Recent Advancements in LAVA for Jet, Rotor-Blade and Fan Noise Prediction

Cetin C. Kiris, Gerrit-Daniel Stich, Joseph G. Kocheemoolayil, Jeffrey A. Housman, Francois Cadieux and Michael F. Barad

Computational Aerosciences Branch
NASA Ames Research Center

Fall 2018 Acoustic Technical Working Group Meeting,
October 16-17, 2018, Cleveland, OH
• Motivation

• LAVA Framework

• Jet Noise Prediction
  • Hybrid RANS/LES efforts on round jet – Overset Curvilinear Navier-Stokes (NS)
  • Orion/MPCV Launch Abort System transient loads prediction - Cartesian NS

• Rotor Blade Noise: Isolated UAS Rotor in Hover Validation
  • Overset Curvilinear NS
  • Cartesian NS
  • Cartesian Lattice Boltzmann

• NASA Rotor Alone R4 Noise Source Diagnostics Test (SDT) – Cartesian NS (Preliminary)
Increase predictive use of computational aerosciences capabilities for next generation aviation and space vehicle concepts.

- The next frontier is to use wall modeled and/or wall resolved large-eddy simulation (LES) to predict:
  - Unsteady loads and fatigue
  - Fan, jet, and airframe noise
  - Buffet and shock BL interaction
  - Active flow control
Challenges in Computational Aero-Acoustics

✓ Grid Generation

• Structured Cartesian, Unstructured Polyhedrals, Structured Curvilinear; each paradigm has its own pros and cons → flexibility to pick best suited approach

• Remains a bottleneck → automation and solution-adaption

✓ Resolving/Modeling Turbulent Scales

• Resolving thin wall-bounded turbulence is too computationally costly for most aerospace applications → hybrid methods & wall-models

• Resolving all relevant scales of turbulent motion away from walls is also prohibitive → Higher order less dissipative numerics & subgrid-scale modeling

✓ Computational Requirements

• Space and time resolution requirements for acoustics problems are demanding.

• Explore revolutionary approaches to reduce computational time to reach converged statistics and spectra like Lattice-Boltzmann
Computational Grid Paradigms

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
Launch, Ascent, and Vehicle Aerodynamics

LAVA Framework

Structured Cartesian AMR

Unstructured Arbitrary Polyhedral Navier-Stokes

Structured Curvilinear Navier-Stokes

Post-Processing Tools

Far Field Acoustic Solver

Conjugate Heat Transfer

Actuator Disk Models

Aero-Structural

6 DOF Body Motion

Other Solvers & Frameworks

Prismatic Layers

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

Object Oriented Framework

C++ / Fortran with MPI Parallelism

Other Development Efforts

• Higher order methods
• Curvilinear grid generation
• Wall modeling
• LES/DES/ILES Turbulence
• HEC (optimizations, accelerators, etc)

Kiris at al. AST-2016 and AIAA-2014-0070
Outline

• Motivation

• LAVA Framework

• Jet Noise Prediction
  • Hybrid RANS/LES efforts on round jet – Overset Curvilinear Navier-Stokes (NS)
  • Orion/MPCV Launch Abort System transient loads prediction - Cartesian NS

• Rotor Blade Noise: Isolated UAS Rotor in Hover Validation
  • Overset Curvilinear NS
  • Cartesian NS
  • Cartesian Lattice Boltzmann

• NASA R4 Noise Source Diagnostics Test (SDT) – Cartesian NS (Preliminary)
High Fidelity Jet Noise Simulation Methodology for Airport Noise Prediction of Emerging Commercial Supersonic Technologies

Grand Challenge

Predict full Aircraft Noise with Installation and Propulsion

Path Towards the Grand Challenge

Radical Installation Concepts

Validation of Jet Prediction Capabilities

Shielding Concept Capabilities

Commercial Supersonic Technologies (CST)
Advanced Air Vehicle Program (AAVP)
Validation of Jet Noise Prediction Capabilities

- Experiment performed by Bridges and Wernet using the Small Hot Jet Acoustic Rig (SHJAR) at NASA Glenn
- Baseline axisymmetric convergent Small Metal Chevron (SMC000) nozzle at Set Point 7 (SP7) & Set Point 3 (SP3)

