Open Rotor Computational Aeroacoustic Analysis with an Immersed Boundary Method

Michael F. Barad§, Christoph Brehm*, Cetin C. Kiris§

Presented at
Stanford University

§Computational Aerosciences Branch
NASA Ames Research Center
*University of Arizona, Tucson

May 4, 2016
1. Introduction to Acoustic Analysis of Contra Rotating Open Rotor

2. Numerical Methods

3. Computational and Experimental Setups

4. Comparison with Experiments

5. Brief Analysis Acoustic Near-Field for High and Low Speed Cases

6. Summary
Introduction – The Big Picture

- Renewed interest in contra-rotating open rotor (CROR) propulsion technology due to large potential of significantly reducing fuel consumption (in context of HWB see Thomas et al. AIAA 2014-0258, Hendricks et al. AIAA 2013-3628)

- Noise generation from CROR is key concern and must meet community noise and cabin noise standards

- Reliable noise prediction capabilities are required for the design of low noise CROR systems

GE36-UDF propfan demonstrator engine installed on MD-81 test bed aircraft (8x8)  Modern contra-rotating open rotor engine design from CFM (12x10)
NASA initiated several efforts that successfully addressed the noise prediction aspects for CROR mainly in free air.

There are two extreme approaches for modeling CROR noise:

- a) Empirical models (cheap but lacks generality)
- b) Fully resolved CFD (general but too expensive)

Model source region separate (hydrodynamics) from acoustic propagation.

Various tools are already available:

- Acoustic: ASSPIN/ASSPIN2, FW-H$_{ps}$, FSC, LINPROP, QUADPROP
- Aerodynamics: SBAC, UBAC, FUN3D, Overflow, LAVA

Different aspects of CROR noise generation have been studied:

- **Broadband noise** can be important (flow conditions & observer angles) (Node-Langlois et al. AIAA 2014-2610, Sree & Stephens AIAA 2014-2744)
- **Initial attempts** have been made to study installation effects (Dunn & Tinetti AIAA-2012-2217, Node-Langlois et al. AIAA 2014-2610)
A key challenge is to devise an efficient method that can capture installation effects.

Current approach:
- Utilizing Cartesian AMR solver module within Launch Ascent and Vehicle Aerodynamics (LAVA) framework
- Ffowcs-Williams and Hawkings (FW-H) method for acoustic noise propagation
- Comparison with experiments and Housman & Kiris (2016) utilizing LAVA’s curvilinear-overset solver

Objectives of this work:
1. Develop moving boundary capabilities inside LAVA-Cartesian
2. Validate LAVA-Cartesian+FW-H approach against experimental data
3. Analyze noise propagation for nominal takeoff and cruise conditions
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Launch Ascent & Vehicle Aerodynamics (LAVA)

LAVA is being developed at NASA Ames Research Center

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

**Unstructured Arbitrary Polyhedral**
- Grid generation is mostly automated
- Body fitted grids
- Grid quality can be questionable
- High computational cost
- Higher order methods are yet to fully mature

**Overset Structured Curvilinear**
- High quality, body fitted grids
- Low computational cost
- Reliable higher order methods are available
- Grid generation is largely manual and time consuming

*Kiris et al.(2014), Sozer et al. (2014), Brehm et al. (2014)*
Immersed boundary method (IB) allows automatic volume mesh generation from water tight surface triangulation.

For problems involving moving and deforming boundaries IB provides clear advantages (for example no mesh deformation needed).

Main disadvantage is that at high Reynolds numbers, IBs become inefficient or require some type of wall function.

Most immersed boundary methods are only lower order accurate.

Sharp higher-order IB inside LAVA-Cartesian:

Circle immersed in Cartesian Grid

Setup in Vicinity of Immersed Boundary

Dependence of Spectral Radius on free stencil coefficient

Brehm et al. (JCP 2013, JCP 2015)
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Extensions of original IB:

1. Address IB challenges that are associated with the moving boundary problem.
2. Deal with geometry queries and recomputation of irregular stencils in an efficient way.

