Jet Noise Prediction for Low Boom Aircraft

Gerrit Stich, Jeffrey Housman, Cetin Kiris
Computational Aerosciences Branch
NASA Ames Research Center

Acoustic Technical Working Group Meeting, NASA GRC, October 22, 2019

Efficient and Accurate Jet-Noise Prediction with LAVA for NASA's Low Boom Flight Demonstrator (LBFD)

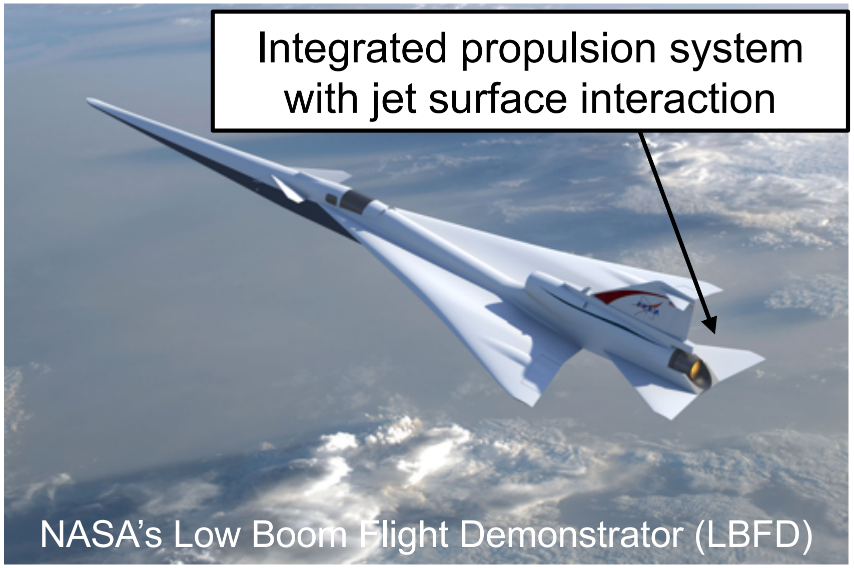
- **Objectives**
  - Enabling jet acoustics simulations on full scale flight vehicles utilizing zonal hybrid RANS/LES within the Launch Ascent and Vehicle Aerodynamics (LAVA) Solver

- **Approach**
  - Perform systematic validation effort to assess predictive capabilities of hybrid RANS/LES for increasingly complex geometries (round jet, chevron, jet surface interaction).

- **Milestones towards Grand Challenge**
  1. Improved best practices for round jet (FWH, WMLES)
  2. Excellent agreement for jet surface interaction noise
  3. Preliminary Chevron nozzle simulations look promising
  4. Utilized immersed boundary method to reduce meshing effort (approx. 90%) while increasing complexity.
  5. Multi-stream nozzle
  6. Grand Challenge TMP017

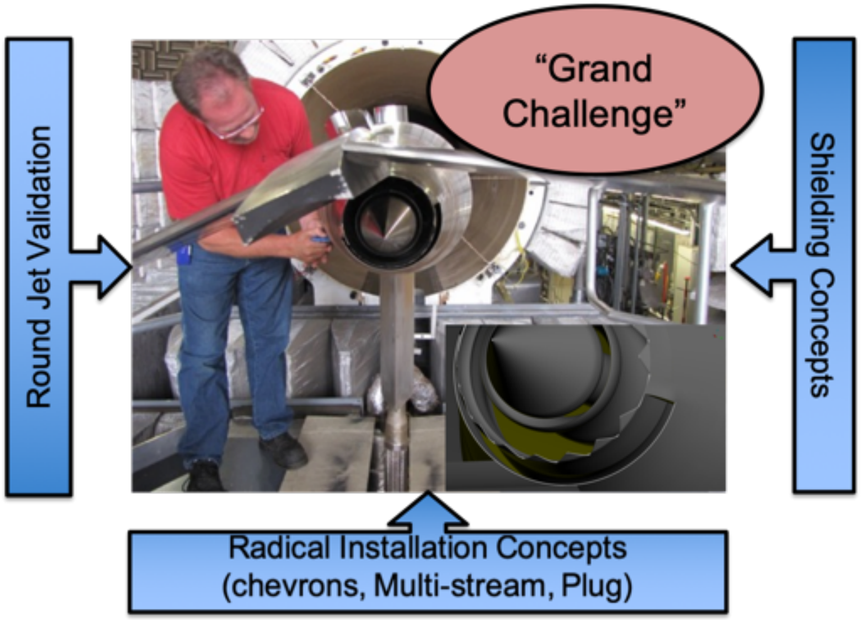
- **Significance**

Hybrid RANS/LES technology will assist in the development for innovative concepts for integrated supersonic propulsion systems. Modeling and simulation practices must be scrutinized further and new methods need to be developed*.



Integrated propulsion system with jet surface interaction

NASA's Low Boom Flight Demonstrator (LBFD)



"Grand Challenge"

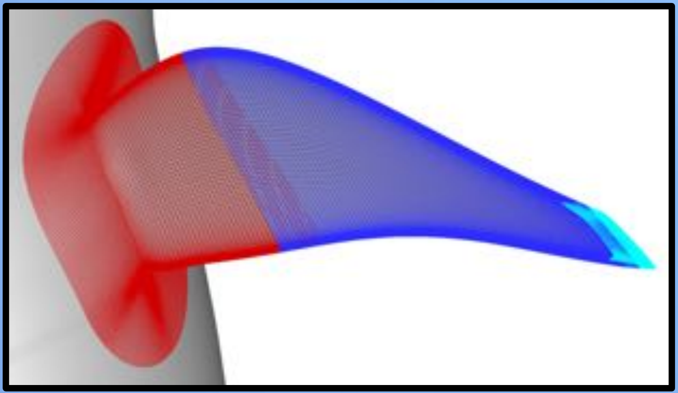
Round Jet Validation

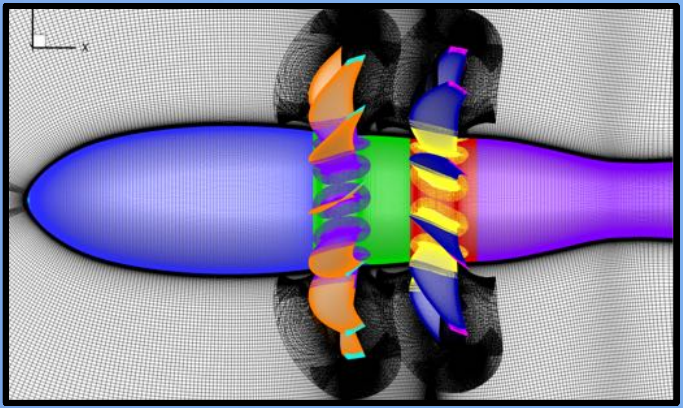
Shielding Concepts

Radical Installation Concepts (chevrons, Multi-stream, Plug)

Figure 2: Experimental Setup of TMP17 "Grand Challenge" problem. Setup includes a 3 stream nozzle geometry with partial chevrons and jet surface interaction components representing an airfoil in close proximity to the jet.

Why Structured Curvilinear Approach?



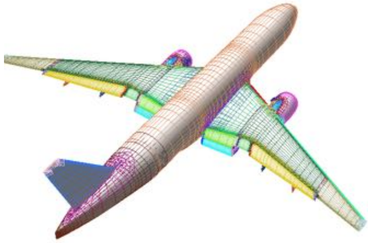


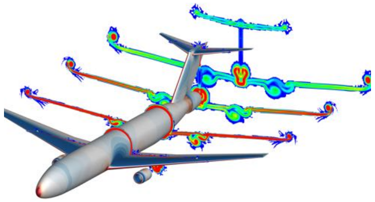
High quality body fitted grids. Resolution of boundary layer requires less points than with Cartesian methods.

Low computational costs compared to unstructured grid paradigm.

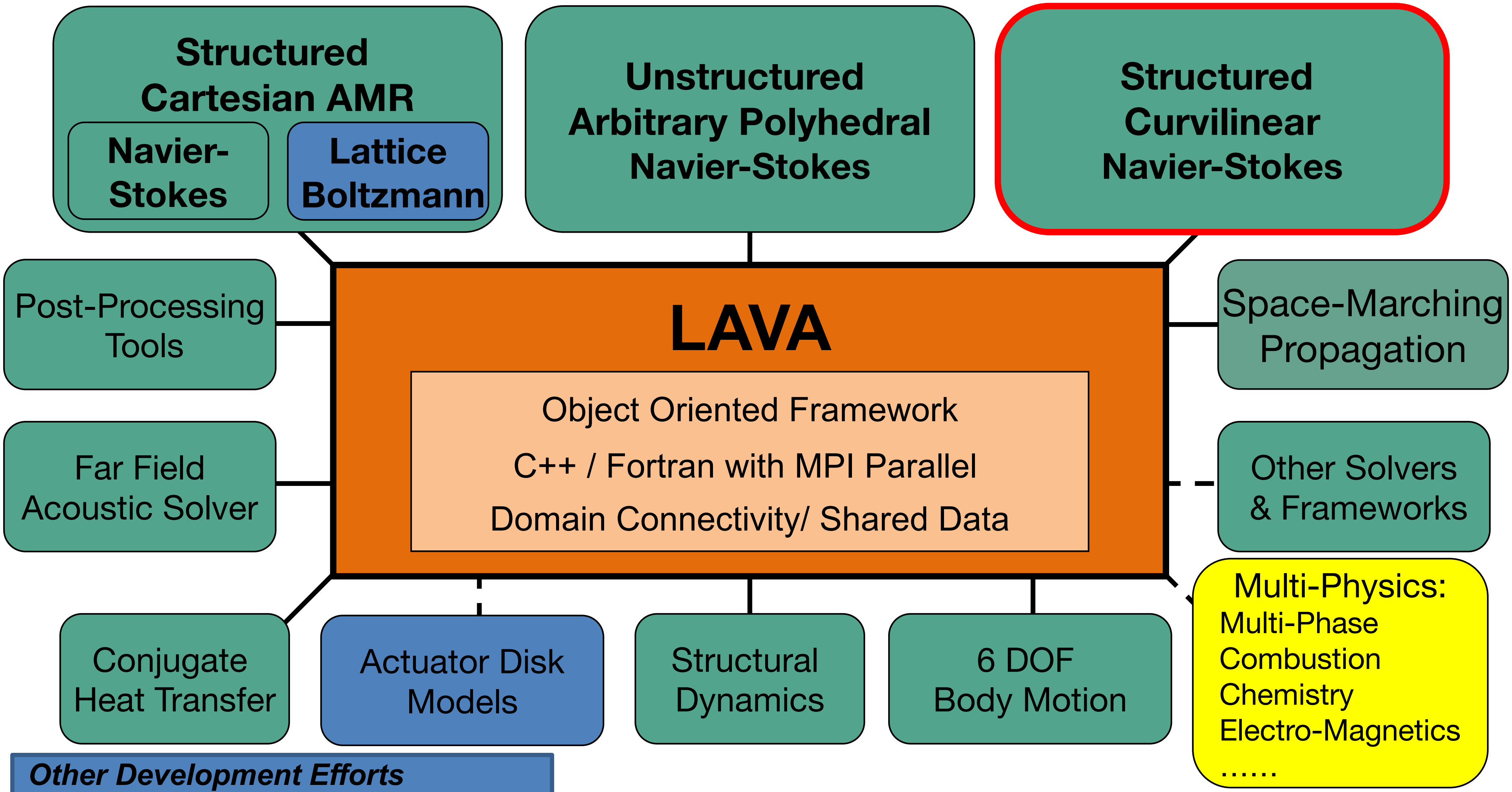
Reliable high order methods are available.