<table>
<thead>
<tr>
<th>Bridges et. al. (NASA-TM-2011-216807)</th>
<th>SP3</th>
<th>SP7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Mach number $U_{jet}/c_\infty$</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Jet temperature ratio $T_e/T_\infty$</td>
<td>0.950</td>
<td>0.835</td>
</tr>
<tr>
<td>Nozzle pressure ratio $p_t/p_\infty$</td>
<td>1.197</td>
<td>1.861</td>
</tr>
<tr>
<td>Nozzle Diameter $D$</td>
<td>0.0508 [m] 2.0 [inch]</td>
<td></td>
</tr>
</tbody>
</table>

Similar conditions were analyzed in Bres et. al. AIAA-2015-2535, but the boundary layer thickness is 5.5 times smaller in this study.
Validation of Jet Noise Prediction Capabilities

Objective:
✓ Assessment of Jet Noise Prediction Capabilities within LAVA solver.

Approach:
✓ Hybrid RANS/LES, wall-modeled LES (ZDES Mode III) efforts on canonical round jet geometries at different Mach numbers (SP7, SP3).

<table>
<thead>
<tr>
<th>solver</th>
<th>x/Dj [-]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridges &amp; Wernet</td>
<td>7.8</td>
<td>-</td>
</tr>
<tr>
<td>Wind, RANS-SA-2D</td>
<td>6.84</td>
<td>-12.3</td>
</tr>
<tr>
<td>Wind, RANS-SST-2D</td>
<td>9.01</td>
<td>15.5</td>
</tr>
<tr>
<td>LAVA, uRANS-SA-3D</td>
<td>7.22</td>
<td>-7.5</td>
</tr>
<tr>
<td>LAVA, RANS-NLES-SEM-3D</td>
<td>7.90</td>
<td>1.2</td>
</tr>
</tbody>
</table>

89.6% improvement

1 Wind Data, Objectives and Metrics from NASA Turbulence Modeling Resource (TMR) website: https://turbmodels.larc.nasa.gov
SP 7 Round Jet – Farfield Results

RMS center-line velocity

RMS lip-line velocity

Exp-Consensus
RANS-NLES
RANS-NLES-SEM
ZDES-Mode3

$\varphi = 60^\circ$

$\varphi = 90^\circ$

$\varphi = 120^\circ$

Band-Limited OASPL (dB)

Strouhal

PSD (dB/Hz)

Exp-Consensus
FWH (RANS-NLES-SEM)
FWH (ZDES-Mode3)

Jet Direction

Degrees

Band-Limited OASPL (dB)
Good agreement with measurements

Lower Jet Mach number significantly more challenging
Objective:
✓ Moving towards radical installation concepts.
✓ Jet-surface interaction noise is difficult to predict.

Approach:
✓ Assess Jet Surface Interaction Noise with ZDES (Mode 3).
✓ Improve Post-Processing tools to gain better understanding of the sound generation and shielding physics (permeable and impermeable FWH, beamforming)
First Step Towards Radical Installation Concepts

- Plate
- Circumferential wake mesh
- Nozzle mesh $y^+ < 1$
- Stretched Cartesian

### Points in Circ. Direction $\theta$

<table>
<thead>
<tr>
<th>Points in Circ. Direction $\theta$</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d\theta_4$</td>
<td>354</td>
</tr>
<tr>
<td>$d\theta_3$</td>
<td>178</td>
</tr>
<tr>
<td>$d\theta_2$</td>
<td>90</td>
</tr>
<tr>
<td>$d\theta_1$</td>
<td>90</td>
</tr>
</tbody>
</table>

### Streamwise Spacing

<table>
<thead>
<tr>
<th>Streamwise Spacing</th>
<th>medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points per nozzle D at 0.1 D</td>
<td>300</td>
</tr>
<tr>
<td>Points per nozzle D at 1 D</td>
<td>71</td>
</tr>
<tr>
<td>Points per nozzle D at 10 D</td>
<td>60</td>
</tr>
<tr>
<td>Points per nozzle D at 25 D</td>
<td>54</td>
</tr>
</tbody>
</table>

Choice of FWH surface not trivial.
Conflicting requirements on resolution and inclusion of all relevant sound generation and shielding physics.
First Step Towards Radical Installation Concepts

