Hybrid RANS/LES of Jet Surface Interaction Noise

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NASA initiated research activities towards Commercial Supersonic Technologies (CST)

Within this project Three main Technical Challenges (TC) have been defined
- TC 1.1 Low Boom Design Tools
- TC 1.2 Sonic Boom Community Response Metric & Methodology
- TC 2.2 Low Noise Propulsion for Low Boom Aircraft

Develop an understanding of the effects of shielding surfaces on the aerodynamic noise sources from jet flows.
Objective
Progress Towards Full Aircraft Noise Prediction

Utilizing Computational Fluid Dynamics (CFD) to evaluate the effects of shielding surfaces on the aerodynamic noise sources from jet flows for a full aircraft configuration "Grand Challenge"

- First systematic validation effort to assess predictive capabilities for jet-noise shielding within NASA Ames Launch Ascend and Vehicle Aerodynamics solver (LAVA)

Picture taken from:
Test Report: Top-Mounted Propulsion Test 2017
by James Bridges
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- First systematic validation effort to assess predictive capabilities for jet-noise shielding within NASA Ames Launch Ascend and Vehicle Aerodynamics solver (LAVA)
Outline

- Motivation
- Experimental Setup
- Computational Methodology
- Structured Overset Grid System
- Axisymmetric Round Jet
  - Flow Visualization
  - Near-Field Results
  - Far-Field Results
- Jet Surface Interaction
  - Near-Field Results
  - Far-Field Results
- Summary and Future Work
Motivation

Experimental Setup

Computational Methodology

Structured Overset Grid System

Axisymmetric Round Jet
  • Flow Visualization
  • Near-Field Results
  • Far-Field Results

Jet Surface Interaction
  • Near-Field Results
  • Far-Field Results

Summary and Future Work
Experimental Facility
NASA Aero-Acoustics Propulsion Lab (AAPL)

- 65” radius anechoic dome
- Located at Glenn Research Center (GRC)
- Small Hot Jet Acoustic Rig (SHJAR)
- Far-field acoustics, phased arrays, flow rakes, hotwire, shlieren, PIV, IR, Rayleigh, Raman, PSP
Experimental Facility
NASA Aero-Acoustics Propulsion Lab (AAPL)

- Baseline axisymmetric convergent Small Metal Chevron (SMC000) nozzle at Set Point 7 (SP7) with 12” extension
- Nozzle axis in downstream flow direction is marked as 180°

<table>
<thead>
<tr>
<th>Bridges et. al. (NASA-TM-2011-216807)</th>
<th>SP7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Mach number $U_{jet}/c_{\infty}$</td>
<td>0.9</td>
</tr>
<tr>
<td>Jet temperature ratio $T_e/T_{\infty}$</td>
<td>0.835</td>
</tr>
<tr>
<td>Nozzle pressure ratio $p_t/p_{\infty}$</td>
<td>1.861</td>
</tr>
<tr>
<td>Nozzle Diameter D</td>
<td>0.0508 [m] 2.0 [inch]</td>
</tr>
<tr>
<td>Reynold number $Re_D$</td>
<td>1 Million</td>
</tr>
<tr>
<td>Reynolds number $Re_{\tau}$</td>
<td>800</td>
</tr>
<tr>
<td>Boundary layer thickness</td>
<td>0.0128 D</td>
</tr>
</tbody>
</table>

Similar conditions were analyzed in Bres et. al. AIAA-2015-2535, but the boundary layer thickness is 5.5 larger
Geometry and Setup
Round Convergent Nozzle (SMC000) with Jet Shielding Plate

- $X_{TE}/D_j = 6$
- $t_1/D_j = 0.5$
- $t_2/D_j = 0.25$
- $h/D_j = 1$
- $W/D_j = 12$

12” straight section
Final convergent nozzle part
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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

Conjugate Heat Transfer

Actuator Disk Models

Structural Dynamics

6 DOF Body Motion

LAVA
Object Oriented Framework
C++ / Fortran with MPI Parallel
Domain Connectivity/ Shared Data

