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 design
- 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*

Euler’s Equations in Generalized Coordinates $(\xi, \eta, \zeta)$

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

where

$$E = \begin{pmatrix} \vec{\rho} U \\ \vec{\rho} \vec{u} U + l_x \vec{p} \\ \vec{\rho} \vec{v} U + l_y \vec{p} \\ \vec{\rho} \vec{w} U + l_z \vec{p} \\ (\vec{\rho} \vec{e} + \vec{p}) U - l_t \vec{p} \\ \vec{\rho} \vec{v} U \end{pmatrix}$$
\[ U = l_t + l \cdot V = l_t + l_xu + l_yv + l_zw \]
\[ V = m_t + m \cdot V = m_t + m_xu + m_yv + m_zw \]
\[ W = n_t + n \cdot V = n_t + n_xu + n_yv + n_zw \]

\[ l = \frac{\nabla \xi}{J} d\eta d\zeta, \quad m = \frac{\nabla \eta}{J} d\xi d\zeta, \quad n = \frac{\nabla \zeta}{J} d\xi d\eta \]

\[ l_t = \frac{\xi_t}{J} d\eta d\zeta, \quad m_t = \frac{\eta_t}{J} d\xi d\zeta, \quad n_t = \frac{\zeta_t}{J} d\xi d\eta \]

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

$$E = E^c + E^p = \begin{pmatrix} \rho U \\ \rho uU \\ \rho vU \\ \rho wU \\ \rho eU \\ \rho \tilde{v}U \end{pmatrix} + \begin{pmatrix} 0 \\ l_xp \\ l_yp \\ l_zp \\ p\bar{U} \\ 0 \end{pmatrix}$$

- 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
*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*
*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 $M=1.6$, $\gamma=1.4$

O-type mesh topology; Grid alignment with mach angle
Coarse mesh size: $65 \times 97 \times 353 = 2225665$; Refined mesh size: $97 \times 129 \times 593 = 7420209$
*Extracted near field signatures at $h=21.2$ inches with different schemes, left: coarse mesh; right: refined mesh*
Signatures at $h=21.2$ inches

*Mesh resolution comparisons with the 3rd-Weno schemes*
**SEEB-ALR**

*Contour plots, left: Mach line; right: pressure line*
69° 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 provided 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 leading 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: Re-fined 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!