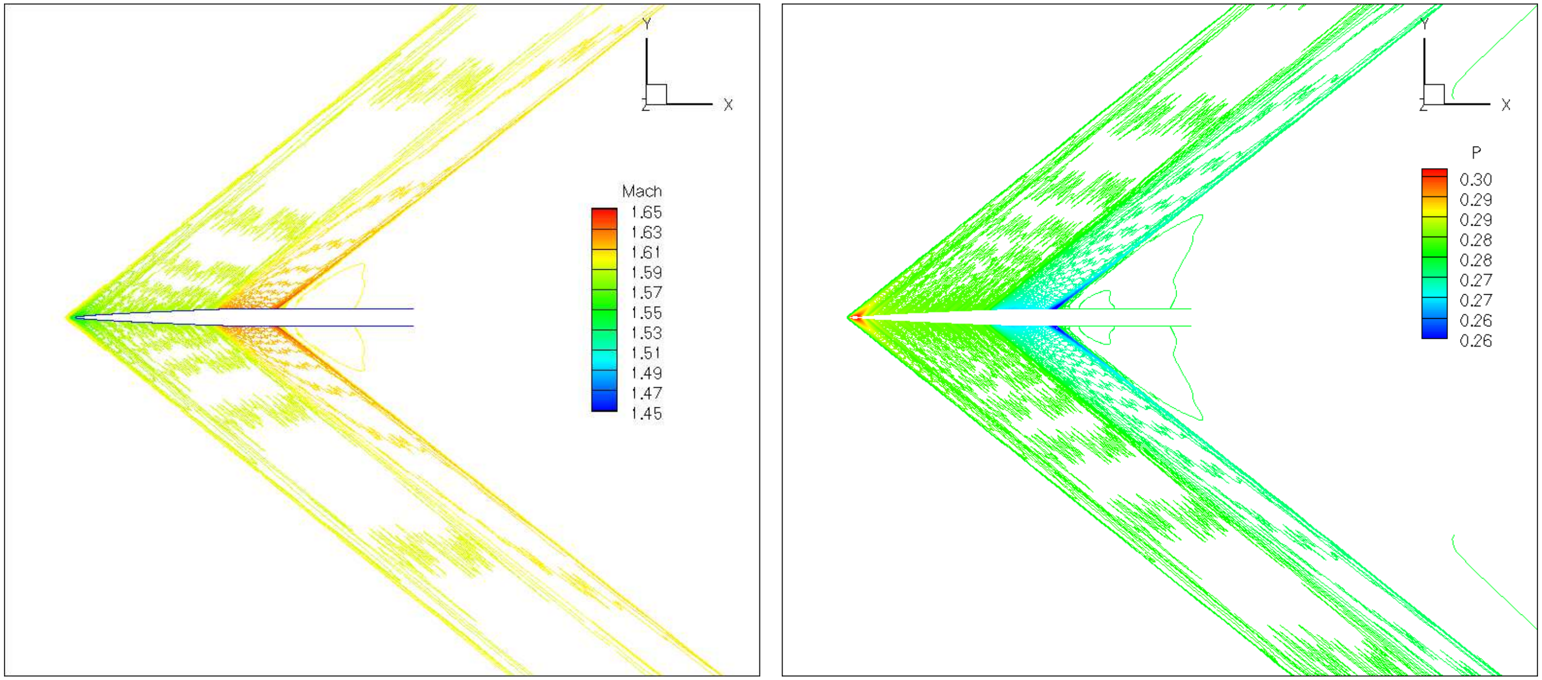
SEEB-ALR *

Signatures at h=21.2 inches



*Mesh resolution comparisions with the 3rd-Weno schemes

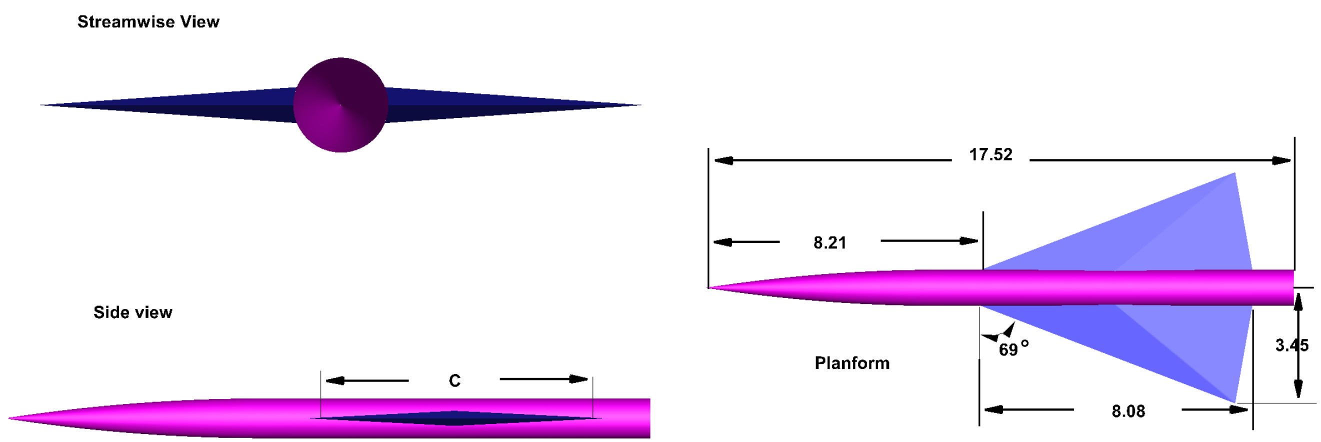
SEEB-ALR *



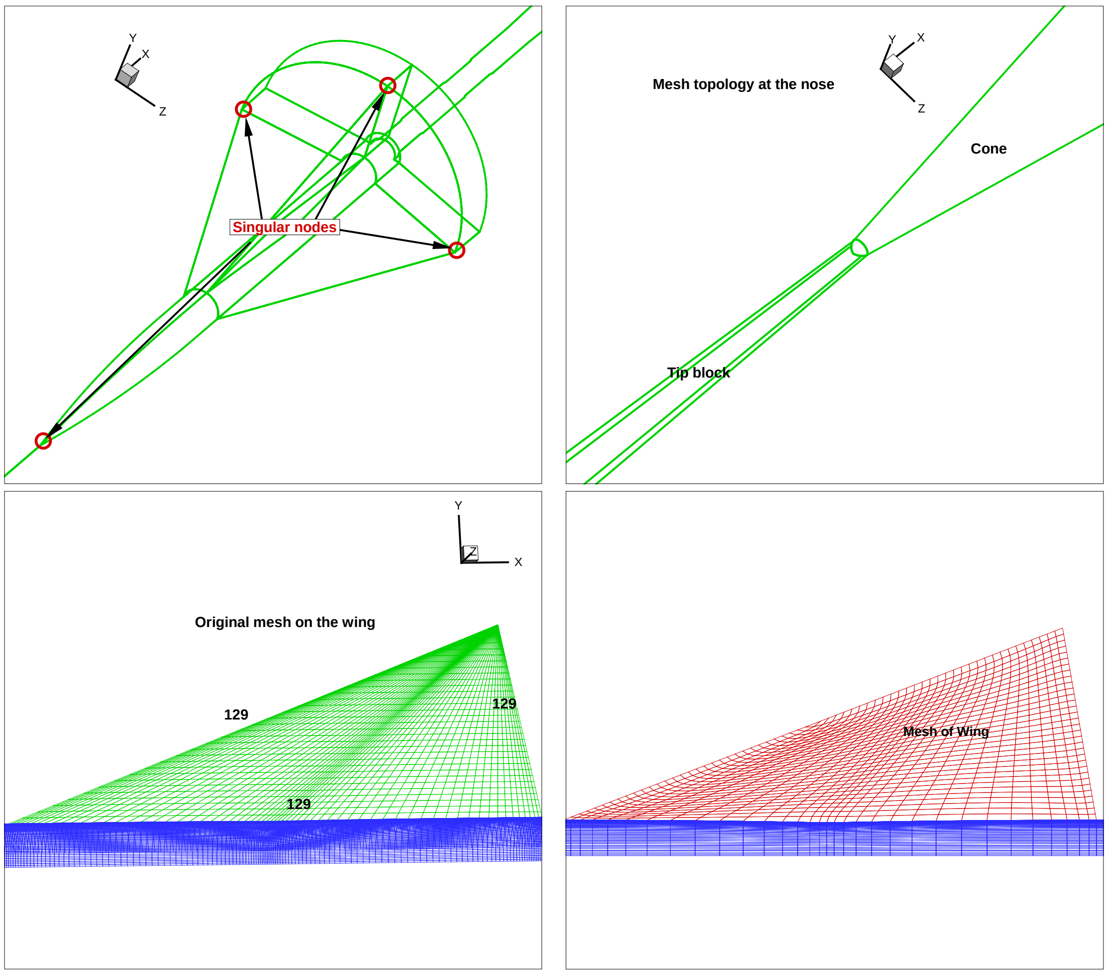
*Countour plots, left: Mach line; right: pressure line

69^o Delta Wing Body

- M=1.7, Gama=1.4
- Angle of Attack(AoA): 0.0, 2.079, 3.588, 4.74
- Extracted near field at H=21.2, 24.8, 31.8 inches below the model
- Geometry:

