Nearfield Summary and Statistical Analysis of the Second AIAA Sonic Boom Prediction Workshop

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Motivation

• Commercial supersonic overland flight is currently prohibited
  – Supersonic overland flight is an enabler for entry into new vehicle market
• An international effort to quantify the accuracy and reliability of prediction methods supports the replacement the prohibition with a certification standard
• Deficiencies in existing methods should be noted to focus research on addressing weaknesses
Motivation

• Nearfield CFD is part of sonic boom prediction
• Impartially compare signatures by uniform investigation of
  – Propagation and Loudness measures
  – Grid refinement
  – Statistics
Models and Cases

• Designed to produce similar signatures with a range of simulation complexity
• Mach 1.6
• Euler and Reynolds-averaged Navier-Stokes (RANS) at flight unit Reynolds number of 5.7 million per meter requested
• US Standard atmosphere at 15,760 meter altitude
• Propulsion boundary conditions provided
C25F (shown) and C25P

- C25F flow-through nacelle (required)
- C25P powered configurations (optional)

Developed in AIAA-2016-2260 and AIAA-2016-2261 with Euler method
JWB

• Inverse design to recover C25F equivalent area distribution by JAXA with Euler and panel methods
AXIE

- Inverse design to recover C25F nearfield at 3 body lengths by Anderson and Aftosmis with Euler method
Nearfield Ensemble Mean R=3, PHI=0°
C25P Pressure Disturbance

dp/p_{inf}
C25F Pressure Disturbance

dp/pinf
JWB Pressure Disturbance

dp/p_{\infty}
AXIE Pressure Disturbance

dp/p_{inf}
AXIE, C25F, and C25P Provided Grids

• Mixed element and tetrahedra only families of core grids with semistructured Mach-aligned collar grids (same as SBPW1, see AIAA-2014-115)
  – 0.6 to 56 million node Euler AXIE (5)
  – 3-104 million node Euler C25F (6)
  – 5-138 million node viscous C25F (6)
  – 3-52 million node Euler C25P (5)
  – 5-70 million node viscous C25P (5)
JWB Provided Grids

- HeldenMesh generated surface and tetrahedral volume grids with anisotropic Mach-aligned spacing function in a single grid topology
  - 6, 11, and 18 million node Euler JWB (3)
Participant Grids

• Participants also provided grids based on their best practices
  – Grids received before the workshop were available as optional grids

• A series of three grids was requested from participants with adaptive methods
  – Final grid and two coarser intermediates
Loudness and Annoyance

• Subjective metrics

• These human experiences are correlated to noise descriptors through experiments
  – Leatherwood et al. JASA 2002
  – Stevens Mark VII Perceived Level (PL)
Expected Grid Convergence

• Consistent methods should approach a value as the grid is refined to “zero” \( h \) (inverse cube root of CFD control volumes, propagation fixed)
• Participant D reported that the collar grid construction was not optimal for their solver
• Participant C reported iterative convergence difficulties in the collar grid, but not at the extraction location
AXIE Grid Convergence, R=5

- A norm of the signature is treated like the PL scalar and the signature is pointwise extrapolated (Richardson, Roache) from three grids to infinitely refined grid (h=0)
- The red area is the extrapolation, largest at shocks
• A norm of the signature is treated like the PL scalar and the signature is pointwise extrapolated (Richardson, Roache) from three grids to infinitely refined grid (h=0)
• The red area is the extrapolation, confirming divergence
JWB PL Grid Convergence, PHI=10°

- JWB has the strongest expansion and extraction distance sensitivity
- JWB grid construction different from other models
- JWB showed the greatest reconstruction limiter sensitivity
• Trend change for the finer meshes (new physics)
• RANS has more fine grid variation than Euler (smaller grids)
• C25P has similar trends (when updates after the workshop included)
Statistical Method

• Goal is to identify “different” results, not “correct” or “wrong”