Grid generation largely manual and time consuming





Launch, Ascent, and Vehicle Aerodynamics
LAVA Framework



Structured Cartesian AMR

Navier-Stokes

Lattice Boltzmann

Unstructured Arbitrary Polyhedral Navier-Stokes

Structured Curvilinear Navier-Stokes

Post-Processing Tools

Far Field Acoustic Solver

LAVA

Object Oriented Framework

C++ / Fortran with MPI Parallel

Domain Connectivity/ Shared Data

Space-Marching Propagation

Other Solvers & Frameworks

Multi-Physics:
Multi-Phase
Combustion
Chemistry
Electro-Magnetics
……

Conjugate Heat Transfer

Actuator Disk Models

Structural Dynamics

6 DOF Body Motion

Other Development Efforts

- Higher order and low dissipation
- Curvilinear grid generation
- Wall modeling
- LES/DES/ILES Turbulence
- HEC (optimizations, accelerators, etc)

——— Connected

– – – Not Yet Connected

Existing

Developing

Future

Framework

Kiris at al. AIAA-2014-0070 & AST-2016

Numerical Method Used

3-D Structured Curvilinear Overset Grid Solver within LAVA framework

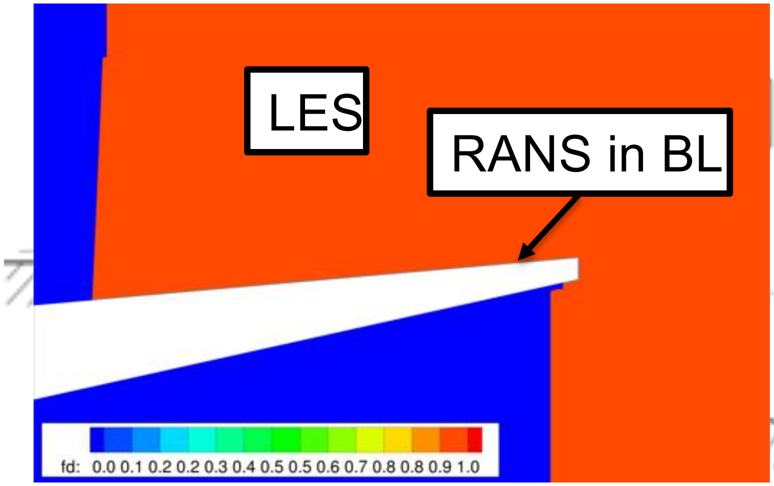
- Spalart-Allmaras turbulence model (baseline turbulence model)

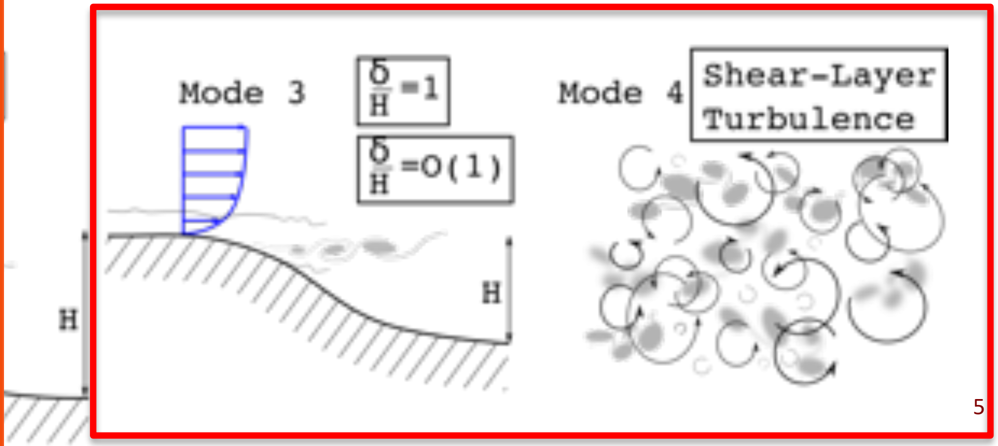
Low-Dissipation Finite Difference Method (Housman et al. AIAA-2016-2963)

- 6th-order Hybrid Weighted Compact Nonlinear Scheme (HWCNS)
- Numerical flux is a modified Roe scheme
- 6th/5th-order blended central/upwind biased left and right state interpolation
- 2nd-order accurate differencing used for time discretization

Hybrid RANS/LES Model

- Zonal Detached Eddy Simulation (ZDES-Mode III & IV) with user selected RANS, LES, and Hybrid RANS LES zones *(Deck, S. Theor. Comput. Fluid Dyn. 2012)*





Jet Noise Prediction for LBFD with LAVA Solver

Improved best Practices for Round Axisymmetric Round Jet

- **Revised validation for Jet noise Prediction**

  Obtained excellent results for round jet with 12” extension both for near as well as far-field.

  - **Established best practice** guide for Ffowcs Williams-Hawkings (FWH) post-processing procedure (end-caps, slope, distance) and meshing.
  - Observed **difference in noise spectra** and near-field comparison for case with 12” extension.

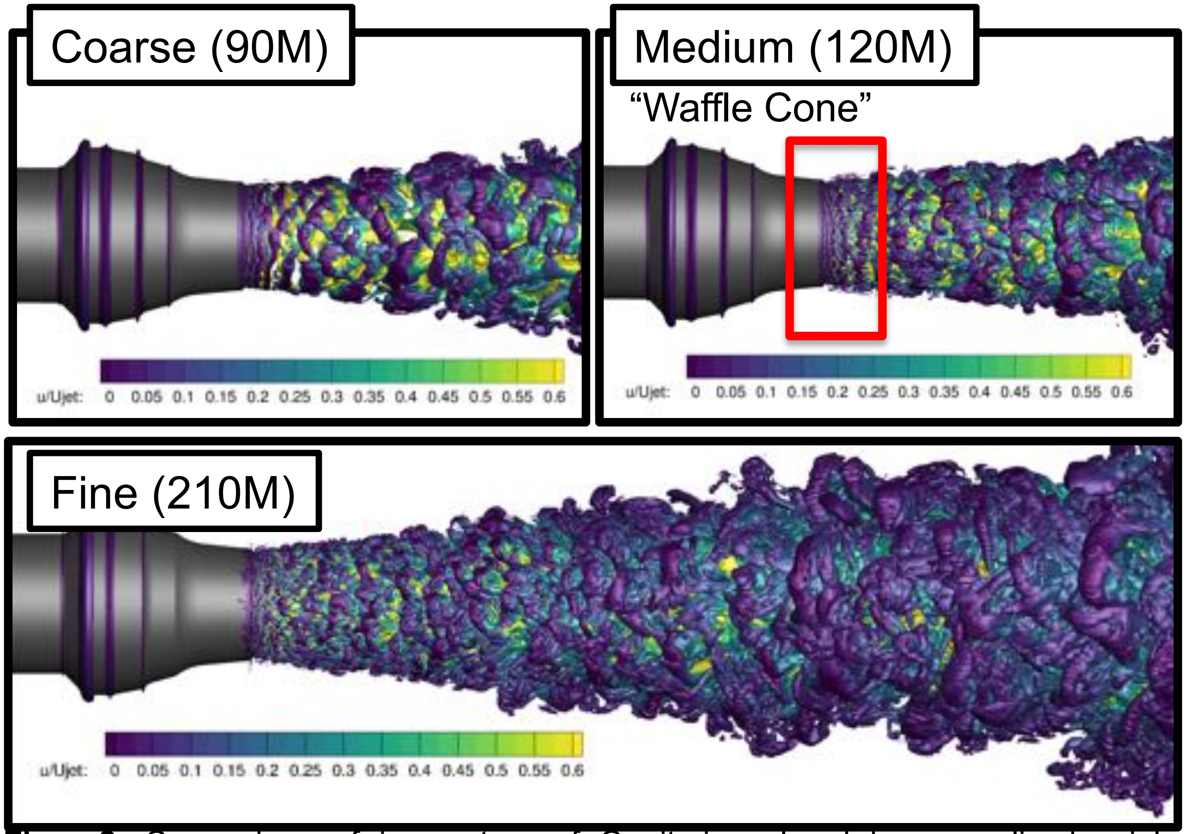


Figure2: Comparison of iso-contour of Q-criteria colored by normalized axial velocity for three different mesh resolution.