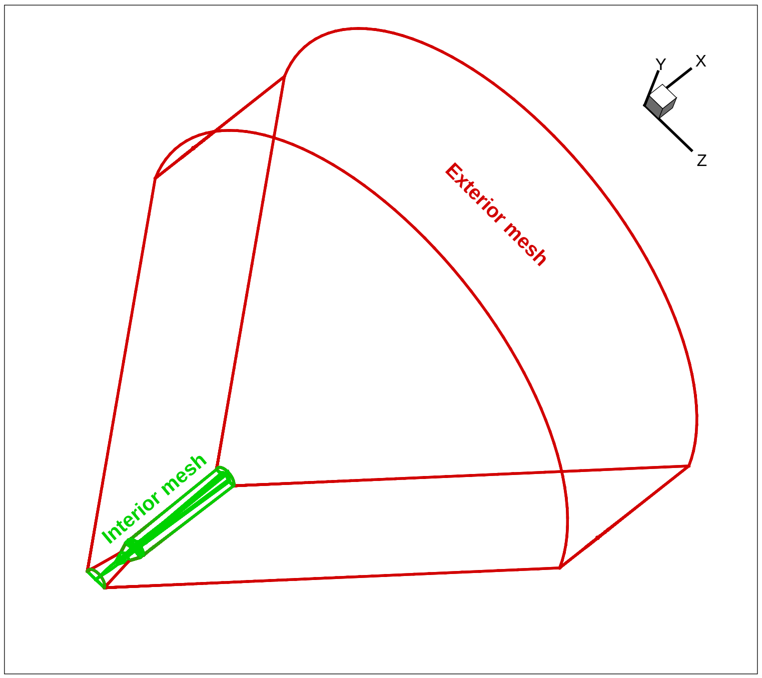


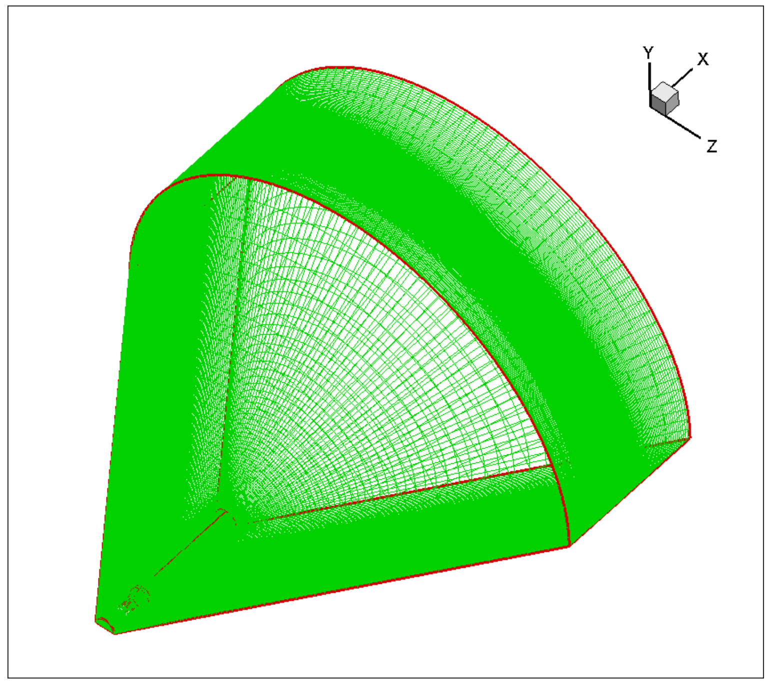
Mesh of Delta wing *



*Mesh regeneration: remove the singular node

Mesh of Delta wing *

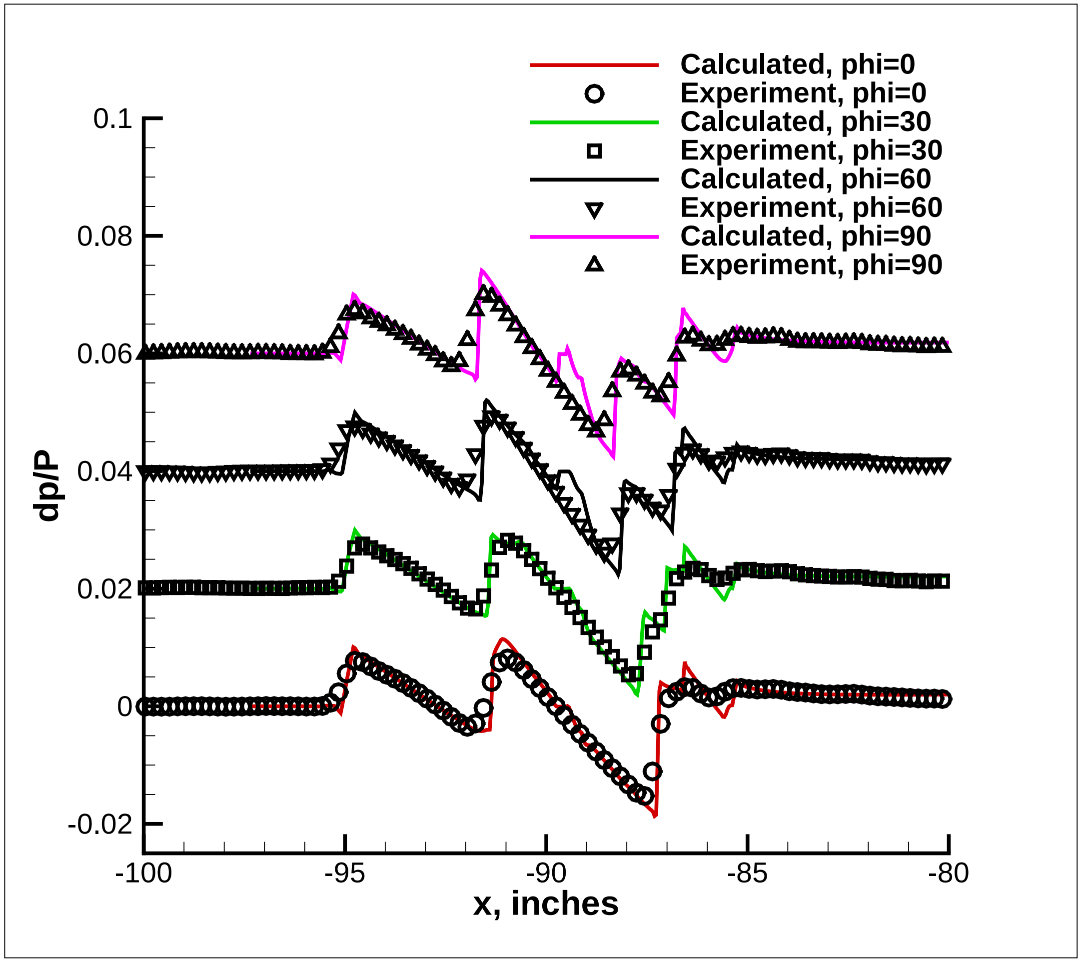