Initial Validation

Shielding Concept

- Measurement x, y, z locations mirrored at yz=0 plane
- R = 100Dₘₐₓ
- φ = 160

- LAVA medium (175M) - FWH2 shielded
- LAVA medium (175M) - FWH2 reflected
- shielded (11747)
- reflected (13390)
- isolated (12842)
Next Step Towards Radical Installation Concepts

Objective:

✓ Significantly increase complexity (last step before “grand challenge”).
✓ Multi-stream nozzle with shielding and installation effects.
✓ Comparison with comprehensive experimental database.

Picture taken from: Test Report: Top-Mounted Propulsion Test 2017 (TMP17), James Bridges
Ensuring Astronaut Safety

NASA is developing technologies that will enable humans to explore new destinations in the solar system. America will use the Orion spacecraft, launched atop the Space Launch System rocket, to send a new generation of astronauts beyond low-Earth orbit to places like an asteroid and eventually Mars. In order to keep astronauts safe in such difficult, yet exciting missions, NASA and Lockheed Martin collaborated to design and build the Launch Abort System.
Validating Acoustics Against 80AS Experiment

-- Wind Tunnel Measurements
-- LAVA Predictions
Launch Abort Vehicle

• Collaborated with the Orion Loads and Dynamics team at JSC to help characterize the vibro-acoustic environment of the Orion Launch Abort Vehicle (LAV) for launch and ascent abort scenarios

• LAVA solver was used to perform many scale-resolving, time-accurate simulations to investigate trends in vibration levels on the LAV surface across a range of Mach numbers and angles of attack, and to help reduce uncertainty in areas where experimental or test data are not available
• Motivation

• LAVA Framework

• Jet Noise Prediction
  • Hybrid RANS/LES efforts on round jet – Overset Curvilinear Navier-Stokes (NS)
  • Orion/MPCV Launch Abort System transient loads prediction - Cartesian NS

• Rotor Blade Noise: Isolated UAS Rotor in Hover Validation
  • Overset Curvilinear NS
  • Cartesian NS
  • Cartesian Lattice Boltzmann

• NASA R4 Noise Source Diagnostics Test (SDT) – Cartesian NS (Preliminary)
Towards Urban Air Mobility (UAM)
High-Fidelity Modeling and Optimization Method Development
NASA Revolutionary Vertical Lift Technology Rotary Project (RVLT)
Isolated UAS Rotor in Hover Validation

Objective:
- Validate LAVA for RVLT applications
- Assess pros and cons of body-fitted/Cartesian Grid as well as Navier-Stokes/Lattice Boltzmann approaches

Computational Methodology:
- Navier-Stokes (NS) URANS solver on Structured Overset Grid
- Navier-Stokes as well as Lattice Boltzmann (LB) on Cartesian Grid

Validation:
- Propeller Performance
- Far-field Acoustics

Experimental Data from Zawodny and Haskin AIAA-2017-3709
Isolated UAS Rotor in Hover Validation

<table>
<thead>
<tr>
<th>Zawodny and Haskin</th>
<th>(AIAA-2017-3709)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Span R</td>
<td>0.1905 [m]</td>
</tr>
<tr>
<td>Microphones (M1-M5)</td>
<td>10R</td>
</tr>
<tr>
<td>Considered RPM</td>
<td>5400</td>
</tr>
</tbody>
</table>

- Experiments conducted at NASA Langley LSAWT as well as in the Structural Acoustics Loads and Transmission (SALT) anechoic chamber.
- Motor-Rotor Assembly as well as Mount and Support structure not considered in simulations.