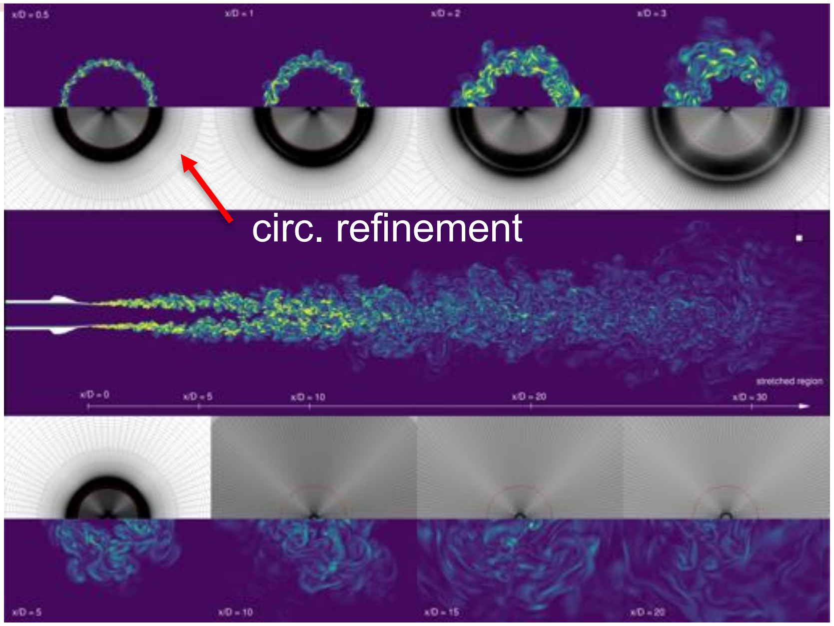


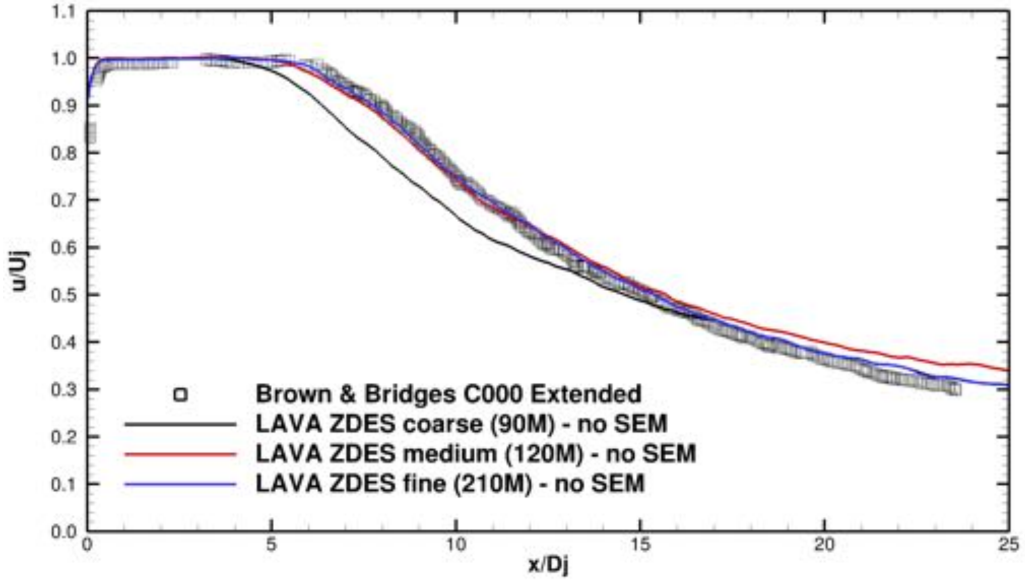
Figure1: Instantaneous vorticity magnitude for isolated isothermal ideally-expanded jet. Tip and bottom of figure show cross flow cuts at different streamwise locations.

Bridges et. al. (NASA-TM-2011-216807)	**SP7**
Acoustic Mach number U_{jet}/c_{∞}	0.9
Jet temperature ratio T_e/T_{∞}	0.835
Nozzle pressure ratio p_t/p_{∞}	1.861
Nozzle Diameter D	0.0508 [m] 2.0 [inch]
Reynold number Re_D	1 Million
Reynolds number Re_{τ}	800
Boundary layer thickness	0.0128 D

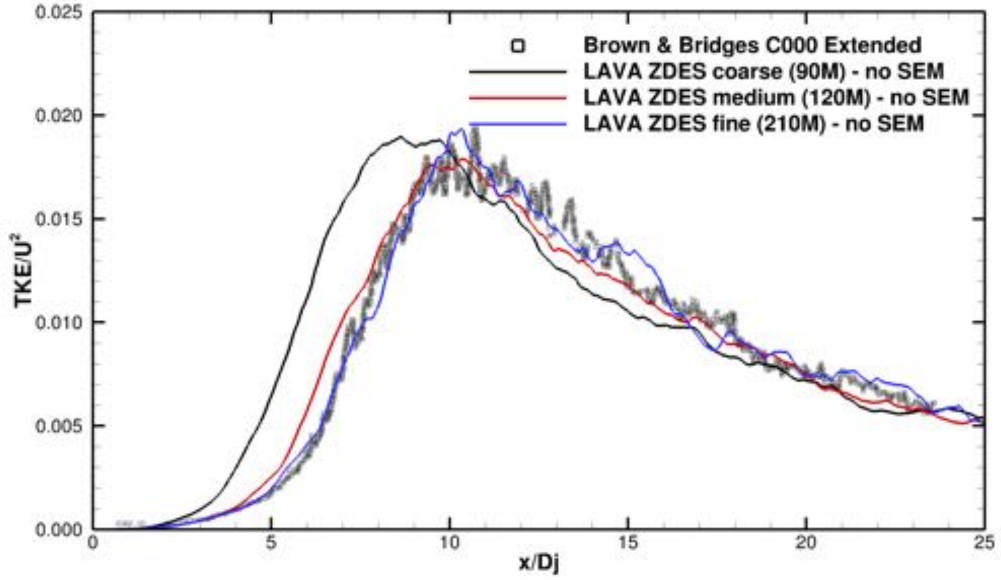
Jet Noise Prediction for LBFD with LAVA Solver

Time-Averaged Axial Velocity, Turbulent Kinetic Energy and Noise Spectra

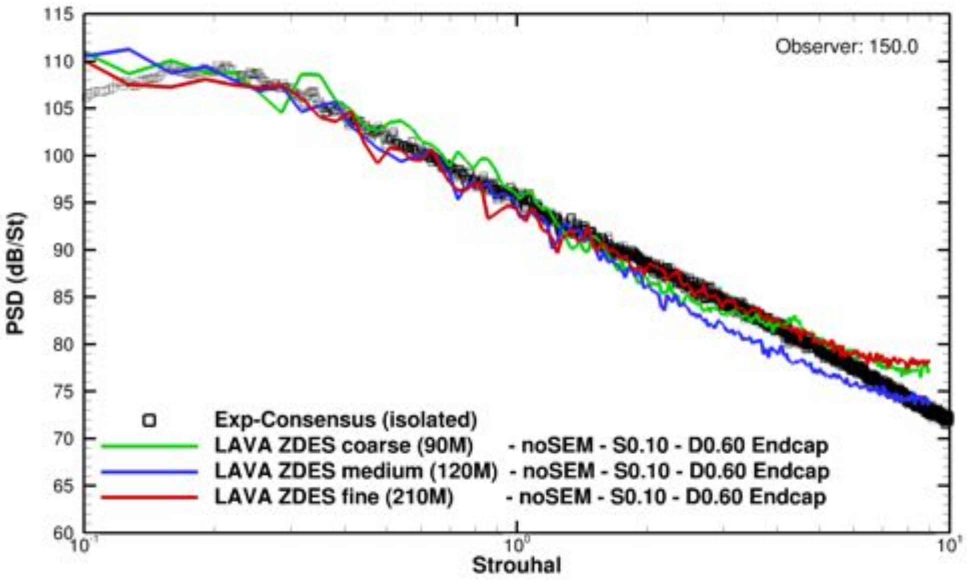
(a) axial velocity



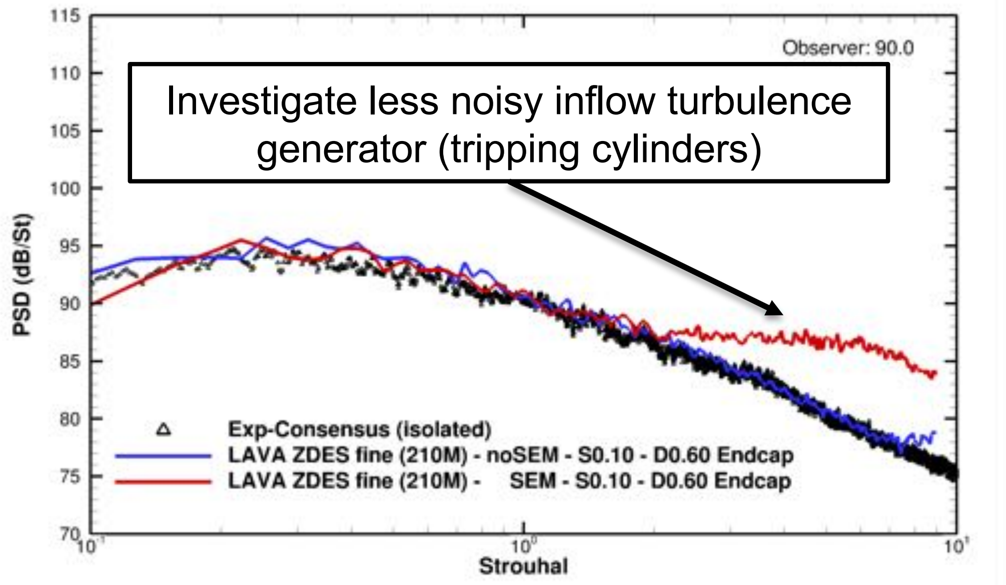
(b) turbulent kinetic energy (TKE)



(c) PSD at 100D for 150.0 observer



(d) Influence of SEM on PSD spectra


Investigate less noisy inflow turbulence generator (tripping cylinders)

Jet Surface Interaction Noise with LAVA

Asses Jet Surface Interaction Noise with Hybrid RANS/LES

- **Assess Jet Noise Shielding Capability**

  Flat plate is inserted in close proximity to Round Jet in order to represent airframe interaction noise.