*The grids near the body are regenerated. The external grids are the same as that of provoided by the workshop

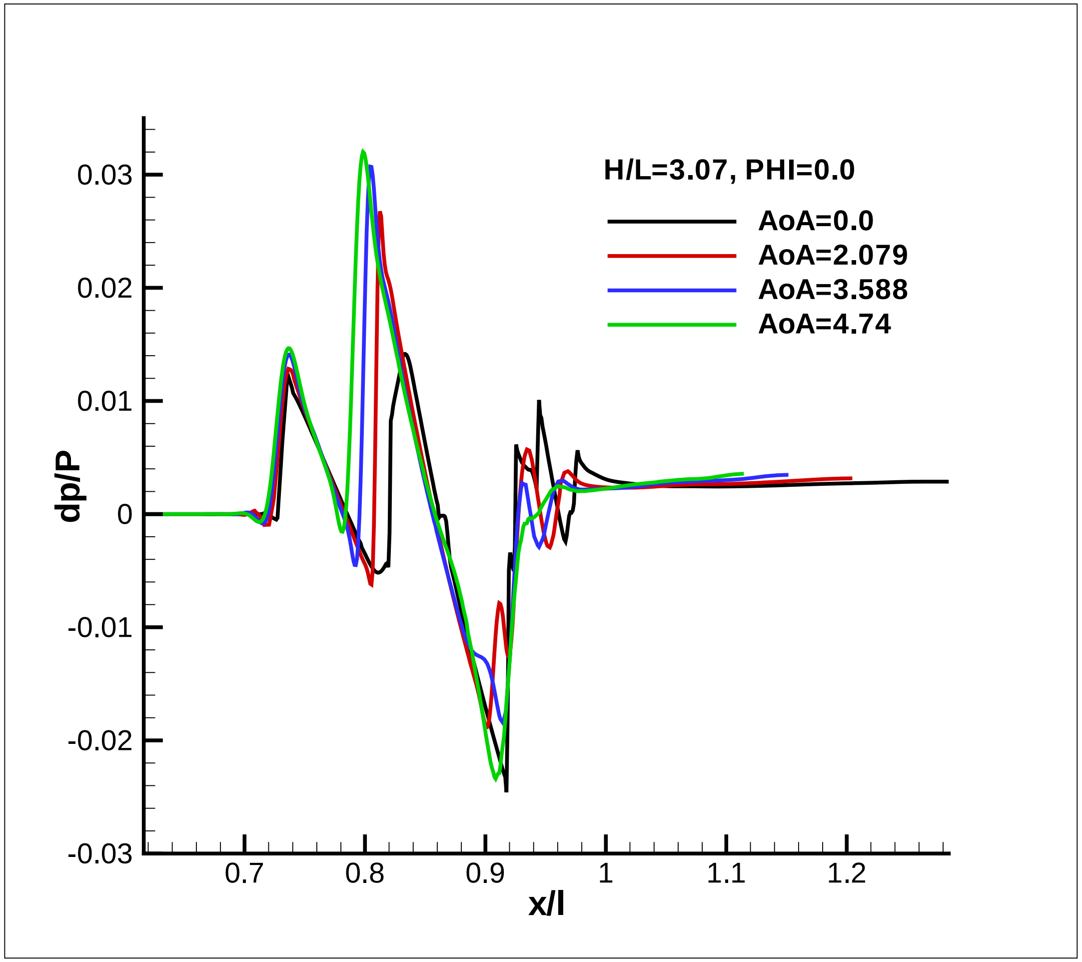
Extracted signatures: AoA=0.0, h=31.8 inches(h/l=4.6)