• Box (half of submissions) and whisker plots (95% coverage for normal distribution)

• Used by Drag Prediction Workshop (AIAA-2017-1209)
PL Euler from R=3

AXIE
N = 17

JWB
N = 14

C25F
N = 17

C25P
N = 6
C25F and C25P from R=3

C25F RANS
N = 15

C25P RANS
N = 9

C25F Euler
N = 17

C25P Euler
N = 6
Progress Since SBPW1

• Much quieter mean PL (dB)
  – SBPW1: 91.8 axisymmetric, 95.5 wing body
  – SBPW2: 77.7 axisymmetric, 79.4 wing body

• Standard deviation is difficult to compare, PL (dB) is logarithmic
  – SBPW1: 0.3 axisymmetric, 0.2 wing body
  – SBPW2: 0.6 axisymmetric, 1.4 wing body

• More complex and more submissions
  – Statistics for required full configuration
  – Optional propulsion boundary condition case
LM1021 PL Carpet, R=1.4

\( \Phi \) (degrees)

PL (dB)

0 10 20 30 40 50 60

84 85 86 87 88 89 90 91 92 93 94 95

1A 2B 3C 4C 5C 6C 7E 8M 9O 10Q 11Q
C25F RANS PL Carpet, R=1

N = 15
C25F Euler PL Carpet, R=1

N = 17
Conclusions

• PL trends with grid refinement were shown for the AXIE, JWB, and C25F
  – AXIE convergence the best with outliers at R=5
  – AXIE observations at R=5 confirmed with examination of nearfield signature convergence
  – JWB had a larger variation than the more complex C25F
Conclusions

• PL statistics visualized with box and whisker plots
  – Euler and RANS analyzed separately when sufficient samples available
  – The size of the box (middle 50%) was largest for the JWB Euler
  – RANS has larger box than Euler for C25F and C25P
Conclusions

• Progress made since the first workshop identified
  – Simple cases much quieter
  – JWB had a larger standard deviation, but PL logarithmic
  – Statistics available for complex C25F and C25P
In the Paper

• Grid convergence of nearfield submissions
  – Confirms and explains the trends shown in PL

• Pointwise mean and standard deviation of nearfield submissions
  – Euler and RANS nearfield differ by more than one standard deviation in many important locations

• Lift and iterative convergence
  – Euler and RANS lift approach different values with grid convergence
In the Paper

• Details of required grid families
• Summaries of participant presentations
• Discussion, recommendations, and next steps toward SBPW3
  – Quieter SBPW2 cases exposed issues not seen in SBPW1
  – Quieter configurations, ideally at or below 75 PL (dB)
  – Additional research needed to reduce sensitivity to convection scheme
  – Establishing benchmark (archived submissions)
Acknowledgments

• All participants
• Mathias Wintzer, Irian Odaz, James Fenbert, and Sriram Rallabhandi for C25F and C25P designs
• George Anderson and Michael Aftosmis for AXIE design
• Atsushi Ueno, Masashi Kanamori, and Yoshikazu Makino for JWB geometry
• Andrew Clemens for JWB grids
• Marie Denisen, Adrein Loseille, Alaa Elmiligui, and Mike Aftosmis for grid evaluation and feedback
• Scott Brynildsen, Bill Jones, and Sriram Rallabhandi for geometry preparation
• Joe Derlaga for statistical tools
• NASA Commercial Supersonic Technology Project of the Fundamental Aerodynamics Program.
Perceived Level (PL)

- Signature sound pressure level is gathered into 1/3 octave bands
- Band levels are converted into sones (loudness)
- Sones from each band are combined
- Sones are converted into PL via logarithm
Nearfield Plotting

• Tau is distance from freestream Mach cone originating at tip of nose

• Delta pressure divided by freestream pressure is scaled by the square root of radius in body lengths
  – Signatures at different radii readily comparable and “aging” effect observed