LAVA Applications to Open Rotors*

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Cetin C. Kiris, Jeff Housman, Mike Barad, Christoph Brehm
Computational Aerosciences Branch (TNA)
NASA Ames Research Center

cetin.c.kiris@nasa.gov

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• **LAVA (Launch Ascent Vehicle Aerodynamics)**
  - **Introduction**
  - **Acoustics Related Applications**

• **LAVA Applications to Open Rotor**
  - **Structured Overset Grids**
  - **Cartesian Grid with Immersed Boundary**
    - **High Speed Case**
    - **High Speed Case with Plate**
    - **Low Speed Case**
Launch Ascent Vehicle Aerodynamics (LAVA)

**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
Multi-Disciplinary Analysis Framework

- Block Structured Cartesian AMR
- Unstructured Arbitrary Polyhedral
- Overset Structured Curvilinear

- Lattice Boltzmann
- Far Field Acoustic Solver
- Conjugate Heat Transfer
- Smoothed Particle Hydrodynamics
- Structural Dynamics
- 6 DOF Body Motion

LAVA
Object Oriented Toolkit
C++ / FORTRAN with MPI Parallel
Domain Connectivity/ Shared Data

Current Development Efforts
- Higher Order Methods
- Grid Generation
- Wall Function
- LES/DES/ILES Turbulence
- HEC (GPU and future platforms)

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

Post-Processing Tools
Other Solvers & Frameworks

Connected
Existing
Developing

Not Yet Connected
Future
Framework
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OASPL predictions within 3 dB are obtained

Good comparison in PSD observed

\[ M = 1.8 \]

\[ \theta = 90^\circ \]

\[ \theta = 120^\circ \]
BANC III Workshop problem has been revisited
QFF tunnel study has been performed for conventional slat and various Krueger slat geometries
Major algorithmic improvements have been implemented in the LAVA solver framework to help support the ERA noise reduction goals:

- Improved DDES model with enhanced LES length scale and zonal DES approach
- Increase from 5th order to 7th order accurate convective flux discretization in the span-wise direction
- Blending of the upwind and central variable interpolation procedures for increased spectral resolution
Figure 10. Time averaged solution for wheel wake plane 4. Contour levels min/max levels are as follows:
-10/75 (U-Mean), -10/75 (V-Mean), 0/100 (Z-Vorticity) and 0/200 (TKE).

**Far Field Acoustic SPL**

**PIV Mean Turbulent Kinetic Energy Comparison**
High fidelity CFD simulation of Four-Jet-Impingement device that is used as broadband noise source

Gauge Pressure (atm)

Engine placement study is performed using linear acoustic scattering code

Comparison of BENS simulation with experimental results by Hutcheson et al. (2014)

Experimental Setup to emulate Broadband Engine Noise

Sound Pressure Level Obtained with Linear Acoustic Scattering Code using Reduced Order Model
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• **LAVA Applications to Open Rotor**
  • *Structured Overset Grids*
  • *Cartesian Grid with Immersed Boundary*
    • High Speed Case
    • High Speed Case with Plate
    • Low Speed Case
LAVA Structured Overset – Open Rotor

- CROR Overset Simulation (High Speed)
  - Computational Approach
  - Overset Grid System
  - Acoustic Propagation Surfaces
  - Flow Visualization
  - Results and Comparison to WT Data
- Single Blade Time-step Resolution Study
  - Geometry and Overset Grid System
  - Solver Parameters
  - Results and Conclusions
- Fine Mesh Overset Grid System (High Speed and Low Speed)
  - Comparison between new and old grid systems
High Speed Case Setup

Conditions:

- Mach = 0.78
- Rotation speed = 6848 [RPM]
- Pressure = 101325.353 [Pa]
- Velocity = (265.4709, 0.0, 0.0) [m/s]
- Temperature = 288.15 [K]
- Condition for blades: fwd @ 64.4, aft @ 61.8 degrees
- Sound field measured at 0.43, 0.51, 0.69, 0.87, 1.16 [m]
- Initial runs have no plate or wind-tunnel geometry included (plate is included in a subsequent analysis)
LAVA Overset - Computational Approach