*

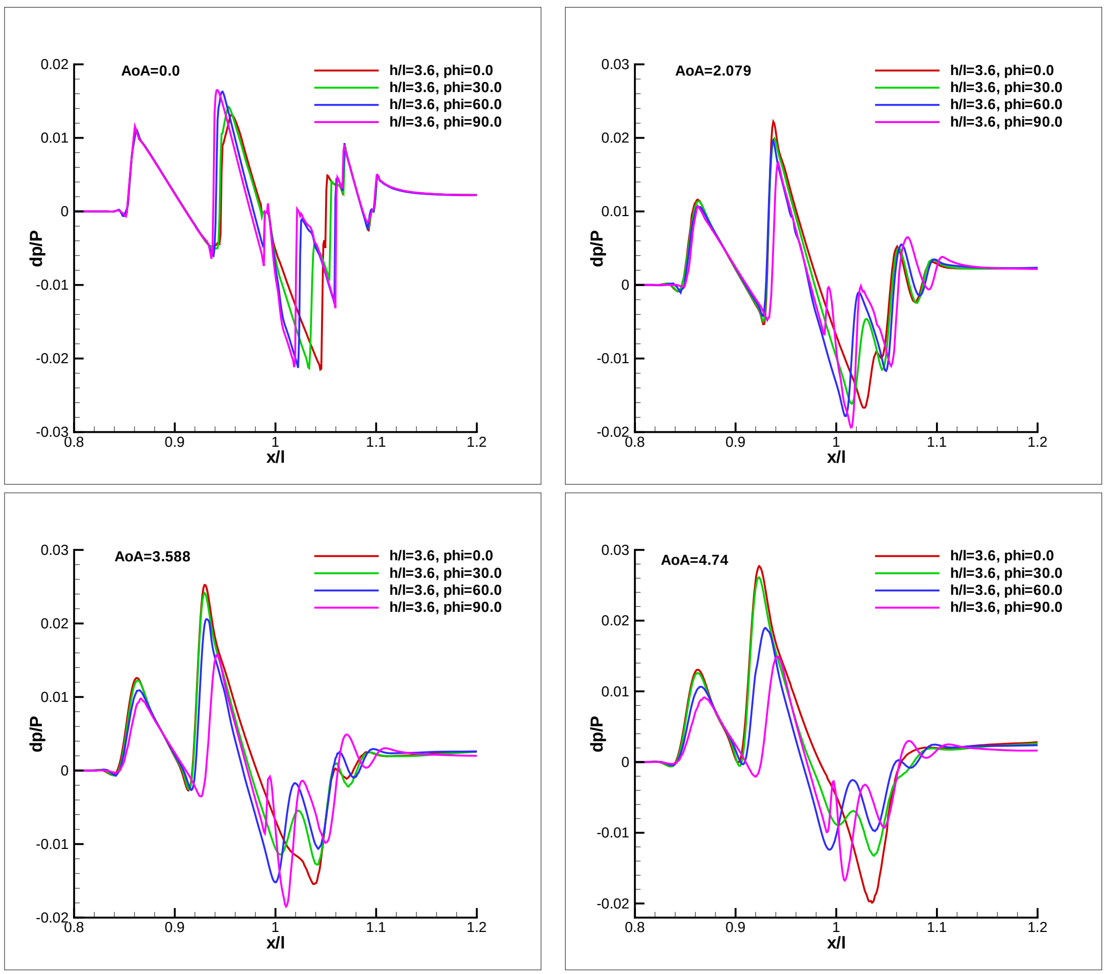


*Curves are offset by 0.02 for each signal with phi larger than 0.0

Extracted signature comparisons with different AoA at h=21.2 inches(h/l=3.07)