  - Mesh around shielding plate consist of 130M grid points and is combined with medium mesh (120M)
  - **Established best practice** guide for Ffowcs Williams-Hawkings (FWH) post-processing procedure. FWH placement non-trivial.
  - Effect of shielding plate captured very well.

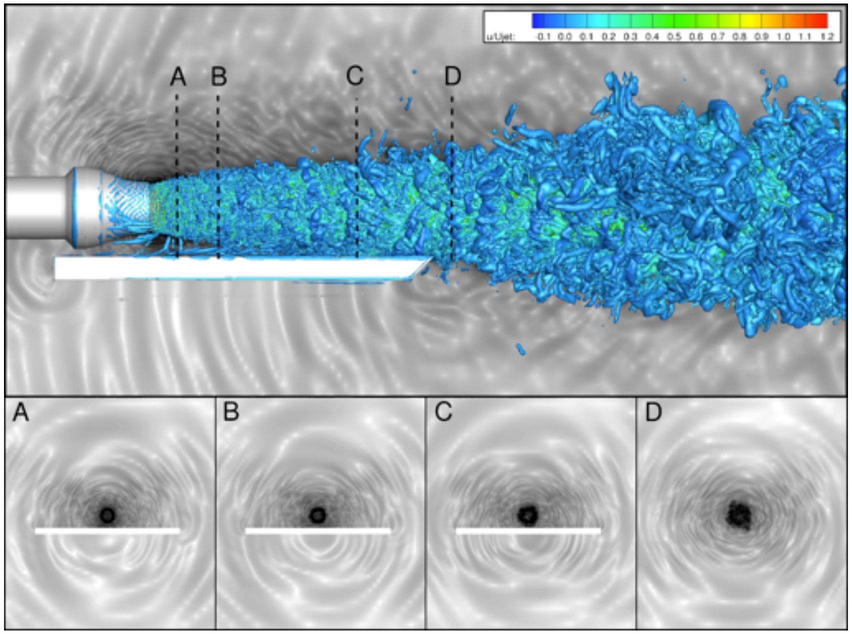
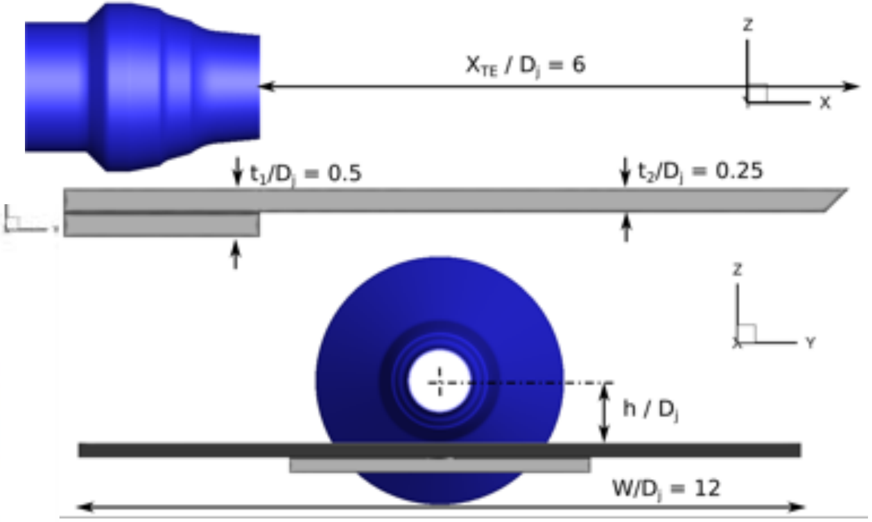


Figure 1: Isocontour of Q-criterion colored by normalized streamwise velocity and density gradient magnitude



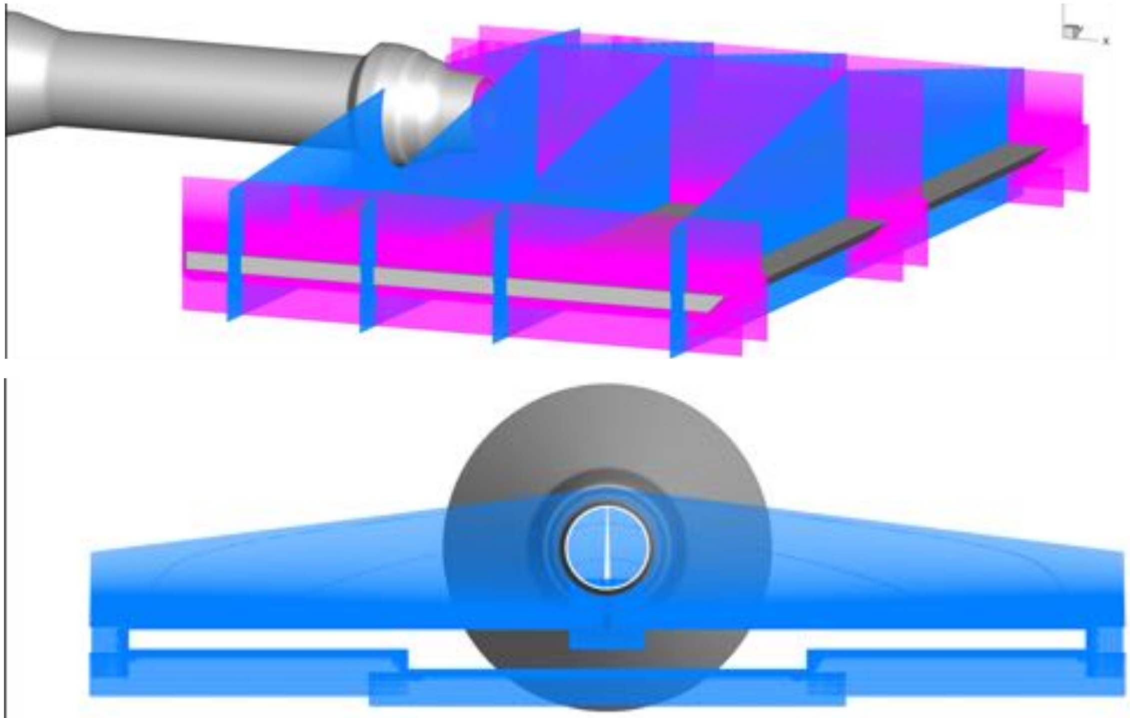
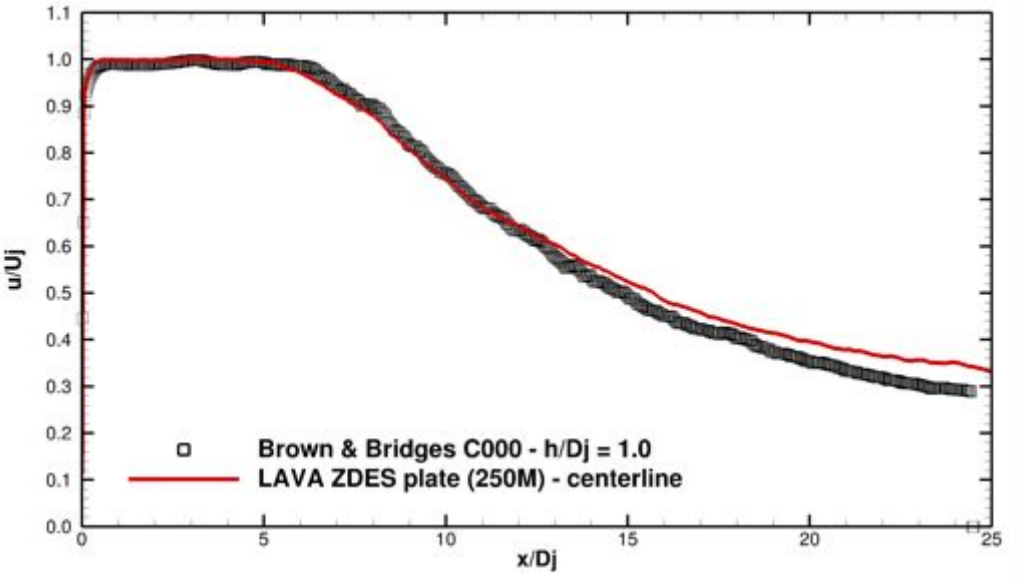


Figure 3: Representation of mesh containing shielding plate (130M) which is combined with medium isolated mesh from round jet (120M)

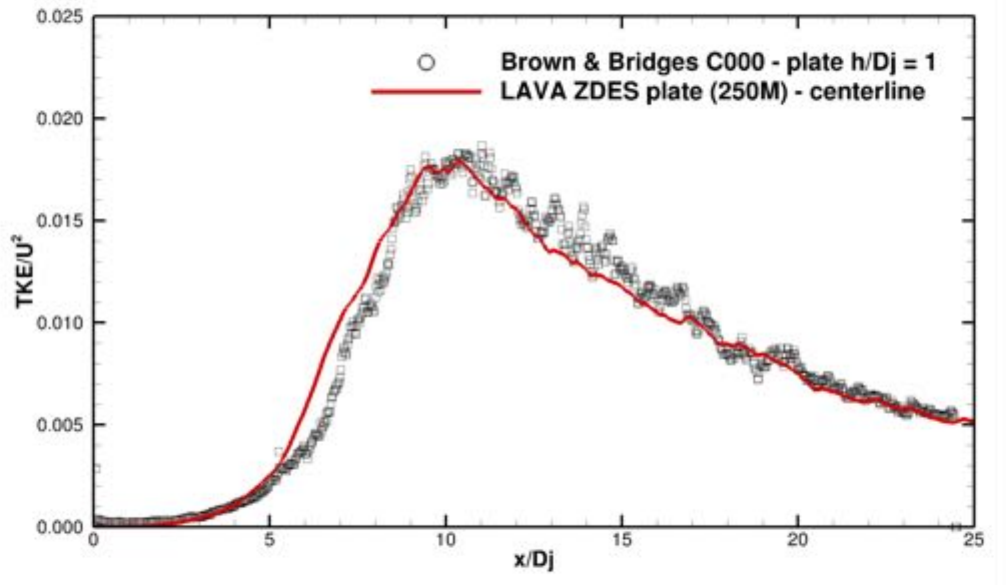
Figure 2: Schematic of the numerical setup including isolated round jet and jet shielding plate.

