Jet Noise Prediction using Hybrid RANS/LES with Structured Overset Grids

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Outline

- Introduction
- Experimental Setup
- Computational Methodology
- Structured Overset Grid System
- Computational Results
  - Near-Field Comparison
  - Far-Field Comparison
- Summary
- Future Work
Introduction

- NASA has initiated research activities toward quiet supersonic flight.
- Reduction of sonic boom ground signature.
- Constraints during takeoff and landing at subsonic speeds must be satisfied.
- Use computational aeroacoustics (CAA) tools to assess new designs.
- First part of a systematic validation effort in jet noise prediction capability for NASA Ames Launch Ascend and Vehicle Aerodynamics Code (LAVA).
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Experimental Setup

- Small Hot Jet Acoustic Rig (SHJAR), which is located in the Aeroacoustics Propulsion Lab (AAPL) at NASA Glenn Research Center

Perspective view of SHJAR

PIV measurement device

Bridges et. al. (NASA-TM-2011-216807)
Experimental Setup

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

Bridges et al. (NASA-TM-2011-216807)  

<table>
<thead>
<tr>
<th>Parameter</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]</td>
</tr>
<tr>
<td></td>
<td>2.0 [inch]</td>
</tr>
<tr>
<td>Reynolds 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 to: Bres et. al. (AIAA-2015-2535)

“Bruit et vent” jet-noise facility at Centre d’Etudes Aerodynamique et Termique
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Computational Methodology

**LAVA Framework** (Kiris et al. Aerospace Science and Technology, Volume 55, 2016)

- Computational Fluid Dynamics Solvers
  - Cartesian, Curvilinear, and Unstructured Grid Types
  - Overset Grid and Immersed Boundary Methods
  - Steady and Unsteady RANS (Reynolds-Averaged Navier-Stokes)
  - Hybrid RANS/LES (Large Eddy Simulation), LES and LBM Capabilities

- Acoustic Solver
  - Linear Helmholtz Scattering Code
  - Permeable Surface Ffowcs Williams-Hawkings Propagation (FWH)
Computational Methodology

**LAVA Framework** (Kiris et al. Aerospace Science and Technology, Volume 55, 2016)

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Computational Methodology

3-D Structured Curvilinear Overset Grid Solver
- Spalart-Allmaras turbulence model (baseline turbulence model)

Low-Dissipation Finite Difference Method \textbf{(Housman et al. AIAA-2016-2963)}
- 6th-order Hybrid Weighted Compact Nonlinear Scheme (HWCNS)
- Numerical flux is a modified Roe scheme
- $6^{th}/5^{th}$-order blended central/upwind biased left and right state interpolation
- 2$^{nd}$-order accurate differencing used for time discretization

Hybrid RANS/LES Models
- Delayed Detached Eddy Simulation (DDES) model with modified length scale \textbf{(Housman et al. AIAA-2017-0640)}
- Zonal RANS-NLES (numerical LES) with user selected zones of URANS, NLES, and wall-distance based hybrid RANS-NLES \textbf{(see paper for details)}

Synthetic Eddy Method
- \textit{Coupling Methodology between RANS and LES to introduce realistic turbulent eddies} \textbf{(Jarrin et al. Int. Journal of Heat and Fluid Flow 30)}
Computational Methodology

- 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 such that first and second order turbulent statistics can be recovered. (approx. from the RANS solution with Bradshaw hypothesis)

Jet Case SP 7

\[
\Delta x S_{EM} = xe_{xit} - xSE_M \\
54 \delta < \Delta xSE_M < 55 \delta
\]
Computational Methodology

- Unsteady RANS until jet is fully developed and eddy viscosity maximum has plateaued
- Restart simulation with Hybrid RANS/LES Models until transient behavior washed out
- Ignore transients which are taken at first 30000 time steps and restart simulation
- Record Volume data at 100 kHz sampling frequency for greater than 0.02 seconds (approx. 205 convective time units)

<table>
<thead>
<tr>
<th></th>
<th>baseline</th>
<th>coarse</th>
<th>refined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processors</td>
<td>1392 (has)</td>
<td>260 (ivy)</td>
<td>960 (has)</td>
</tr>
<tr>
<td>Wall-Clock Time [days]</td>
<td></td>
<td></td>
<td>12.5</td>
</tr>
<tr>
<td>Sub-iterations</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Convergence</td>
<td></td>
<td></td>
<td>2-4 orders every sub-iteration</td>
</tr>
<tr>
<td>Number Eddies (SEM)</td>
<td></td>
<td>5000</td>
<td>5000</td>
</tr>
</tbody>
</table>