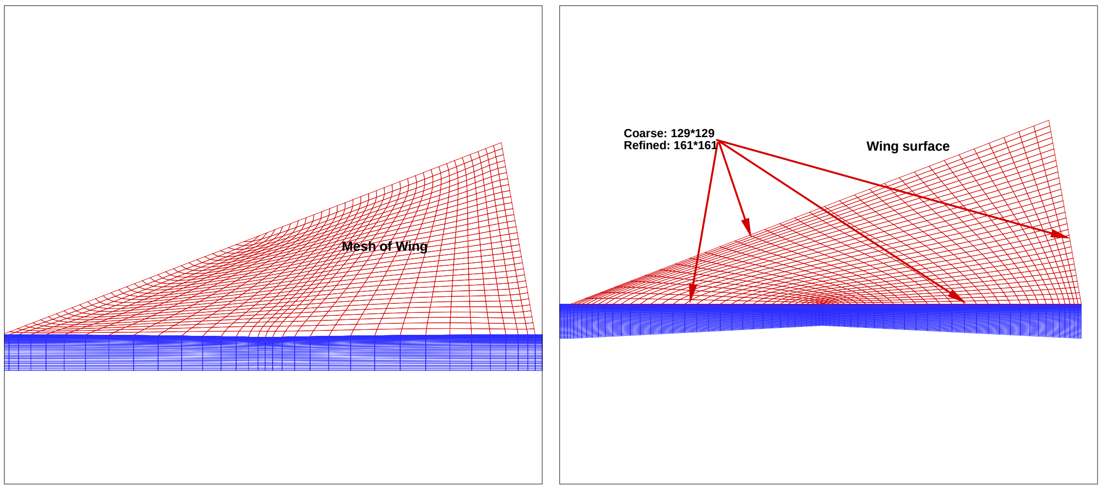


Extracted signature comparisons with different AoA at h/l=3.6(h=24.8 inches)



Change of mesh topology on the wing surface

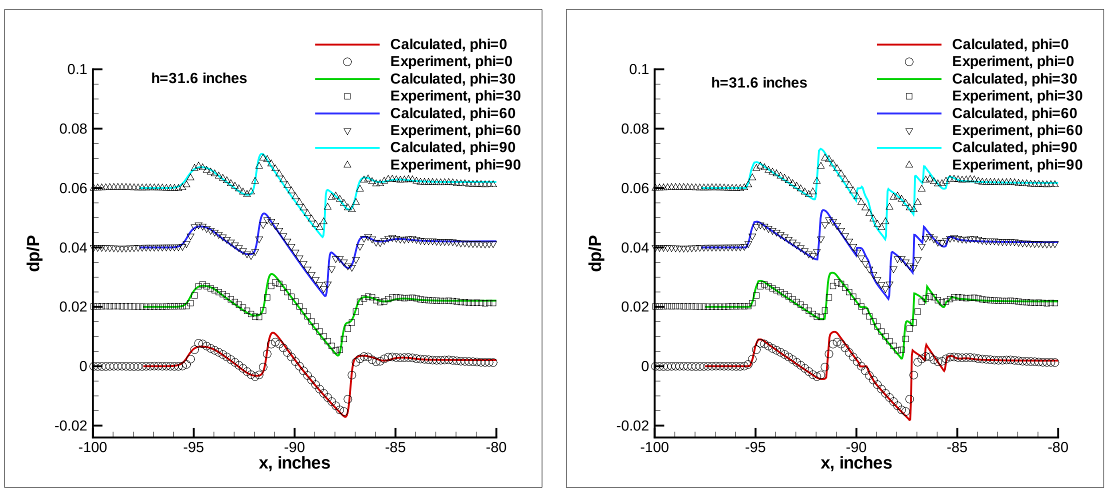
Comparison of the edges splitting:
- Splitting the leadging edge will double the mesh size away from the wing
- Splitting the edge connected to the body can keep the mesh size as the original mesh
- Coarse mesh: 12.21 million grid points with 174 blocks; Refined mesh: 24.04 million grid points with 313 blocks.