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

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

Space-Marching Propagation

Other Solvers & Frameworks

11

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
Computational Approach

- **uRANS**
  \[ \Delta t_{\text{conv}} = 0.5 \]
- **Initialize Hybrid RANS/LES**
  \[ \Delta t_{\text{conv}} = 0.5 \]
- **Initialize Hybrid RANS/LES**
  \[ \Delta t_{\text{conv}} = 0.05 \]
  \[ \Delta t_{\text{conv}} = 0.005 \]
- **Initialize Hybrid RANS/LES**

- Unsteady RANS until jet is fully developed and eddy viscosity maximum has plateaued
- Restart simulation with Hybrid RANS/LES and larger timestep
- Decrease time-step once flow is fully developed
- Ignore transients from changing model and time-step size (20,000 time-steps for this case)
- Record volume data at 100kHz sampling frequency for 30,000 steps (\( \Delta t_{\text{conv}} = 200 \)) on isolated case and 120,000 steps (\( \Delta t_{\text{conv}} = 800 \)) for shielding case.

\[ \Delta t_{\text{conv}} = \Delta t \frac{c_{\infty}}{D_j} \]
Inflow Turbulence Generation

- When transitioning from RANS to LES in wall-bounded flows it is necessary to insert meaningful three-dimensional content at the interface.
- The synthetic eddy method (SEM) is one approach which adds eddies in such a way that first and second order turbulent statistics can be satisfied. (approx. from the RANS solution with Bradshaw hypothesis)

Jet Case SP 7

\[
\Delta x_{SEM} = x_{exit} - x_{SEM}
\]

\[54 \delta < \Delta x_{SEM} < 55 \delta\]
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Geometry and Setup
Computational Mesh Round Jet

- Three mesh resolution for isolated axisymmetric round jet: coarse (90M), medium (120M), fine (210M)

<table>
<thead>
<tr>
<th>Mesh Resolution</th>
<th>Streamwise Points per $D_j$</th>
<th>Circumferential Points</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1$D_j$</td>
<td>1$D_j$</td>
</tr>
<tr>
<td>coarse</td>
<td>250</td>
<td>45</td>
</tr>
<tr>
<td>medium</td>
<td>300</td>
<td>61</td>
</tr>
<tr>
<td>fine</td>
<td>300</td>
<td>71</td>
</tr>
</tbody>
</table>
Geometry and Setup
Computational Mesh Round Jet

- Circumferential coarsening in axial and radial direction
Bres et al. (AIAA-2015-2535)

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>θ₁</td>
</tr>
<tr>
<td>coarse</td>
</tr>
<tr>
<td>medium</td>
</tr>
<tr>
<td>fine</td>
</tr>
</tbody>
</table>
• Mesh surrounding jet shielding plate consists of 130M grid points (combined with medium isolated mesh 230M)
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Flow Field Visualization
Isocontour of Q-Criteria colored by axial Velocity

Coarse (90M)

Medium (120M)

Jeff H.: “Waffle Cone”

Fine (210M)
Flow Field Visualization

Coarse (90M) vorticity magnitude
Flow Field Visualization

Isocontour of $Q$-criteria colored by axial Velocity

vorticity magnitude
Near-Field Centerline Axial Velocity and Turbulent Kinetic Energy

(a) axial velocity

(b) turbulent kinetic energy (TKE)

- Length of potential core $X_C$ taken where centerline velocity 98% $U_{jet}$
- Prediction of medium and fine mesh within 2.5% of measured value.
- Peak and location of Turbulent Kinetic Energy (TKE) predicted very well.