- 3-D Structured Overset Curvilinear Navier-Stokes Solver
- Hybrid RANS/LES using Spalart-Allmaras
- Modified Roe convective flux – 5th order WENO reconstruction
- 2nd order central differencing for viscous fluxes
- 2nd order backward differencing in time (\(dt = 1.2e-05\) s – \(\frac{1}{2}\) deg.)
- Implicit dual-time stepping (\(CFL_{loc} = 10\), \(CFLT_{loc} = 10\))
  - 20 sub-iterations (approx. 2-3 orders of residual reduction)
  - Alternating Line Jacobi Relaxation (2 sweeps)
- A total of 11 rotor revolutions were simulated from an impulsive start using free-stream conditions (1 rev. \(\approx\) 20hrs. on 980 cores)
- Impermeable Ffowcs Williams-Hawkings formulation for far-field propagation from solid surfaces
- SPL Spectral data obtained by averaging 5 segments, each segment contains 4 rotor revolutions with a single rotor revolution overlap
CROR Overset Grid System

- 123 zones and 164.6 M grid points
- Triple fringe with 0 orphans
- Grid script required $< 2$ days to make
- Blade deflection angle parameterized
- Grid generation + connectivity 7-10 min.
- Computed $y+$ 4-5 at blade tip
- $\Delta \theta = 6\text{mm}$ $\Delta r = 7\text{mm}$ near blade tip
3 closed surface triangulations were generated to store unsteady CFD data for acoustic propagation.

- An edge length 8.65 mm is used.
- Triangulation is labeled with component IDs allowing various combinations of surfaces to be included in propagation.
Overset Grids – Flow Visualization

Iso-contour of vorticity magnitude colored by pressure

Magnitude of Density Gradient

Acoustic waves generated by the fwd and aft blades propagated in both the upstream and downstream directions and interact with the fish tail shock on the strut of the hub
• Time-averaged thrust appears slightly larger than the WT data
• Computed y+ near the blade tips are between 4 and 5 causing an under-prediction of the viscous contribution leading to larger thrust
• Small oscillations appearing every 4.5 to 5 rotor revolutions is caused by inflow boundary condition reflection effects (these effects have been reduced using highly stretched far-field grid and non-reflecting BCs)
Overset — SPL Spectral Comparison

- Capturing nBPF₁ and nBPF₂ (n ≤ 4 and higher)
- Capturing BPF₁ + BPF₂, BPF₁ + 2 BPF₂, 2 BPF₁ + BPF₂, and BPF₁ + 3 BPF₂
- Loss of magnitude at 3 BPF₁ + BPF₂

Not capturing magnitude of subtractive interactions well

Kulite 9 H = 0.51m

SPL (dB) vs. Shaft Order
Acoustic surface 2 appears to provide the best comparison at interaction frequencies.

2BPF₁+2BPF₂ and greater interaction amplitudes not well captured.
Overset - SPL Tone Comparison

**Kulite 9**

- **BPF2**
  - WT Data (-6dB)
  - CFD+FWH

- **BPF1**
  - WT Data (-6dB)
  - CFD+FWH

- **BPF1 + BPF2**
  - WT Data (-6dB)
  - CFD+FWH

**Sound Pressure Level (dB)**

**Vertical Distance From Rotor Axis (m)**

- 0.5
- 0.6
- 0.7
- 0.8
- 0.9
- 1.0
- 1.1
- 1.2

- 120
- 125
- 130
- 135
- 140
- 145
- 150
- 155
- 160
- 165
Curvilinear solver utilized implicit 2\textsuperscript{nd} order backward differencing in time allowing large time-steps to be utilized while maintaining stable solutions with viscous meshes

When utilizing high-resolution spatial discretizations, temporal error discretization may dominate if too large a time-step is used

A time-step resolution study for a single forward rotor (modeling 1/12\textsuperscript{th} of the geometry) was performed to determine an accurate time-step for the finest mesh open rotor calculation

Outline of the study:

- Geometry and overset grid description
- Numerical discretization and solver parameters
- Simulation results
- Conclusions

Recent enhancements implemented in the Curvilinear LAVA code to be used in future Open Rotor simulations
**Geometry and Overset Grid**

- Single forward blade mounted on hub with cylindrical extension (1/12th model)
- 11 zones, 52.1 M points
- Triple fringe (no orphans)
- Entire grid rotates (no relative motion)
Discretization and Solver Parameters