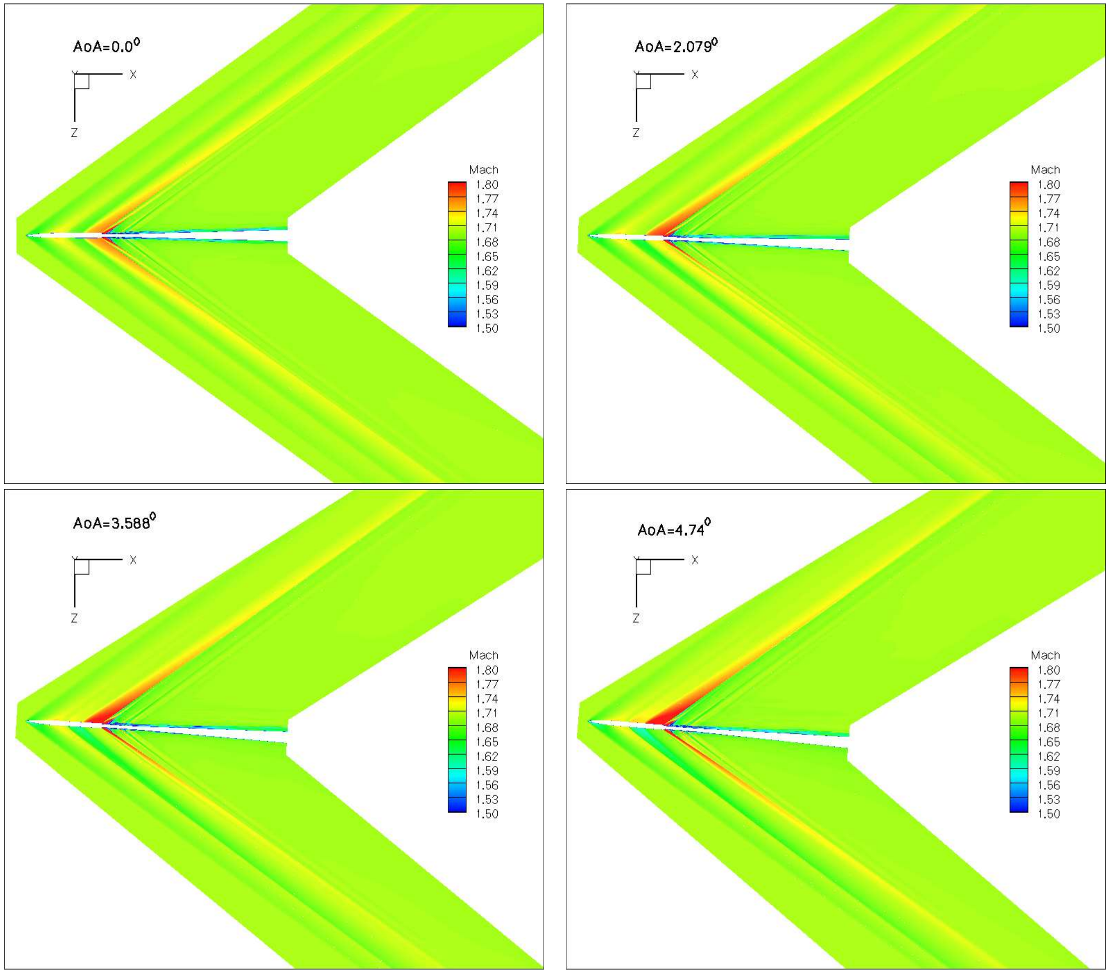
Extracted signature comparisons with different mesh sizes

AoA=0, h=31.6 inches

Left: coarse mesh with 129*129 on the wing. Right: Refined mesh with 161*161 on the wing