**Computational Methodology**

- **uRANS**
  \[ \Delta t = 1 \cdot 10^{-4} \text{[s]} ; 0.4 \text{[s]} \]

- **initialize Hybrid RANS/LES**
  \[ \Delta t = 1 \cdot 10^{-6} \text{[s]} ; \text{time steps > 30000} \]

- **final Hybrid RANS/LES**
  \[ \Delta t = 1 \cdot 10^{-6} \text{[s]} \]
  \[ St_{\text{max}} = 16.25, St_{\text{min}} = 0.008 \]
  \[ T_{\text{conv}} \approx 205 \]
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Structured Overset Grid System

- Baseline (256 M)
- Coarse (28 M)
- Refined (106 M)
- Seven point overlap
- No orphan points
- Minimum stencil quality 0.9
- Baseline follows Bogey et. al (AIAA-2016-0261)
Structured Overset Grid System

- Circumferential refinement in axial and radial direction
  Bres et. al. (AIAA-2015-2535)
Structured Overset Grid System

- Circumferential refinement

  Bres et. al. (AIAA-2015-2535)

Circumferential refinement in axial and radial direction

Coarse (28 M) vs. Refined (106 M)
Structured Overset Grid System

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

coarse | refined
90 | 180
180 | 360
360 | 720
baseline 360
Structured Overset Grid System

**axial/radial AR**

<table>
<thead>
<tr>
<th></th>
<th>$(x-x_{exit})/D$</th>
<th>AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>wall</td>
<td>-0.7</td>
<td>321.15</td>
</tr>
<tr>
<td>core</td>
<td>-0.7</td>
<td>0.50</td>
</tr>
<tr>
<td>wall</td>
<td>0.0</td>
<td>34.50</td>
</tr>
<tr>
<td>core</td>
<td>0.0</td>
<td>0.06</td>
</tr>
<tr>
<td>shear</td>
<td>$0.5 – 25.0$</td>
<td>10.50</td>
</tr>
<tr>
<td>core</td>
<td>$0.5 – 25.0$</td>
<td>1.05</td>
</tr>
</tbody>
</table>

**circumferential/radial AR**

<table>
<thead>
<tr>
<th></th>
<th>$(x-x_{exit})/D$</th>
<th>AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>wall</td>
<td>-0.7</td>
<td>436.82</td>
</tr>
<tr>
<td>core</td>
<td>-0.7</td>
<td>1.00</td>
</tr>
<tr>
<td>wall</td>
<td>0.0</td>
<td>221.00</td>
</tr>
<tr>
<td>core</td>
<td>0.0</td>
<td>1.00</td>
</tr>
<tr>
<td>shear</td>
<td>$0.5 – 25.0$</td>
<td>1134</td>
</tr>
<tr>
<td>core</td>
<td>$0.5 – 25.0$</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Structured Overset Grid System
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Computational Results
Computational Results

Flow Field Visualization: Iso-contours of Q-criteria colored by axial velocity

Visible 2D structures near the nozzle exit.

How can we improve/remove the 2D structures?
Computational Results

Indicator Function: DDES-256M

- Indicator function $f_d$ indicates RANS or LES mode.
- Stays in RANS mode in nozzle interior and quickly transitions to LES downstream of nozzle lip.
- Retains large eddy viscosity throughout the boundary layer.

$\mu_T/\mu_\infty$ : DDES-256M

$\phi_d = 1 - \frac{1}{2} [1 - \tanh(\epsilon_d (d_{wall} - d_0))]$

- $d_{wall}$ : wall distance
- $d_0$ : transition distance (user)
- $\epsilon_d$ : blending (user)
Computational Results

Indicator Function: DDES-256M

$\mu_T/\mu_\infty$: DDES-256M

Indicator Function: RANS-NLES-SEM-106M

$Y^+ \approx 100$
Computational Results

A

DDES-256M

B

RANS-NLES-106M

C

Waffle Cone Structure

D

RANS-NLES-SEM-28M

RANS-NLES-SEM-106M
Computational Results

RANS-NLES-SEM Refined Mesh

- Quasi-2D waffle cone structures at nozzle exit
- Size of turbulent structures appears to be too large inside nozzle
- Structures deep in the boundary layer show very little azimuthal variation
- Features are elongated and too highly correlated in both the streamwise and azimuthal direction
- *Do we have realistic, fully developed BL turbulence at the exit?*
Near-field turbulent statistics computed from DDES, RANS-NLES and RANS-NLES-SEM models for comparison with PIV data from the SHJAR