**Length Potential core:**
- Experiment 5.9$D_j$
- coarse 4.85$D_j$
- medium 5.75$D_j$
- fine 5.8$D_j$
Near-Field
Time-Averaged Axial Velocity at Radial Slices

- Location of axial slice normalized by potential core length $X_C = 5.9$
• Interpolate Volume solution to FWH surface at sampling rate 100kHz
• Samples taken over last 200 convective time units (\(\Delta t c_{\infty}/D_j\))
• Time Sample Split in 5 segments with 50% overlap \(S_{t_{\text{bin}}} = 0.02\)
• Hanning Window is applied in the time-domain (PSD multiplied with \(\text{sqrt}(8/3)\) to recover energy loss from Hanning window)
• PSD data assemble averaged over 360 observers per angle (60, 90, 120, 150)
• Developed automated tool to adapt number of faces on FWH surface
Density gradient magnitude (grey)
Iso-contour of Q-criteria (color)
Far-Field – CFD Mesh Resolution
Comparison of PSD Spectrum 100D away from nozzle exit

- Details of selected FWH Surface can be found in paper
- Overall excellent agreement with Exp-Consensus
1. Start radial Flare at $x/D_j = 0.6$ or $x/D_j = 0.55$
2. Variation of slopes $S = 0.12$, $S = 0.11$, $S = 0.10$
3. Combination of (1) and (2)
Results sensitive to choice of FWH surface.
Less dissipative scheme than WCNS might reduce sensitivity
• Influence of inflow turbulence on PSD spectra.
• Smaller effect of inflow turbulence on shallower angles (150.0)
Far-Field – Inflow Turbulence (SEM)
Comparison of PSD Spectrum 100D away from nozzle exit

- Enhanced influence on noise spectra for SMC000 with 12"
- Addition inflow generation methods currently under consideration.
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reflected

shielded

trailing edge noise

Video credit: Timothy Sandstrom NASA Ames
Near-Field Comparisons

(a) PIV measurements from Experiment
(b) Contour plot from CFD
Near-Field
Time-Averaged Axial Velocity and Turbulent Kinetic Energy

(a1) Centerline Velocity

(a2) Centerline TKE

(a1) Lipline Velocity

(a2) Lipline TKE

lack of 3D structures inside nozzle
Far-Field – FWH Surface Definition
Tight FWH Surface

- Best practice guidelines established for isolated round-jet do not apply directly on case with enclosed surface (non-symmetric)
- Inclusion of all necessary sources important to predict noise spectra correct
Far-Field – FWH Surface Definition

Tight FWH Surface

- 1000 convective time units
- 25 FWH segments $St_{bin} = 0.02$
• Excellent agreement with measurements, split captured accurately.
• Resolution in plate region not sufficient for high-frequencies.
Far-Field – FWH Surface Definition
Loose FWH Surface

• 1000 convective time units
• 25 FWH segments $St_{bin} = 0.02$
Far-Field – Tight FWH Surface
Comparison of PSD Spectrum 100D away from nozzle exit

- Excellent agreement with measurements, split captured accurately.
- Resolution in plate region not sufficient for high-frequencies.
• Mesh surrounding jet shielding plate consists of 130M grid points (combined with medium isolated mesh 230M)
Future Work
Progress towards the "Grand-Challenge"

Round Jet Validation

"Grand Challenge"

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

Shielding Concepts
Future Work
Progress towards the "Grand-Challenge"

Round Jet with chevron nozzle SMC001
• Completed structured curvilinear mesh for complex chevron nozzle design.

• Automated mesh refinement/ redistribution to track flow features of chevron nozzle (see Uzun et.al. 2012)
Future Work
Progress towards the "Grand-Challenge"

Combination of isolated problems into one nozzle TMP17
(Multi-stream, Plug, Chevron, Shielding)
• Surface meshing for TMP17 almost completed

Picture taken from: Test Report: Top-Mounted Propulsion Test 2017 by James Bridges
Summary

- 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.
- 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.
Acknowledgments

• This work was partially funded by the Commercial Supersonics Technology (CST) project and the Transformational Tools and Technology (T³) project under the Aeronautics Research Mission Directorate (ARMD).

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• Timothy Sandstrom from NASA Ames visualization team for particle flow visualizations.

• Team members of LAVA group for helpful discussions and advice
Questions?