- LAVA structured overset grid curvilinear Navier-Stokes solver
- Hybrid RANS/LES using Spalart-Allmaras
  - Unsteady Reynolds Averaged Navier-Stokes (URANS)
  - Manual specification of RANS/LES interface based on URANS
  - Delayed Detached Eddy Simulation (DDES)
- Modified Roe convective flux – 5th order reconstruction
- 2nd order central differencing for viscous flux
- 2nd order backward differencing in time
  - $dt = 1.217\times10^{-5}$ seconds (1/2 deg.)
  - $dt = 6.085\times10^{-6}$ seconds (1/4 deg.)
  - $dt = 3.042\times10^{-6}$ seconds (1/8 deg.)
  - $dt = 1.521\times10^{-6}$ seconds (1/16 deg.)
  - $dt = 7.606\times10^{-7}$ seconds (1/32 deg.)
- Strict 2-orders of magnitude residual reduction each physical time-step (requires different number of sub-iterations for each $dt$)
- 3.5 - 5 rotor revolutions completed for each case
**Time-step Resolution Results**

**Single Forward Blade Loads**
- Thrust appears to converge within 3.5 to 4 rotor revs
- Almost no difference is observed in the predicted loads with respect time-step changes
Wake Resolution Time-Step Sensitivity

Very Smooth Structures

Starting to develop 3D structures

\( dt = \frac{1}{2} \) deg.

\( dt = \frac{1}{4} \) deg.
Wake Resolution Time-Step Sensitivity

Earlier Development

Slightly better resolution and lower cost (better convergence)

\[ \text{dt} = 1/8 \text{ deg.} \]

\[ \text{dt} = 1/16 \text{ deg.} \]
Time-step Resolution Results

Wake Resolution Time-Step Sensitivity

No significant change in wake resolution and twice the cost

\( dt = 1/16 \) deg.

\( dt = 1/32 \) deg.
Time-step Resolution Results

Wake Resolution Turbulence Model Sensitivity
($dt = 1/16$ deg.)
**Trailing Edge/Hub Corner Separation**

Separated flow interacts with downstream boundary layer of the hub.

Strong separation occurs at the intersection of the blade trailing edge and the hub.
Fine Mesh Overset Grid System

- 268 zones, 836.7 M points
- Triple fringe layer
- No orphans
- Finer wall spacing for y+ 1
- Extended farfield
- Improved blade grids
- Circumferential spacing < 0.25 deg.
Fine Mesh Overset Grid System

5.5 M to 10.6 M points per blade

Improved topology

Highly Refined

Old

New
Summary and Future Work

LAVA Structured Overset

• Algorithm improvements:
  • Far-field BCs and Grid-Stretching Strategy to reduce reflections
  • High-order Blended Upwind/Central Variable Interpolation

• Lessons Learned:
  • Smaller time-step (1/16th deg.) leads to more accuracy and efficiency with increased sub-iteration convergence
  • Utilization of DDES model with improved length scale increases the resolution capacity of the grid and reduces delay in the development of 3D turbulent structures

• Open rotor simulations:
  • High speed case
    • Coarse mesh (164M) complete
    • Fine mesh (837M) in progress
  • Low speed case
    • Fine mesh (837M) in progress
OUTLINE

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Computational Approach:

- 3D Cartesian Navier-Stokes Solver
- 5th and 6th order WENO spatial discretization
- Higher-order immersed boundary method
- 4th order explicit Runge-Kutta time stepping \( (dt = 1/16 \text{ degree}) \)
- Rotor revolutions are simulated from an impulsive start using free-stream conditions
- Advanced post-processing used final rotor revolutions
Cartesian Immersed-Boundary

- Sharp interface immersed-boundary representation of geometry
- Boundary condition imposed at grid line intersection points
- No ghost cells needed inside body (thin body capturing capability)
- Stencil optimized for stability and higher-order accuracy
- Parallel geometry kernels are implemented:
  - Inside-outside testing by multi-resolution binning
  - Exact distance to surface triangulation
    (including point to plane and point to edge cases)
- Excellent for highly complex geometry, and AMR

Brehm et al. (JCP 2013, 2015)
**Cartesian Grid with Moving OR Geometry**

**High Speed Case**

**Grid System**

- 35846 zones and 146.8 M grid points
- No manual volume gridding, only surface triangulation required
- $\Delta x = 2\text{mm}$ near blades, $\Delta x = 4\text{mm}$ in wake region
**Grid System**

- 35846 zones and 146.8 M grid points
- No manual volume gridding, only surface triangulation required
- $\Delta x = 2\text{mm}$ near blades, $\Delta x = 4\text{mm}$ in wake region