- Comparison of measurements to data at lipline (z/R=1) and centerline (z/R=0)
Near-Field: Time-Averaged Centerline

- Exp-Consensus
- DDES-257M
- RANS-NLES-106M
- RANS-NLES-SEM-106M

U/Ujet vs. x/D graph with different lines representing various simulations.
Near-Field: Time-Averaged Lipline

- Exp-Consensus
- DDES-257M
- RANS-NLES-106M
- RANS-NLES-SEM-106M
Near-Field: RMS Centerline

![Graph showing RMS Centerline](image)
Near-Field: RMS Lipline

![Graph showing RMS Lipline with different datasets: Exp-Consensus, DDES-257M, RANS-NLES-106M, RANS-NLES-SEM-106M.](image)

- **x/D** range from 0 to 25
- **Urms/Ujet** range from 0.00 to 0.25

Datasets:
- **Exp-Consensus**
- **DDES-257M**
- **RANS-NLES-106M**
- **RANS-NLES-SEM-106M**
Computational Results – Far-Field

FWH Permeable Surface

- Generated surface triangulation embedded within the overset grid
- FWH surface spans the entire axial domain of the computational grid
- Edge length of the triangles set to 5 mm

Observers 100 D away
FWH Permeable Surface

- Generated surface triangulation embedded within the overset grid
- FWH surface spans the entire axial domain of the computational grid
- Edge length of the triangles set to 5 mm

Observers 100 D away

currently used under consideration
Interpolate Volume solution to FWH surface at sampling rate of 
\[ \Delta t = 0.00001 \text{ s (100 kHz)} \]

Split time sample into 5 windows (or segments) with 50% overlap at 
\[ St_{bin} = 0.02 \]

Compute Integrands of FWH over each window independently 
- \( Q_n, F_1, F_2, F_3 \)
- Hanning Window is applied in the time-domain
- FFT is applied and stored for computing far-field observer noise levels

FWH surface integrals computed over each observer and window 
- 360 observers, uniformly distributed along the azimuth, for each angle 
  \( (60^\circ, 90^\circ, 120^\circ, 150^\circ) \)
- The PSD is ensemble averaged over the 360 observers
- PSD is multiplied by \( \sqrt{8/3} \) to recover RMS levels lost from Hanning Window

Finally, PSD spectrum is averaged over the 5 windows for final comparison to the experimental consensus.
Far-Field Comparison: PSD Spectrum at 100D from exit
Computational Results – Far-Field

Far-Field Comparison: Band-Limited OASPL ($0.08 \leq St \leq 8.0$)
Computational Results – Far-Field

Far-Field Comparison: Band-Limited OASPL ($0.08 \leq St \leq 8.0$)

[Diagram showing far-field comparison with computational results and experimental consensus.]

- Exp-Conensus
- FWH (5 windows $dSt = 0.02$)

[Graph showing PSD (dB/St) with Strouhal frequency and Band-Limited OASPL (dB).]
Computational Results – Far-Field

Time-Domain Pressure Associated with Peak Frequency (1100Hz) in 150°
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Summary

- The hybrid RANS/LES approach, within the LAVA framework, using structured curvilinear overlapping grids for the prediction of jet noise and compared our results to existing near-field PIV and far-field microphone data.

- Demonstrated improvements:
  - Hybrid RANS-NLES reduces the delay in transition to 3D turbulent structures and improved lip-line RMS prediction
  - SEM eliminates delay even further

- Completed far-field acoustic propagation
  - Mach wave radiation noise in the jet direction is well-captured
  - Sideline noise caused by turbulent fluctuations is over-predicted, likely due to elevated lip-line RMS at nozzle exit

- BL needs to be resolved better inside of nozzle for further improvements
A Posteriori Error Analysis

- Analyze the difference in turbulent kinetic energy using the resolved velocity field with filtered version of resolved velocity field.
- Independent filtering in each direction leads to anisotropic measure for refinement.

AIAA-2017-0978 Anisotropic grid-adaptation in LES of wall-bounded and free shear flows, Toosi and Larsson
Future Work

_A Posteriori_ Error Analysis

- Resolution in streamwise direction is lacking the most.
- The error estimate has largest magnitude in circumferential direction.
- Radial direction pretty good.
- Improved mesh (191 M) for further investigation of SP7 and all SP3 runs.