Experimental Data from Zawodny and Haskin AIAA-2017-3709
Structured Overset Curvilinear URANS Mesh Refinement Study

Family of 3 Structured Overset Grid Systems
Coarse: 6.64 M grid points
Medium: 14.61 M grid points
Fine: 35.73 M grid points
Each mesh built with double fringe and 0 orphans
Structured Overset Curvilinear URANS Rotor Performance at Different RPM

- Coarse
- Medium
- Fine
- SALT Exp

✓ uRANS with Spalart Allmaras Turbulence model SA
✓ Results verified to be grid independent
✓ No strong sensitivity to timestep choice or number of sub iterations per implicit timestep
Structured Overset Curvilinear URANS
Farfield Noise – Comparison to Microphone Data M1 & M3

Acoustic propagation using permeable FWH formulation
Good agreement with SPL spectrum for leading harmonics of the Blade Pass Frequency (BPF)
Structured Overset Curvilinear URANS
Farfield Noise – Directivity for Linear Microphone Array

- Excellent agreement observed in directivity for different RPM
- Better Agreement with SALT data for RPM 4800
LAVA Cartesian Methods

- Refinement ratio of 2:1
- Very Coarse: 40% tip chord (8lev)
- Coarse: 20% tip chord (9lev)
- Medium: 10% tip chord (10lev)
- Fine: 5% tip chord (11lev)

Isocontour of Q-criterion colored by Pressure. Simulation on medium Cartesian mesh.
Lattice Boltzmann Method
Rotor Performance at 5400 RPM

✓ Excellent agreement with experimental measurements
✓ Differences (< 1%) well within measurement uncertainty (highlighted in blue)
Lattice Boltzmann Method
Farfield Noise – SPL Spectrum for Observer M1 & M3

- Excellent agreement with BPF1-BPF5 for M1 (0.0°) microphone location
- Excellent agreement with BPF1 & BPF2 for M3 (45.0°)
- Different FWH formulations (permeable and impermeable) currently under investigation
✓ Consistent agreement for BPF1 on all mesh levels, BPF2 more sensitive.
✓ Good agreement for BPF 1 even on very coarse mesh.
Consistent prediction using both approaches

- Computational efficiency and complete absence of manual volume mesh generation key advantage of LBM

- Manual meshing efforts significantly increase upon considering installation effects (e.g. full Quadcopter or tiltwing urban air taxis)
**Outline**

- Motivation

- LAVA Framework

- Jet Noise Prediction
  - Hybrid RANS/LES efforts on round jet – Overset Curvilinear Navier-Stokes (NS)
  - Orion/MPCV Launch Abort System transient loads prediction - Cartesian NS

- Rotor Blade Noise: Isolated UAS Rotor in Hover Validation
  - Overset Curvilinear NS
  - Cartesian NS
  - Cartesian Lattice Boltzmann

- **NASA R4 Noise Source Diagnostics Test (SDT)** – Cartesian NS (Preliminary)
Aircraft Noise Reduction (ANR)

High Fidelity Acoustic and Performance Simulation of NASA R4 Noise Source Diagnostics Test (SDT)

POC for the experimental data : Ed Envia (GRC)
R4 Source Diagnostic Test
Toward Fan Broadband Noise Prediction

✓ Fan Noise Workshop Realistic Case 2 (RC2v2) at approach speed (7808 RPM) with baseline OGV design with goal to compare to hot-wire, LDV, and microphone test data

✓ LAVA Cartesian with fixed isotropic refinement zones from fan to exhaust

✓ Running two cases:
  – 6th order adaptive WENO [1]

✓ Moving geometry with immersed boundary representation
  – Impose slip boundary condition with 2nd order ghost cell method with ghost-in-fluid for thin geometry

✓ Coarse grid:
  – Min cell size = 2 mm
  – Number of degrees of freedom = 84M

✓ Medium grid:
  – Min cell size = 1 mm
  – Number of degrees of freedom = 387M

Isosurface of Q-criterion colored by axial velocity from LAVA Cartesian medium grid scale-resolving simulation with 2nd order kinetic energy preserving scheme (KEP)
Particle traces colored by U velocity magnitude
Particle traces colored by U velocity magnitude
Summary

Demonstrated predictive computational aeroacoustics capabilities
• Flexibility with respect to mesh paradigms
• Advancing revolutionary approaches like Lattice-Boltzmann Method

- Jet and aircraft noise
- Rotor and Fan noise
- Orion Launch Abort System
- Launch Pad design
This work was partially supported by the NASA ARMD’s Transformational Tools and Technologies (T^3), Advanced Air Transport Technology (AATT), Commercial Supersonic Transport (CST), Revolutionary Vertical Lift Technology (RVLT), and NASA HEOMD’s projects.

Computer time provided by NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center.