Jet Surface Interaction Noise with LAVA

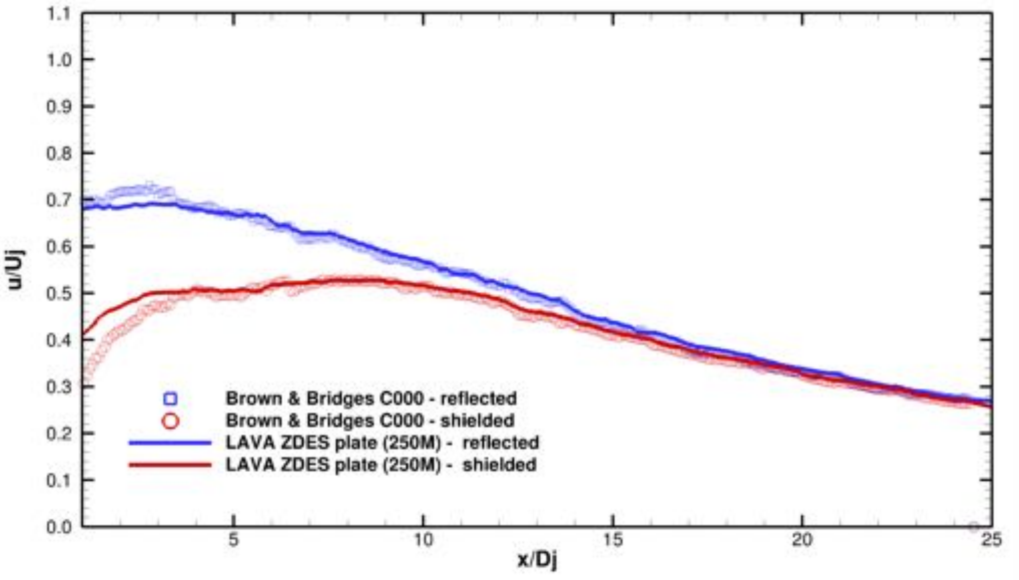
Time-Averaged Axial Velocity and Turbulent Kinetic Energy