AIAA-2017-0978 Anisotropic grid-adaptation in LES of wall-bounded and free shear flows, Toosi and Larsson
Future Work

LES with explicit subgrid-scale (SGS) model and SEM

- No RANS downstream of SEM location
- Waffle cone structures inside nozzle reduced
- Artificial turbulence from SEM decays towards nozzle exit due to lack of resolution
- Recommended resolution: wall-resolved $\Delta s_{circ}^+ = 20$ (12.5k points)
  wall-modeled $\Delta s_{circ} = 0.1\delta$ (2450 points)

QUESTION:
”How will SGS model affect our lipline RMS and farfield solutions”
Acknowledgements

- This work was also 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.

- Patrick J. Moran from NASA Ames visualization team for rendering of numerical schlieren video.

- Team members of LAVA group for helpful discussions and advise: Joseph George Kocheemoolayil, Francois Cadieux, Michael Barad
Questions?
Far-Field PSD

Far-Field Comparison: PSD Spectrum at 100D from exit
Hybrid RANS/LES

Non-Zonal model:

- DES suffers from model stress depletion (forces transition to LES but mesh too coarse to resolve field)
- DDES remains in RANS mode in attached BL. Shielding function often shows strange behavior in transition (RANS -> LES -> RANS -> LES)
- Improved length scale (Shur, Spalart, Strelet): depletes eddy viscosity faster.
- Grey-Zone-Problem: mesh fine enough to trigger 3d fluctuations in the BL, but not fine enough to resolve largest scales in BL for accurate skin-friction.

Zonal model:

- User defines zones of RANS, LES and RANS/LES
- Numerical LES (NLES) includes wall distance and $y^+$ based transition
- Grey-Zone-Problem is still an issue

\[
f_d = 1 - \frac{1}{2} \left[ 1 - \tanh\left( \epsilon_d (d_{\text{wall}} - d_0) \right) \right]
\]

- $d_{\text{wall}}$ : wall distance
- $d_0$ : transition distance (user)
- $\epsilon_d$ : blending (user)
Hybrid RANS/NLES

\[ LES/RANS = (1 - \Gamma(\eta)) \cdot [LES] + \Gamma(\eta) \cdot [RANS] \]

\[ \Gamma(\eta) = \frac{1}{2} - \frac{1}{2} \cdot \tanh \left[ C_1 \cdot (\eta - \eta_0) \right] \]

\( \eta \) distance from the wall
\( \eta_0 \) controls where the blending starts
\( C_1 \) controls the blending “width“
Synthetic Eddy Method (SEM)


1. Define a Box of eddies with:

\[ x_{j,\text{min}} = \min_{x \in S} (x_j - \sigma_{ij}(x)) \quad x_{j,\text{max}} = \max_{x \in S} (x_j + \sigma_{ij}(x)) \]

2. Generate for each eddy \( k \) random vectors for the location \( x^k \) and intensity \( \varepsilon^k \)

3. Compute the velocity signal on the set of Points \( S \) with:

\[
 u_i = U_i + \frac{1}{\sqrt{N}} \sum_{k=1}^{N} a_{ij} \varepsilon^k f_{\sigma_{ij}} (x - x^k) 
\]

\[
 f_{\sigma_{ij}} (x - x^k) = \sqrt{V_b} \cdot \frac{1}{\sigma_{i1}} f \left( \frac{x_1 - x_{1}^k}{\sigma_{i1}} \right) \cdot \frac{1}{\sigma_{i2}} f \left( \frac{x_2 - x_{2}^k}{\sigma_{i2}} \right) \cdot \frac{1}{\sigma_{i3}} f \left( \frac{x_3 - x_{3}^k}{\sigma_{i3}} \right) 
\]

\[
 f(x) = \begin{cases} 
 \sqrt{\frac{3}{2}} (1 - |x|) & x < 1 \\
 0 & \text{else} 
\end{cases} 
\]

4. Convect the eddies through \( B \) with velocity \( U_{\text{ref}} \)

\[ x^k(t + dt) = x^k(t) + U_{\text{ref}} \cdot dt \]

5. Generate new locations \( x_k \) and intensities for eddies which were convected out of \( B \).
   Advance to next time step and go back to step 3
Launch Ascend and Vehicle Aerodynamics (LAVA)

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 Parallelism
Domain Connectivity/ Shared Data

Other Solvers & Frameworks

Prismatic Layers

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

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

Connected

Existing

Developing

Not Yet Connected

Future

Framework

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