Brehm et al. (JCP 2013, JCP 2015)
IB Challenges for Moving Boundary Problems

X-Ray Tracing Algorithm:

- Use discrete triangulations instead of level-set functions
- Using an optimized bounding volume hierarchy (BVH) based ray-tracing method [thanks to Intel's Embree and Tim Sandstrom]
IB Challenges for Moving Boundary Problems

Identification of Trapped Points:
- Occur in gaps that are smaller than irregular stencil size
- Current treatment is to reduce order of accuracy in the relevant direction

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Point Cloud Selection:

- Current method does not use ghosts
- Graph walking for stencil clouds: Full clouds are build up from individual clouds at irregular points (reduces number of intersection tests)
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Freshly-Cleared Cells (FCC):
- Invalid time history at FCC
- Utilize neighboring information to update data in FCC (exclude other FCCs in point cloud), i.e., backfilling with least-squares + BC.
- More advanced approaches are being considered

$t = t_n$
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Viscous Wall Treatment at High Reynolds Number

- Utilize wall model to mimic effect of viscous wall
- No-slip separates too early and slip wall stays attached all the way
- Viscous wall treatment is an ongoing research topic

presented at AIAA BANC III
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6. Summary
Flow Conditions

9 x 15 Low-Speed Wind Tunnel

8 x 6 Supersonic Wind Tunnel

<table>
<thead>
<tr>
<th>Cases</th>
<th>Low Speed</th>
<th>High Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation Speed [RPM]</td>
<td>6303/6303</td>
<td>6848/6848</td>
</tr>
<tr>
<td>Blade Setting (fwd/aft) [°]</td>
<td>40.1/40.8</td>
<td>64.4/61.8</td>
</tr>
<tr>
<td>Mach</td>
<td>0.20</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Pressure Sensors

- M=0.2
- M=0.78
Computational Setup

- 4th-order explicit RK time-integration with Δt defined through CFL≈1
- Implicit large eddy simulation based on previous experience with jet impingement problem

Block Structured Cartesian Mesh

- Each box contains $16^3$ grid points

Grid Refinement Study for $M=0.2$:

- 8 Levels: $\Delta x_{\text{min}}=8\times10^{-3}$, $N_{\text{tot}}=65M$
- 9 Levels: $\Delta x_{\text{min}}=4\times10^{-3}$, $N_{\text{tot}}=110M$
- 10 Levels: $\Delta x_{\text{min}}=2\times10^{-3}$, $N_{\text{tot}}=160M$
- 11 Levels: $\Delta x_{\text{min}}=1\times10^{-3}$, $N_{\text{tot}}=350M$
Unsteady Flow Field – Passive Particle Viz
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Comparison With Experiments (Low Speed)

Velocity Magnitude Contours

Iso-surface of velocity magnitude with $|v|/|v_\infty|=0.84$ (red) and 1.91 (blue)

- Good agreement of velocity magnitude contours with experiment
- Evolution of tip vortices seems to be well captured
Thrust Comparison

- Note that only pressure drag was considered (ratio 4:100 for $M=0.78$).
- Fluctuations in thrust values for LAVA-Curvilinear are due to reflections at outflow boundaries.
- Agreement with experiment is in the range of other computations (LAVA-Curvilinear, Overflow, and FINE™/Turbo).
Far-Field Spectra

- **BPF** = blade passing frequency
- **Shaft order (SO)** = frequency/shaft rotation rate

**Low Speed (at Probe 9)**

**High Speed (at Probe 9)**

- **SPL [dB]**
- **shaft order**
Far-Field Spectra

Only consider tones with $SO(m,n)=12m+10n$
Plate effect was accounted for by assuming perfect reflection (6dB=10\log_{10}(2^2))

- Simulation with plate at first row of acoustic sensors
- Numerical simulations results with plate show odd tones
- Plate affects broadband noise level
- Plate does not affect the most dominant tones
Fundamental tones decay rapidly away from the blades.

OASPL is increasing with increasing geometric angle.

Small difference in OASPL for fine and medium mesh.