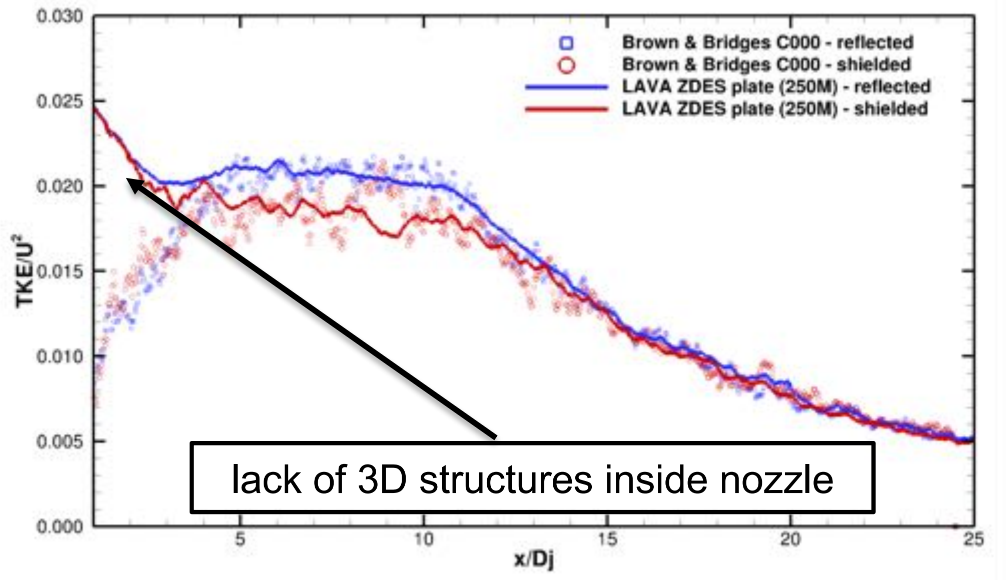
(a1) Centerline Velocity



(a2) Centerline TKE



(a1) Lipline Velocity



lack of 3D structures inside nozzle

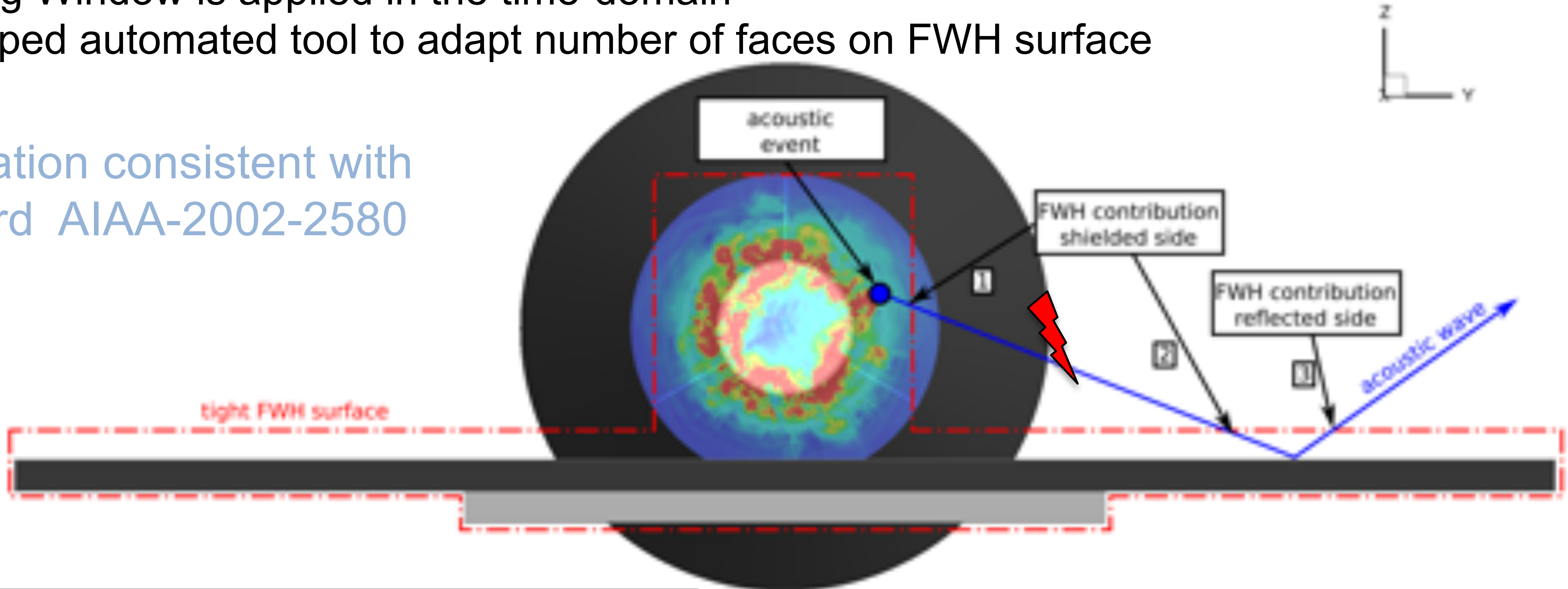
(a2) Lipline TKE

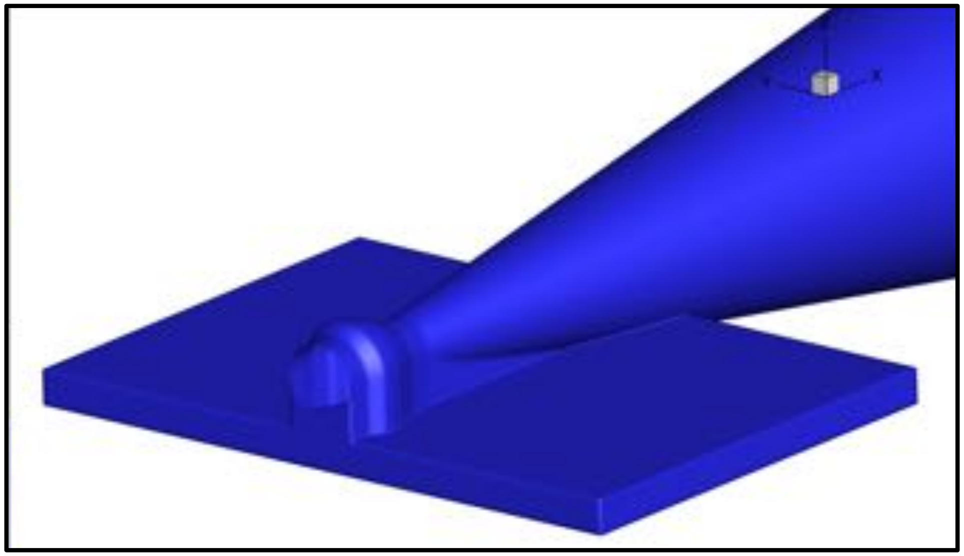
Jet Surface Interaction Noise with LAVA

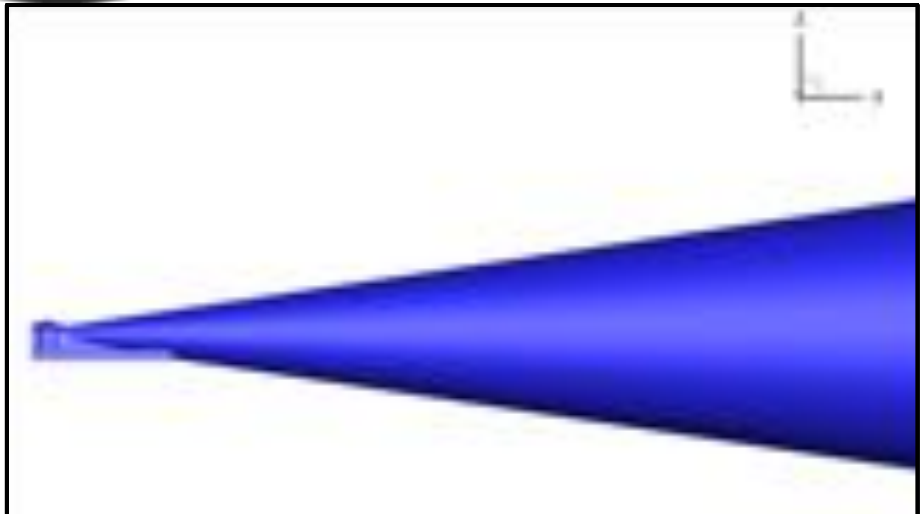
Frequency Domain Permeable Ffowcs Williams-Hawkings (FWH)

- Samples taken over last 1000 convective time units ($\Delta t\ c_\infty/D_j$) with sampling rate of 100kHz
- Time Sample Split in 25 segments with 50% overlap $St_{bin} = 0.02$
- Hanning Window is applied in the time-domain
  Developed automated tool to adapt number of faces on FWH surface

Formulation consistent with
Lockhard AIAA-2002-2580

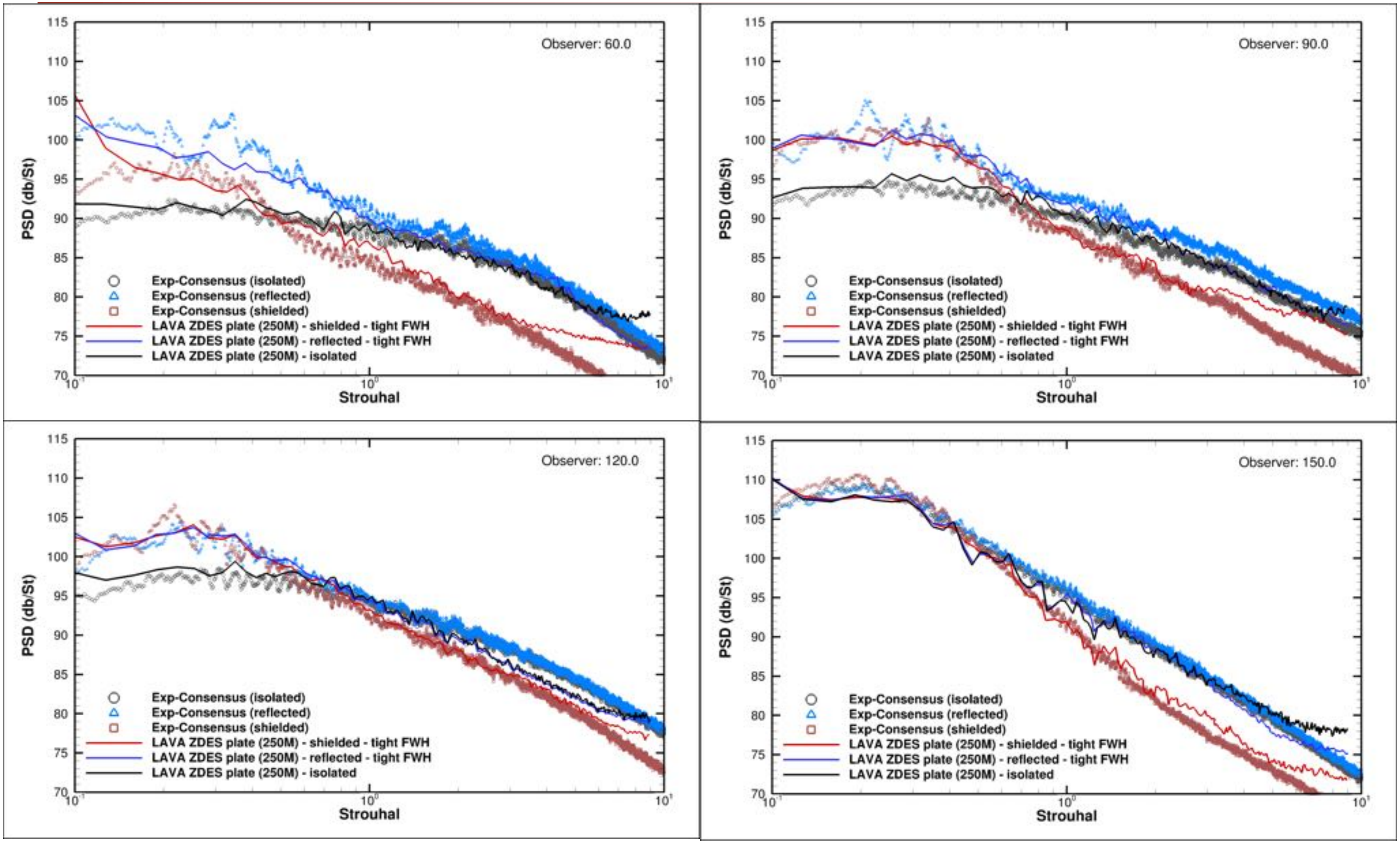






Jet Surface Interaction Noise with LAVA

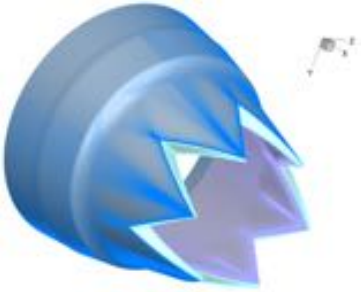
Comparison of Noise Spectrum at 100D Downstream of Nozzle Exit with Tight FWH



- Excellent agreement with measurements, split captured accurately.
- Resolution in plate region not sufficient for high-frequencies.

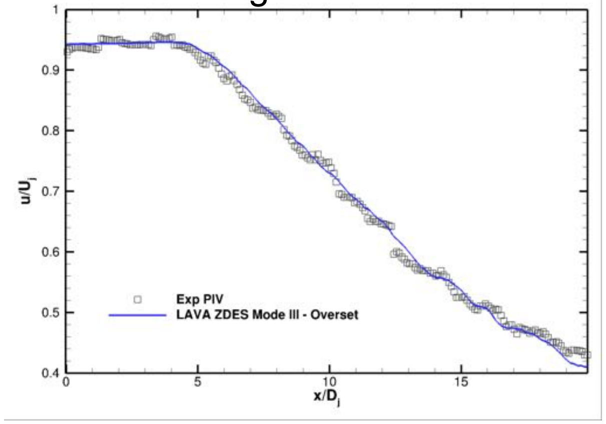
Increased Geometric Complexity of Nozzle Shape

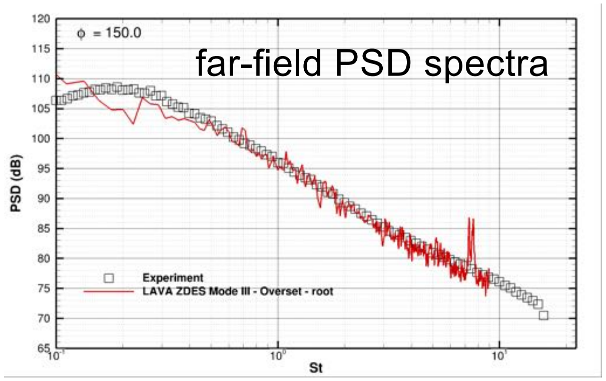
Chevron Nozzle with Bodyfitted Curvilinear Overset Mesh