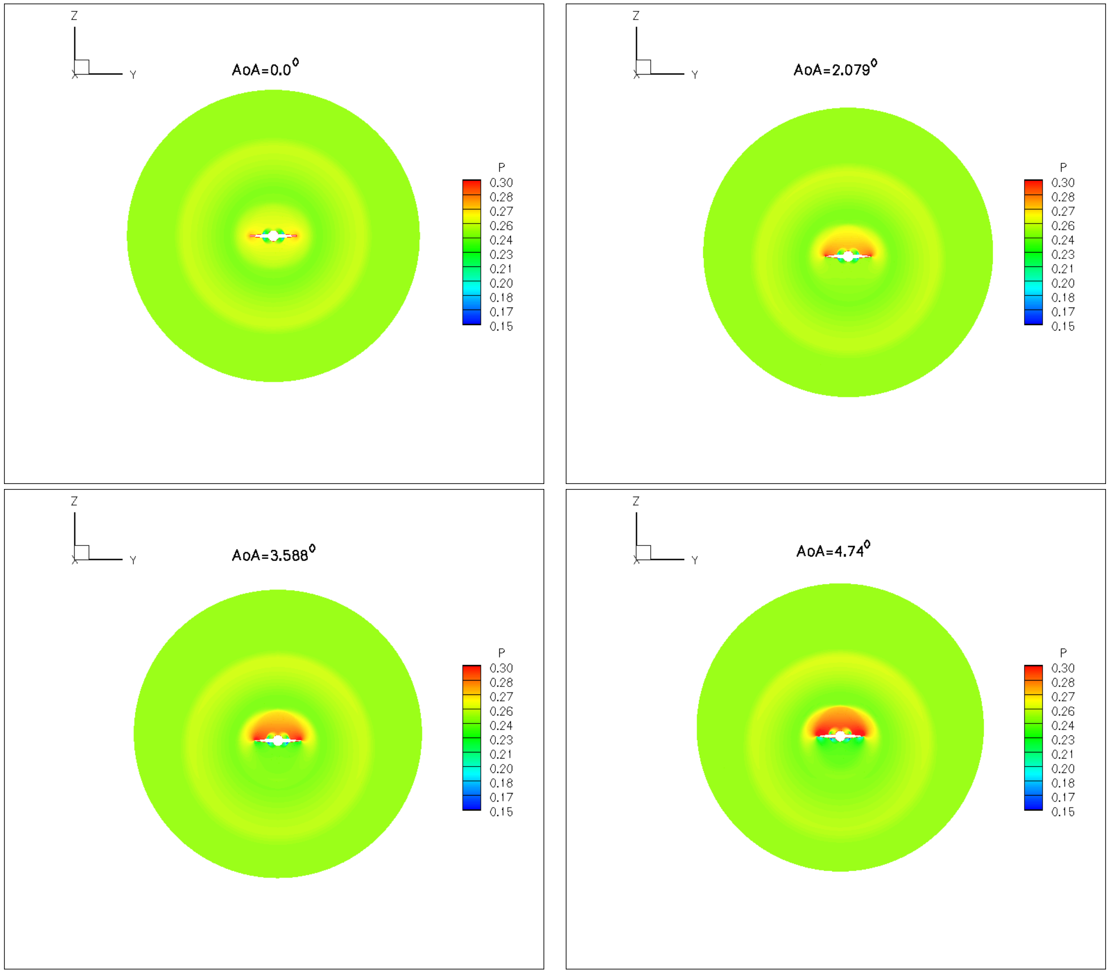


Mach contours varied with AoA in streamwise *

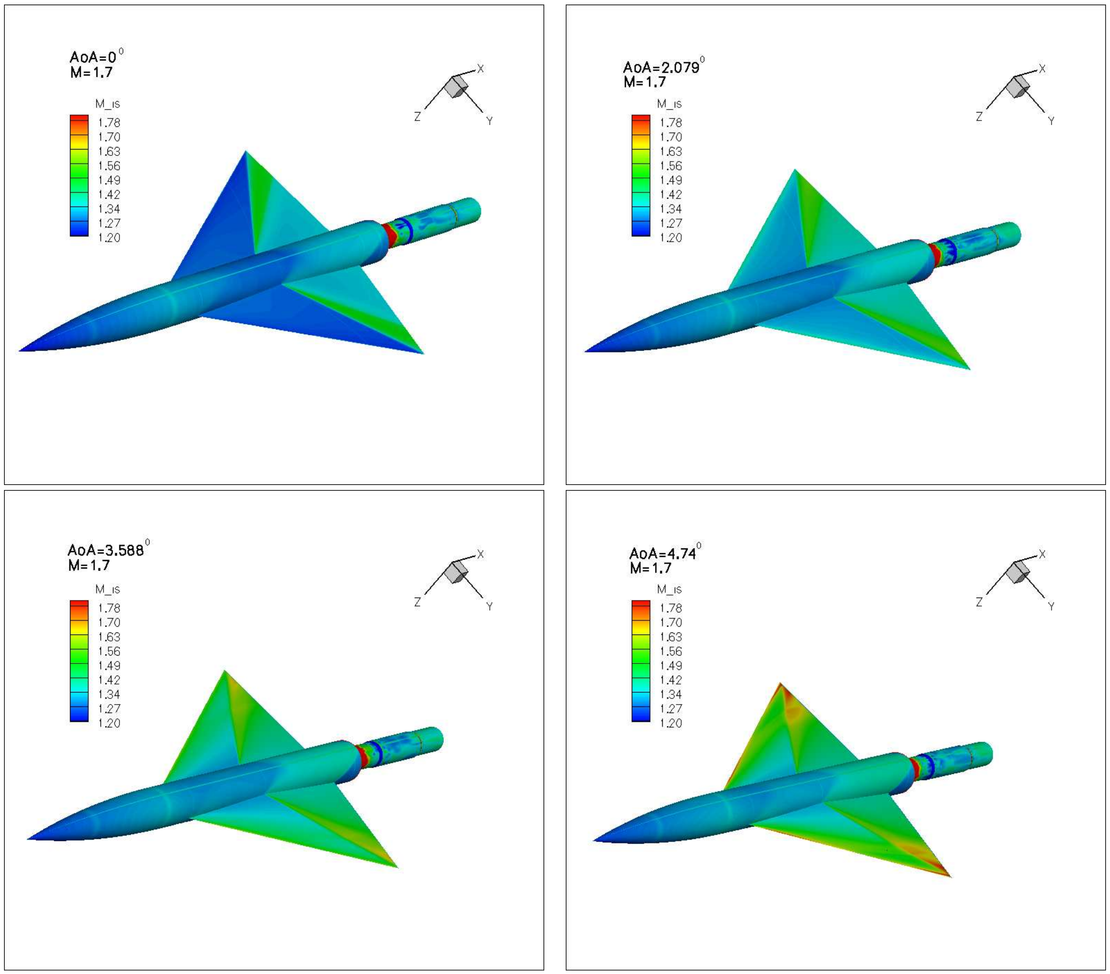


*Top left: AoA=0.0; Top right: AoA=2.079; Bottom left: AoA=3.588; Bottom right: AoA=4.74

Pressure contours varied with AoA cross the wing



Isentropic mach number distribution around the body surface



Conclusion

- Near field pressure can be predicted well with Euler equations
- A inclined mesh matched the Mach cone angle is needed to predict the strength of the shock wave accurately
- Mesh refinement on the location of shock wave is needed to capture the shock wave accurately.

Thank you !