Boxes are shown, where each box is $16^3$ cells.
LAVA Cartesian : WENO5 vs WENO6

Vorticity contours @ 10000 [1/s]
LAVA Cartesian: WENO6 Vorticity

Vorticity contours @ 10000 [1/s], colored by pressure
Passive particles seeded at trailing edges of blades: red is fwd, blue is aft seeding
LAVA Cartesian – WENO5
Disturbance Pressure

\[ P' = P - P_{ave} \]
LAVA Cartesian – WENO5
Density Gradient
SPL Spectral Comparison

- Capturing nBPF\(_1\) and nBPF\(_2\) (n ≤ 4 and higher)
- Capturing BPF\(_1\) + BPF\(_2\), BPF\(_1\) + 2 BPF\(_2\), 2 BPF\(_1\) + BPF\(_2\), and BPF\(_1\) + 3 BPF\(_2\)
- Loss of magnitude at 3 BPF\(_1\) + BPF\(_2\)

Kulite 9 H = 0.51m

Experiment
Immersed WENO5
Curvilinear

4 Revs Used for FFT
SPL Spectral Comparison

- Capturing nBPF\(_1\) and nBPF\(_2\) (n ≤ 4 and higher)
- Capturing BPF\(_1\) + BPF\(_2\), BPF\(_1\) + 2 BPF\(_2\), 2 BPF\(_1\) + BPF\(_2\), and BPF\(_1\) + 3 BPF\(_2\)
- Loss of magnitude at 3 BPF\(_1\) + BPF\(_2\)
Thrust Comparison

Note immersed approach is not accounting for viscous effects (pressure force only)
Different noise generation mechanisms are dominating different parts of the flow field.
Different noise generation mechanisms are dominating different parts of the flow field.
Inserted plate into existing Cartesian (WENO5) simulation. Preliminary results:

- Additional grid points for plate
- Elevated velocity/CFL occurred at leading and trailing edge
- Plate trailing edge has unsteady wake shedding
Comparisons show that the plate (@43cm) introduces flow differences:
- Asymmetry in vortex core “web” due to confinement (below right)
- Plate wake break-down (below left)
Comparisons show that the plate (@43cm) introduces flow differences:

- Acoustic blocking can be seen when compared to no-plate case
- Elevated pressure levels due to confinement
- Possible higher-harmonics
Comparisons show that the plate (@43cm) introduces flow differences:

- Elevated broadband levels
- Finer grid resolution should further improve broadband content
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- Elevated broadband levels
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LAVA Cartesian: Plate Effects

Frequency at peak amplitude [shaft orders] 

Amplitude at peak frequency
Shaft Order = 14 \( (2 \times \text{BPF}_1\text{-BPF}_2) \)
 Shaft Order = 30  (3 x BPF₁)
LAVA Cartesian : Plate Effects

Shaft Order = 33

Amplitude

Phase
Shaft Order $= 36 \ (3 \times \text{BPF}_2)$

LAVA Cartesian: Plate Effects
Low Speed Case Setup

• **Conditions:**
  
  • Mach = 0.2
  
  • Rotation speed = 6303 [RPM]
  
  • Pressure = 101325.353 [Pa]
  
  • Velocity = (68.06946, 0.0, 0.0) [m/s]
  
  • Temperature = 288.15 [K]
  
  • Takeoff condition for blades: fwd @ 40.1, aft @ 40.8 degrees
  
  • Sound field measured at 1.524 [m] or 60 inches (as given by E. Envia)
  
  • No plate or wind-tunnel geometry included
Cartesian Immersed Boundary: Mesh

2mm

4mm

8mm

Total: 147 Million Cells
Cartesian Immersed Boundary Startup Transient (Pressure)
LAVA Cartesian - Pressure Movie

Time = 0 (s)
Time step = 0
Mach = 0.20, RPM = 6303
LAVA Cartesian - Vorticity @ 5000 [1/s]
LAVA Cartesian - Vorticity @ 2000 [1/s]
Summary and Future Work

LAVA Cartesian Immersed

- Algorithm improvements:
  - Thin blade handling for Immersed Boundary Method (IBM) ✓
  - High-order IBM ✓
  - Optimizations for moving bodies with IBM
    - Geometry kernels (progressing)
    - Stencils (progressing)
- Open rotor simulations:
  - High speed case
    - Coarse mesh (146M) ✓
      - Convective scheme sensitivity ✓
      - Plate effects ✓
    - Wind tunnel walls (8’x6’) ✗
  - Low speed case
    - Coarse mesh (147M) (running, currently at 7 revs)
      - Once enough revs are computed, will conduct more detailed analysis

Ref: AIAA-2014-2606