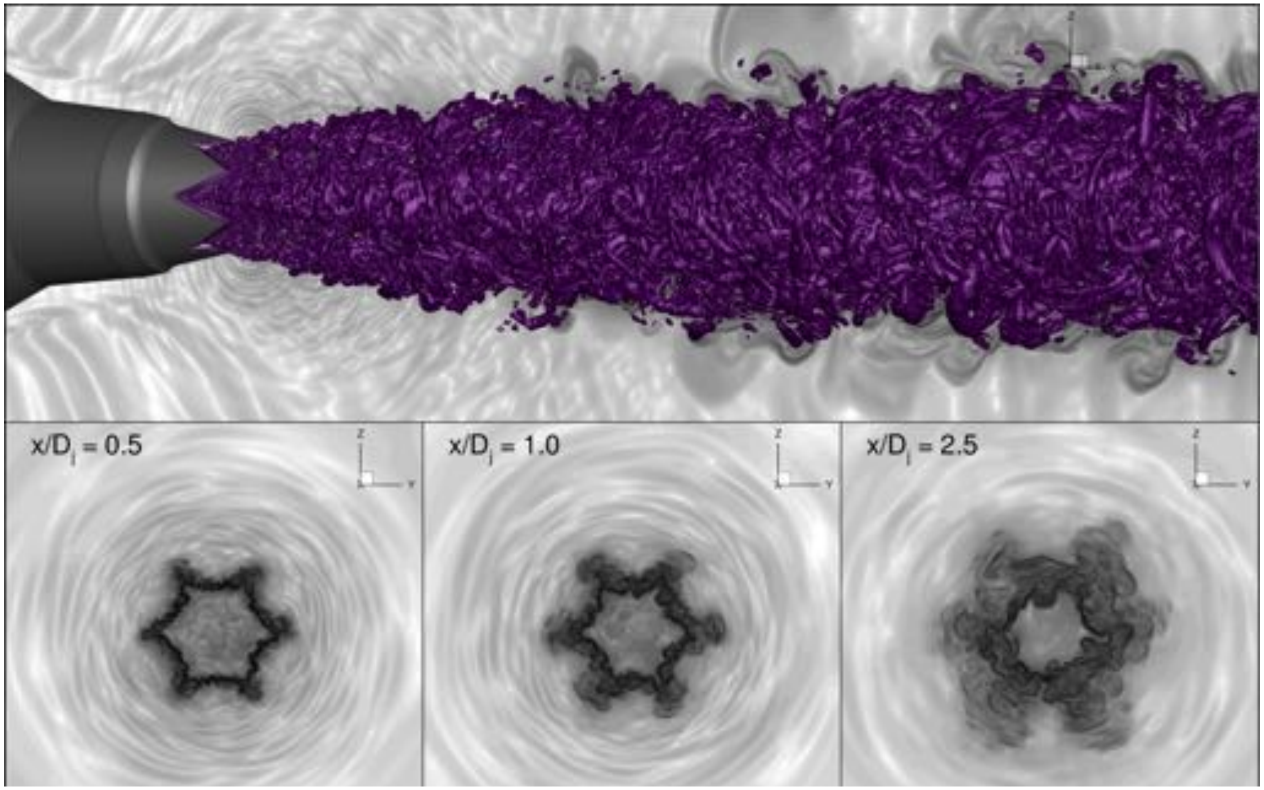


- **Current Status**
  - Applied different mesh strategies to SMC001 chevron nozzle (multiblock vs overset)
  - Preliminary results for chevron SMC001 look promising.
- **Significance of Milestone**
  - **High quality mesh generation for acoustics on complex Geometries challenging** (Between 1-2 weeks for experienced mesh generator)
  - Developing best practice is a big step towards ”Grand Challenge” (mesh generation reduces to < 1 week)

time-averaged centerline velocity







Isocontour of Q-criterion colored by normalized streamwise velocity and density gradient magnitude.

Increased Geometric Complexity of Nozzle Shape

Innovative Approach Towards Full Aircraft Jet Noise Predictions

- **Objective**

  Significantly reduce time to solution by decreased manual meshing efforts while increased geometric complexity.

- **Approach**
  - Utilizing Immersed Boundary (IB) Method in regions where resolving the boundary layer is not crucial. Cells get tagged as ”in-body” and a penalty term is applied.
- **Significance**
  - Initial Chevron nozzle generation takes between 1-2 weeks. (With best practice can be reduced to 1week)
  - **IB Method reduces meshing efforts by around 90% (meshing time < 1day)**

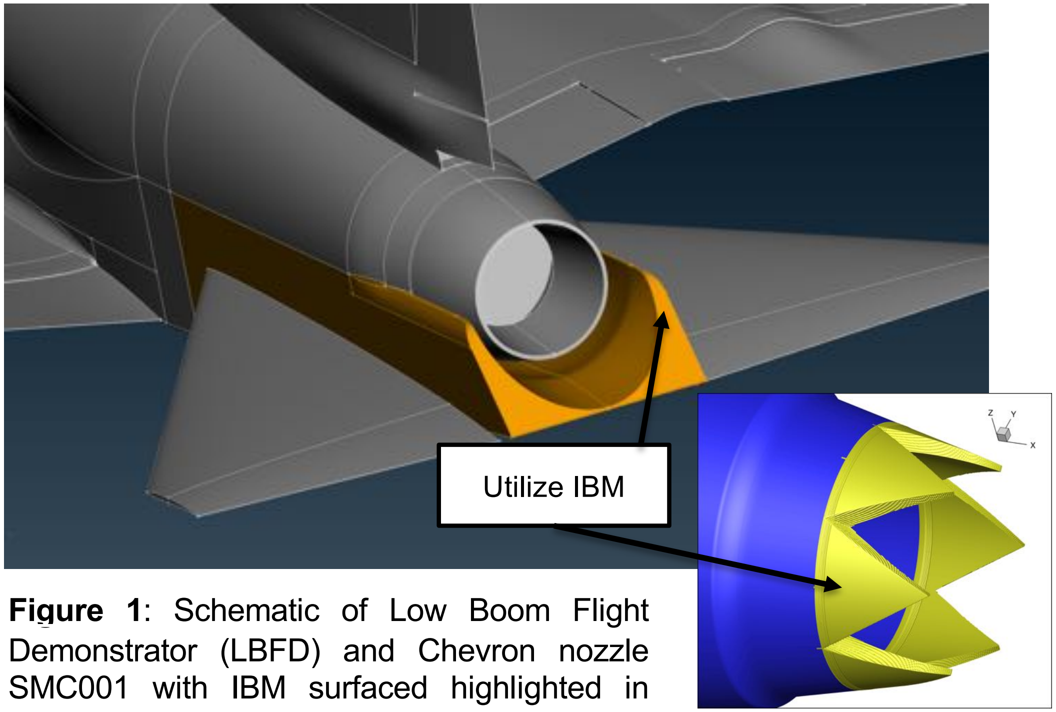

Utilize IBM

Figure 1: Schematic of Low Boom Flight Demonstrator (LBFD) and Chevron nozzle SMC001 with IBM surfaced highlighted in orange and yellow.