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- Small difference in OASPL for fine and medium mesh.
Spatial Dependence Of Tones (Low Speed)

Fundamental Tones

- Fundamental tones decay rapidly away from the blades
- OASPL is increasing with increasing geometric angle
- Small difference in OASPL for fine and medium mesh
- Higher-order interaction tones obtain significant amplitudes similar to fundamental tones

Higher-Order Interactions

- Experiment
- CFD
Spatial Dependence Of Tones (high Speed)

- Fundamental tones dominate OASPL
- Added tonal SPL with BPF1+BPF2 only for comparison
- General trends are well captured for low and high speed cases
- Broadband noise important at small x (<-0.4) and large x (>0.4)
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Unsteady Flow Field — Numerical Schlieren

Low Speed

High Speed
Near Field Acoustic Analysis (Low Speed)

- Analysis captures acoustic waves but also hydrodynamic instability waves
- BPF1 and BPF2 are dominant in a very small region around the rotors and along the tip vortices
- Various higher-order interactions play an important role
BPF1 and BPF2 are the dominant frequencies

BPF1+BPF2 is dominant along the tip vortices and induces unsteady shock motion that generates acoustic waves in the back
Near Field Acoustic Analysis (BPF2)

- BPF2 amplitude is dominant in small region around rotor for $M=0.3$ while strong acoustic waves radiate away from the front rotor for $M=0.78$

- BPF2 remains dominant along the tip vortices for $M=0.2$

- Similar observations for BPF1
Interaction of rear rotor with tip vortex from front rotor generates BPF1+BPF2 tone (C, D & F)

- Region B appears to originate from midsection of rear rotor
- Region E originates from the wake and plays dominant role for large geometric angles
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6. Summary
LAVA’s sharp immersed boundary (IB) method was used to simulate flow around a contra-rotating open rotor for nominally takeoff and cruise conditions.

Key issues for simulating moving boundaries with IB were addressed:
- Treatment of freshly cleared cells
- Efficient geometry queries
- Efficient computation of irregular stencils (every time-step!)
- Treatment of thin geometry:
  - Interior only scheme
  - Stencil cloud selection
  - Interpolation to thin surfaces

Acoustic data obtained from combination of CFD near-field + FW-H method compare well with experiments.

Distinct differences in low and high speed acoustic fields:
- OASPL for $M=0.78$ peaks around $90^\circ$ while OASPL keeps increasing with increasing geometric angle.
- High speed case is dominated by BPF1 and BPF2.
- Low speed case showed complicated higher-order interactions that are relevant for the OASPL.
This work was supported by the NASA Advanced Air Transport Technology (AATT) project under the Advanced Air Vehicles Program (AAVP)

Edmane Envia and Christopher Miller of NASA Glenn Research Center for information on modeling open rotor noise and meshing requirements

Jeff Housman of NASA Ames Research Center for many fruitful discussions on modeling open rotor noise

Tim Sandstrom (optimized ray-tracing kernels, and particle visualizations) and Patrick Moran (Schlieren visualization) of NASA Ames Research Center

Team members of the acoustic working group

Computer time provided by NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center
Unsteady Flow Field – Passive Particle Viz

M=0.2

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Unsteady Flow Field – Numerical Schlieren

Low Speed Case

High Speed Case
Odd and Difference Tones

- Following theory by Envia (IJA-2015, Vol 13, No. 3&4)
- Theory predicts dominant tones with $SO(m,n)=12m+10n$
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- Difference tones decay rapidly? $\Rightarrow f(n)$ and $g(n)$ control the radiation efficiency

Thickness Noise:

$$p'_{T_{n}}(x) = iB_{1} \sum_{n=1}^{2} \frac{A_{T_{n}}^{(n)}}{R^{n}} e^{mB_{1}(\mu - i\Psi)} d_{0,n} \left\{ \frac{A_{1} \left[ (mB_{1})^{2/3} \gamma^{2} \right]}{mB_{1}} \right\} dS(\tilde{y}),$$

Loading Noise:

$$p'_{L_{n,k}}(x) = iB_{1} \sum_{n=1}^{2} \frac{A_{L_{n,k}}^{(n)}}{R^{n}} e^{(mB_{1}-kB_{2})(\mu - i\Psi)} d_{0,n} \left\{ \frac{A_{1} \left[ (mB_{1}-kB_{2})^{2/3} \gamma^{2} \right]}{|mB_{1}-kB_{2}|^{1/3}} \right\} dS(\tilde{y}),$$
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Taken from Envia (IJA-2015)
Far-Field Spectra

**Low Speed**

- Difference tones excluded: Less efficient radiators

**High Speed**

- Loading noise is dominant on aft blade

Envia (IJA-2015)
Spatial Dependence Of Tones (high Speed)

- Fundamental tones dominate OASPL
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