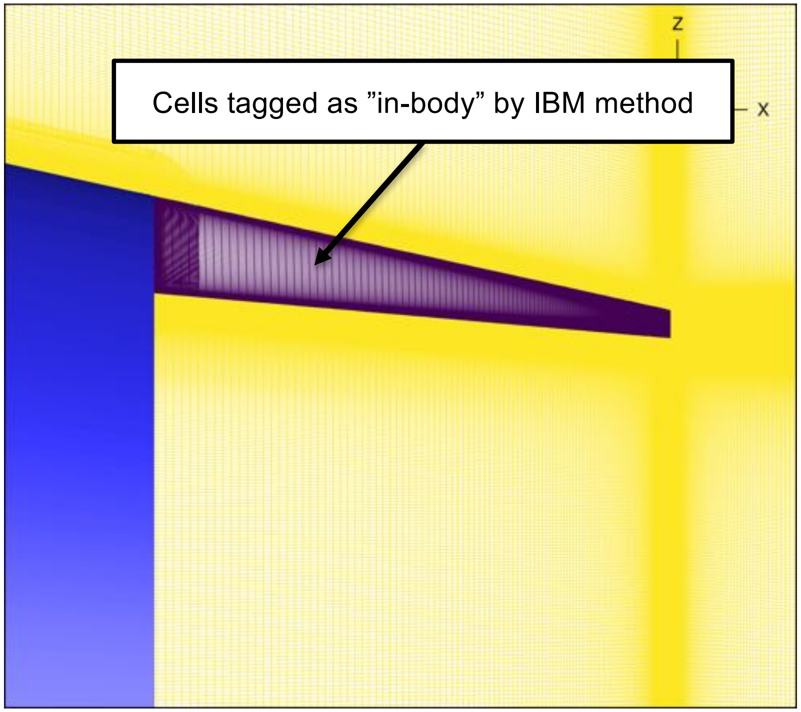

Cells tagged as ”in-body” by IBM method

Figure 2: Slice of chevron nozzle mesh with tagged cells marked in color

Increased Geometric Complexity of Nozzle Shape

Innovative Approach Towards Full Aircraft Jet Noise Predictions

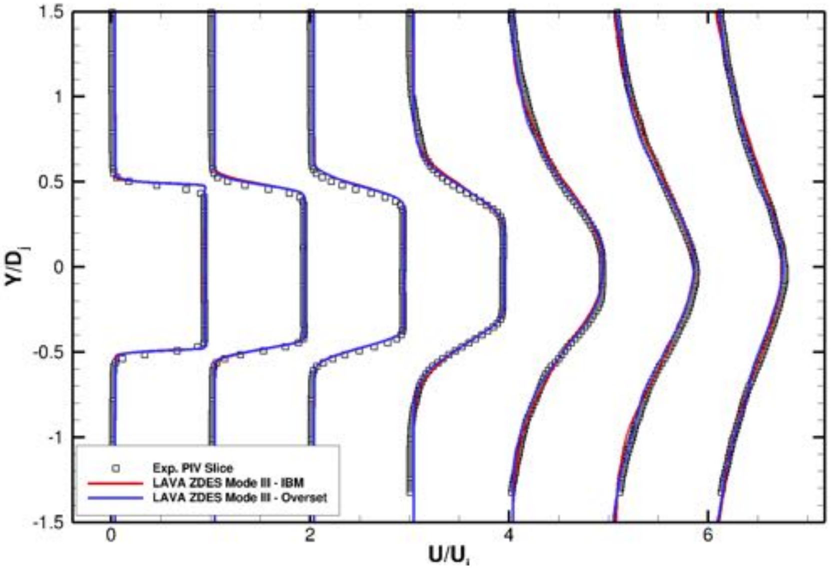


Figure 1: axial velocity profiles at different streamwise slices

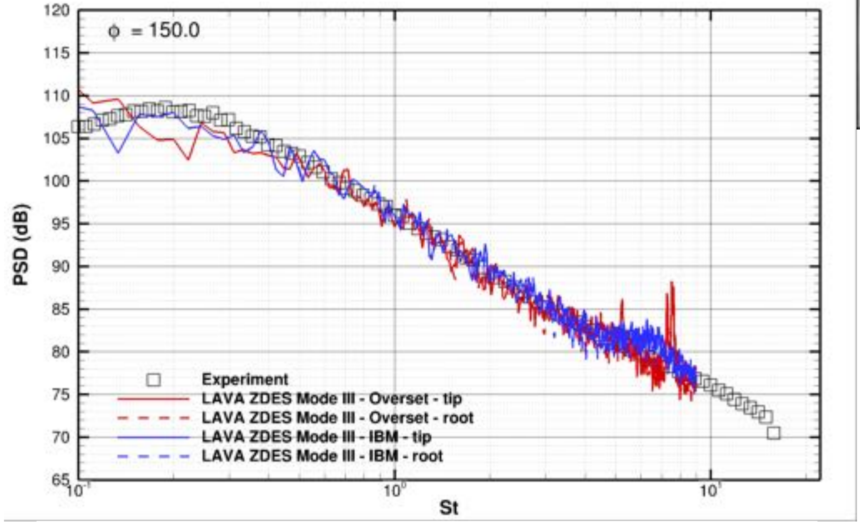


Figure 2: Noise spectra at 100D downstream of nozzle

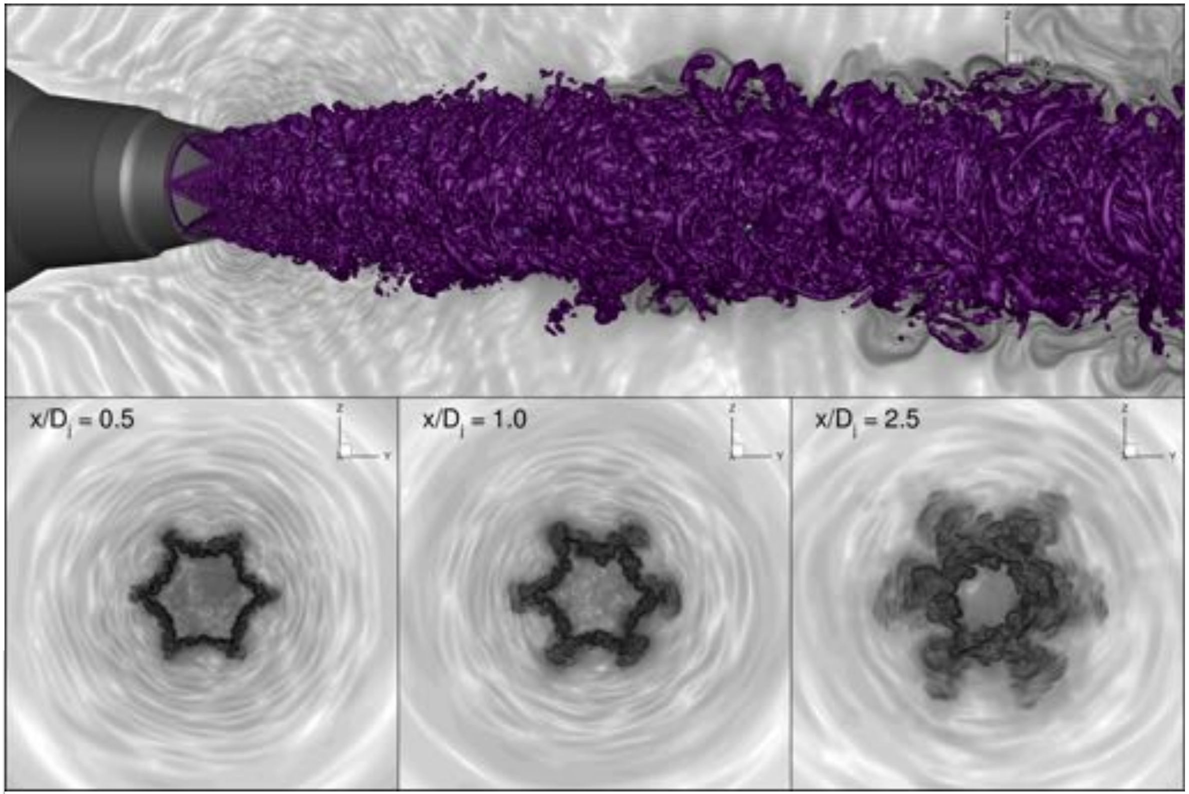


Figure 3: Isocontour of Q-criterion colored by normalized streamwise velocity and density gradient magnitude.

- Excellent agreement between Immersed Boundary Method (IBM) and curvilinear body fitted Mesh
- Significantly reduced manual meshing effort (reduction by around 90%)

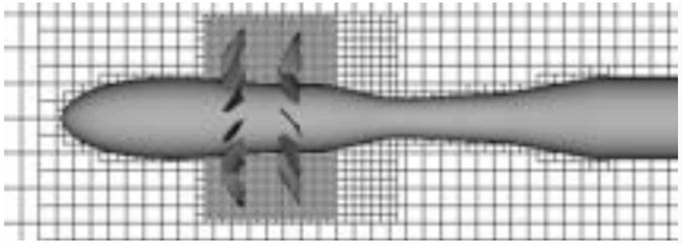
Summary and Lessons Learned

- Hybrid RANS/LES within the LAVA framework using structured curvilinear overlapping grids is successfully applied to predict jet noise.
- Good comparison with experiments for both near-field and far-field achieved for round-jet as well as surface interaction noise case and chevron nozzle
- Completed far-field acoustic propagation
    - Mach wave radiation noise in the jet direction is well-captured
    - Strong influence on utilized SEM investigated, further improvements necessary (tripping, quitter inflow)
- BL needs to be resolved better inside of nozzle for further improvements.
- Chevron nozzle siulations showed an excellent agreement between Immersed Boundary Method and curvilinear body fitted Mesh.

Acknowledgents

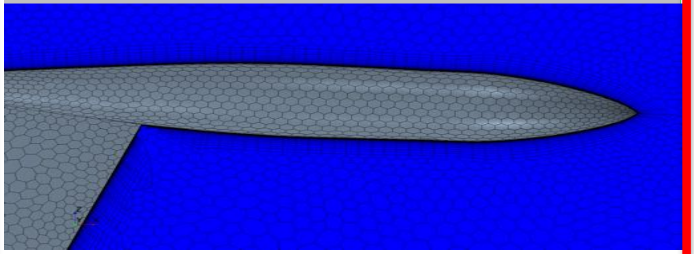
- Special thanks to **James Bridges** and **Clifford Brown** of NASA GRC for a fruitful collaboration and for providing the CAD geometry along with measured data.
- This work was partially funded by the Commercial Supersonics Technology (CST) project and the Transformational Tools and Technology (T^3) project under the Aeronautics Research Mission Directorate (ARMD).
- Computer time has been provided by the NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center.
- Team members of LAVA group for helpful discussions and advice

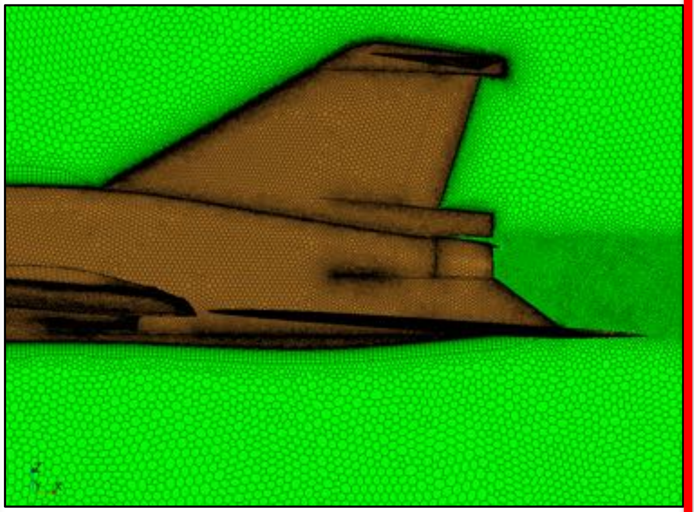
Structured Cartesian AMR



- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient

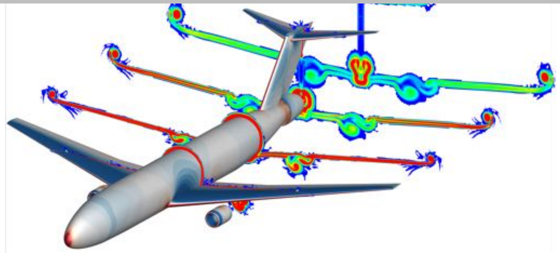
Unstructured Arbitrary Polyhedral

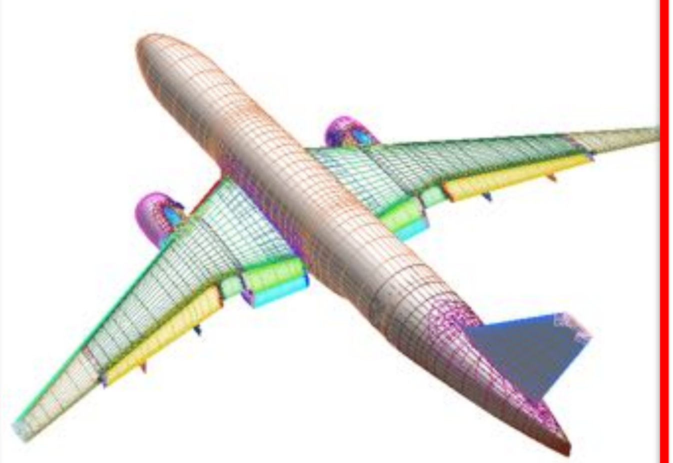




- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

Structured Curvilinear





- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming