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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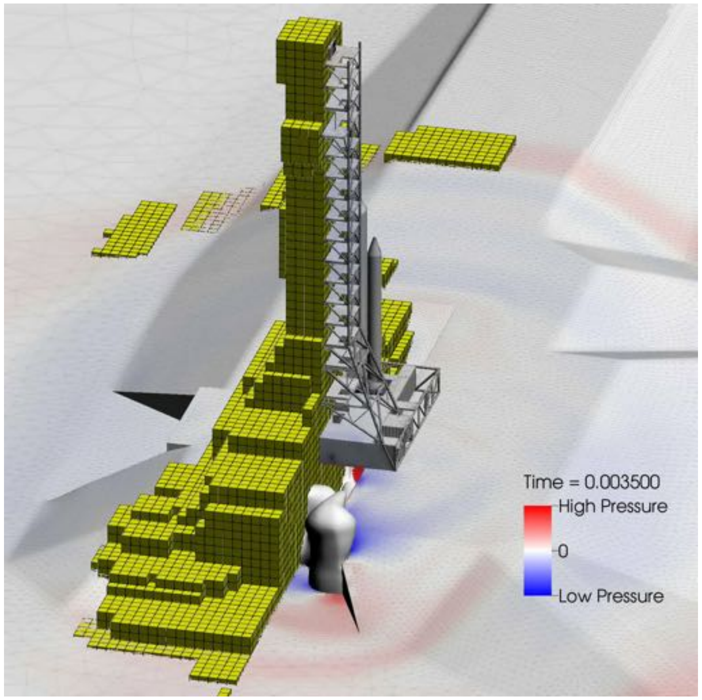
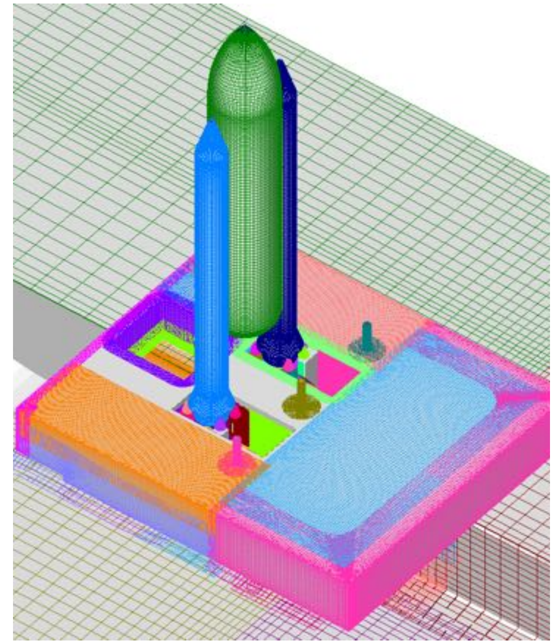
Outline

- *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

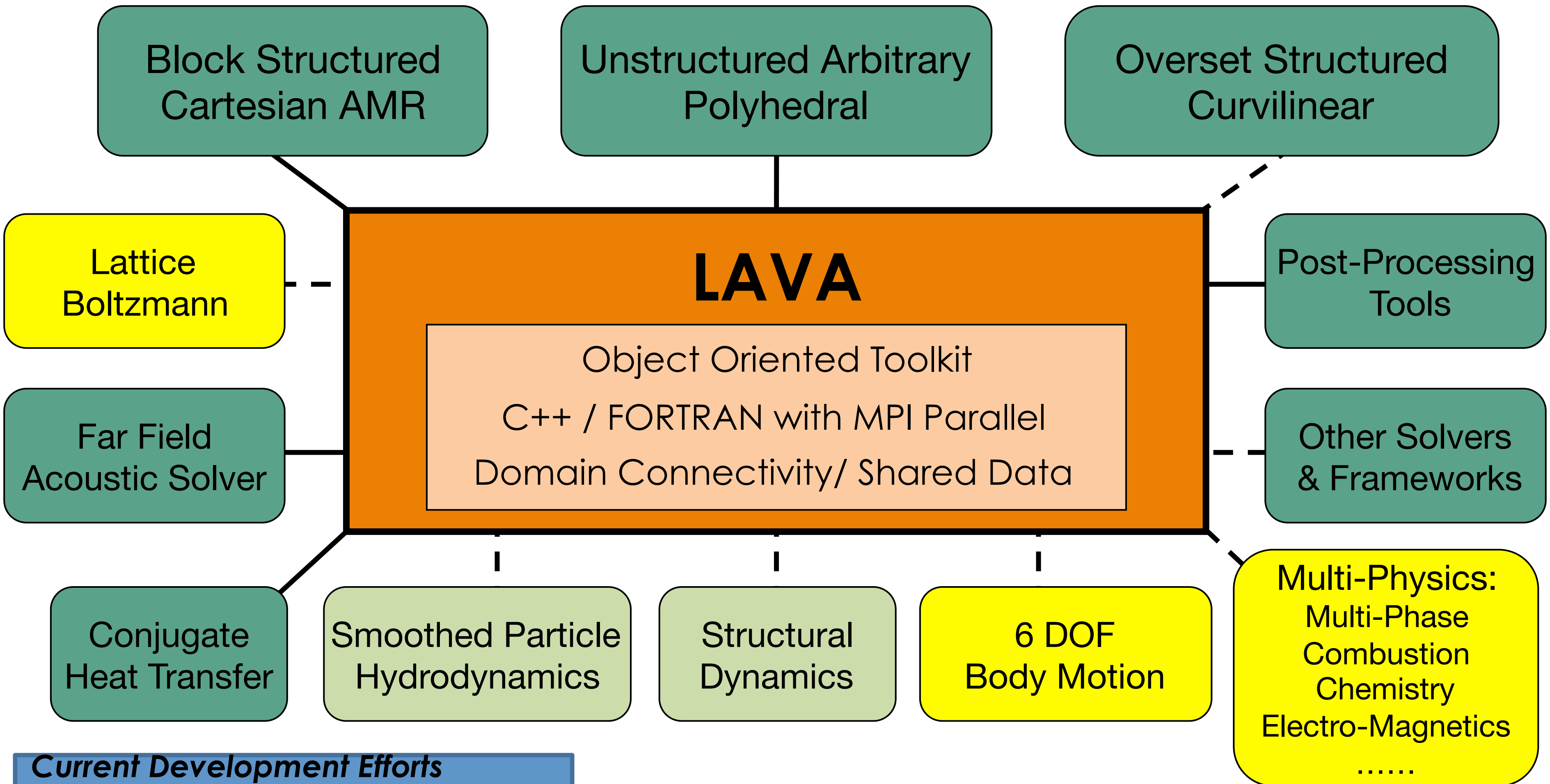
Unstructured Arbitrary Polyhedral

- 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



Current Development Efforts

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

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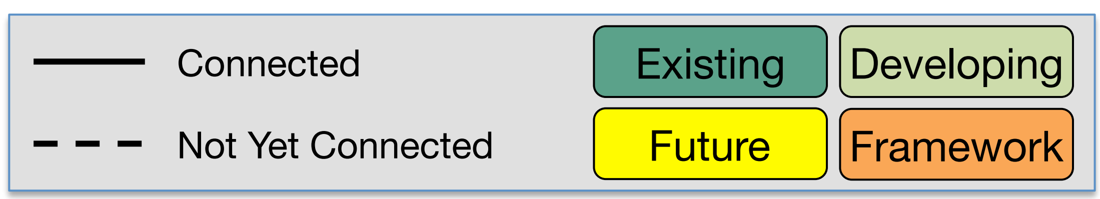

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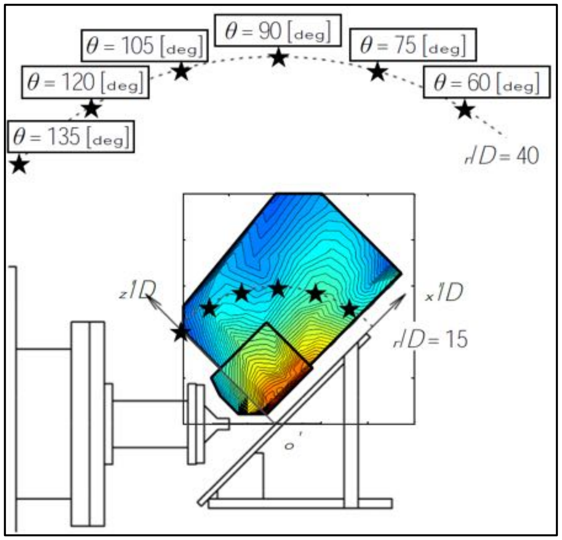
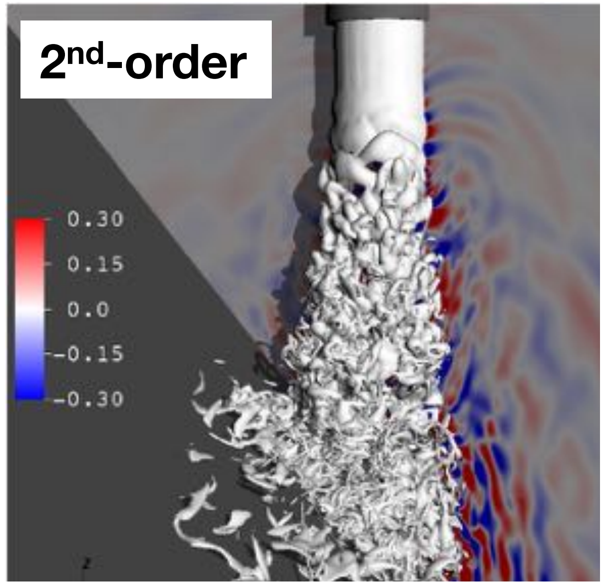
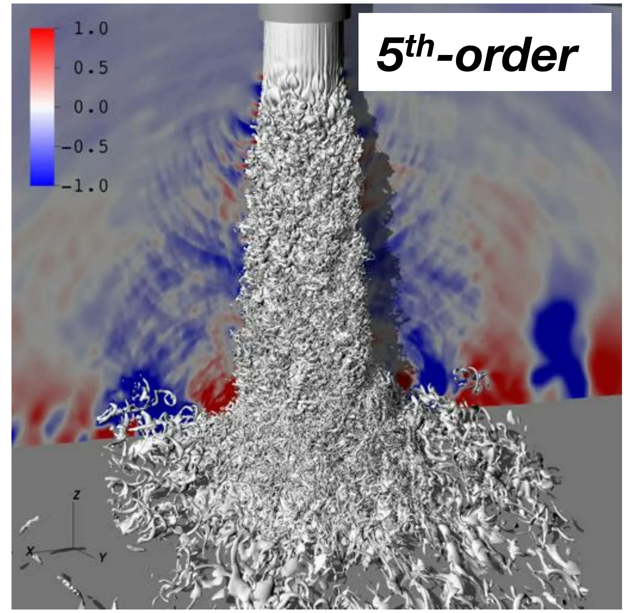
JAXA Collaboration - Jet Acoustics

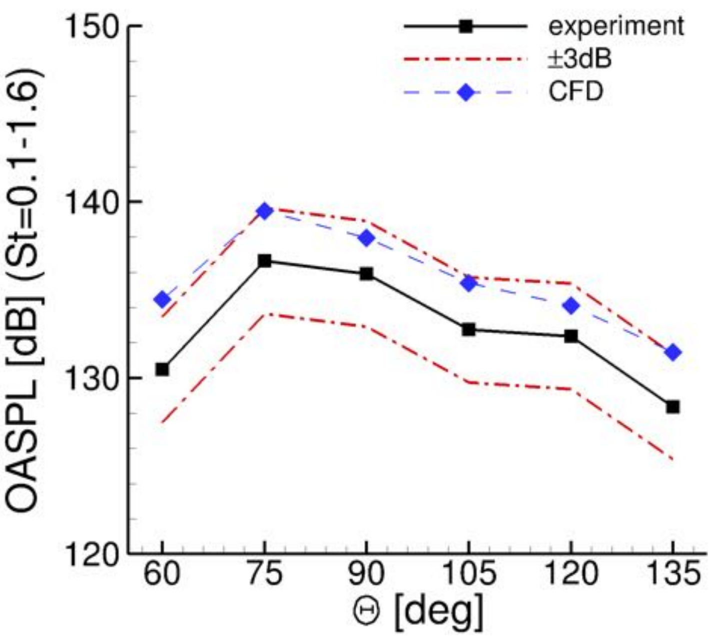


University of Tokyo Experiment
Nakanishi et. Al. AJCPP2012-129

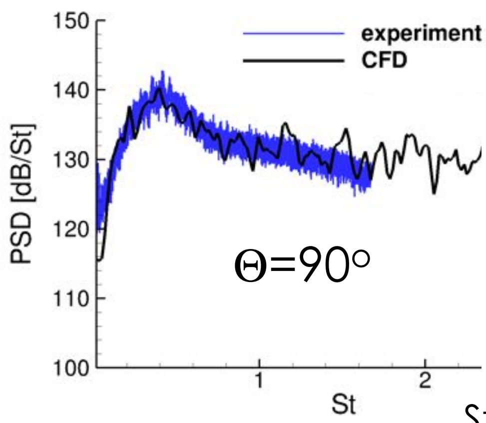


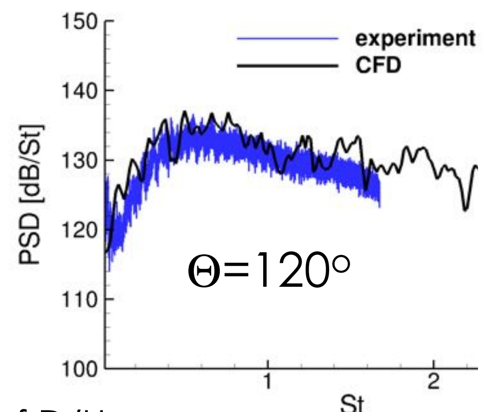


M=1.8



- OASPL predictions within 3 dB are obtained
- Good comparison in PSD observed

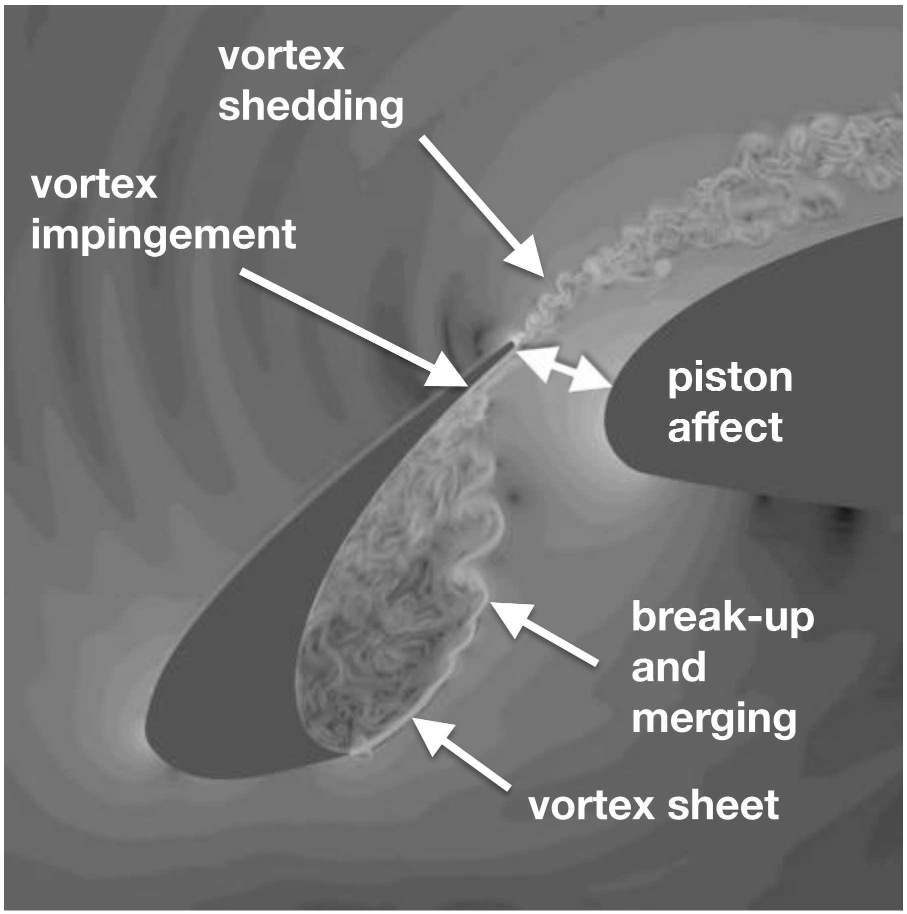




St = f D/U

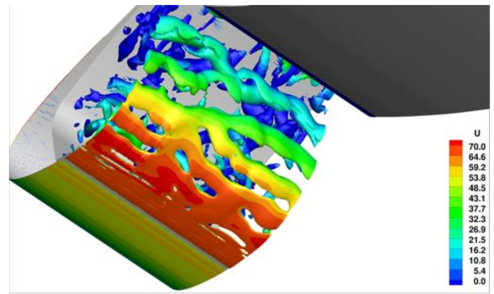
ERA/TTT – Slat Noise Prediction

- BANC III Workshop proplem has been revisited
- QFF tunnel study has been performed for conventional slat and various Krueger slat geometries

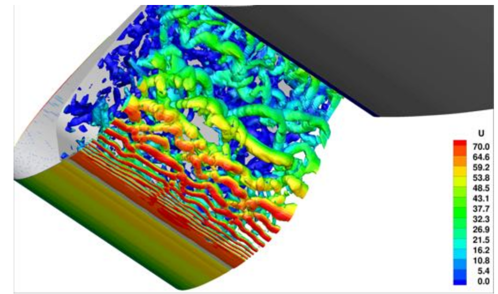


TTT –Enhancement in LAVA for Slat Noise

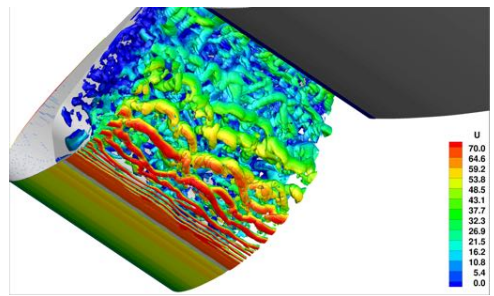
- Major algorithmic improvements have been implemented in the LAVA solver framework to help support the ERA noise reduction goals:
  - Improved DDES model with enhanced LES length scale and zonal DES approach
  - Increase from 5th order to 7th order accurate convective flux discretization in the span-wise direction
  - Blending of the upwind and central variable interpolation procedures for increased spectral resolution



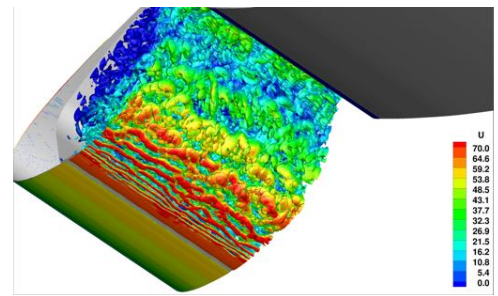
Original Algorithm



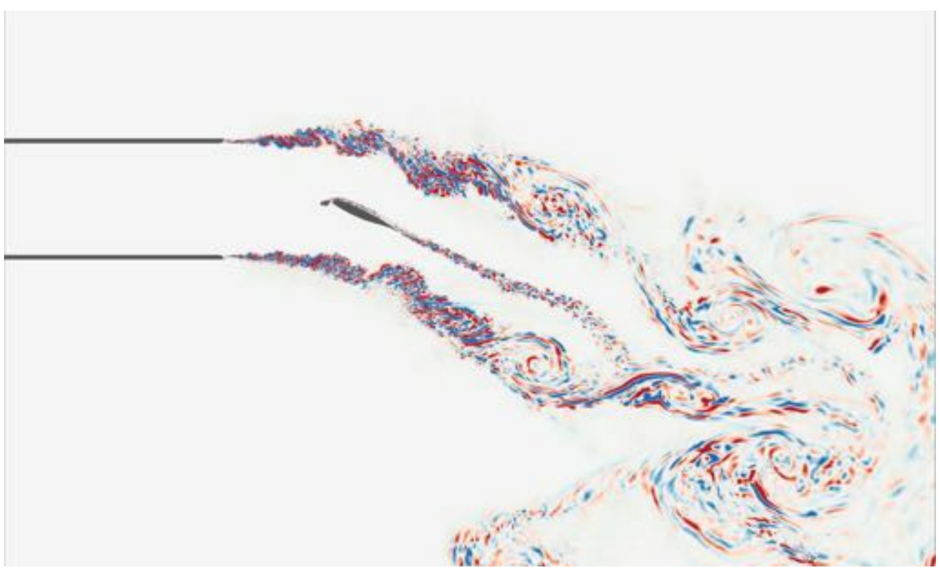
Improved DDES model

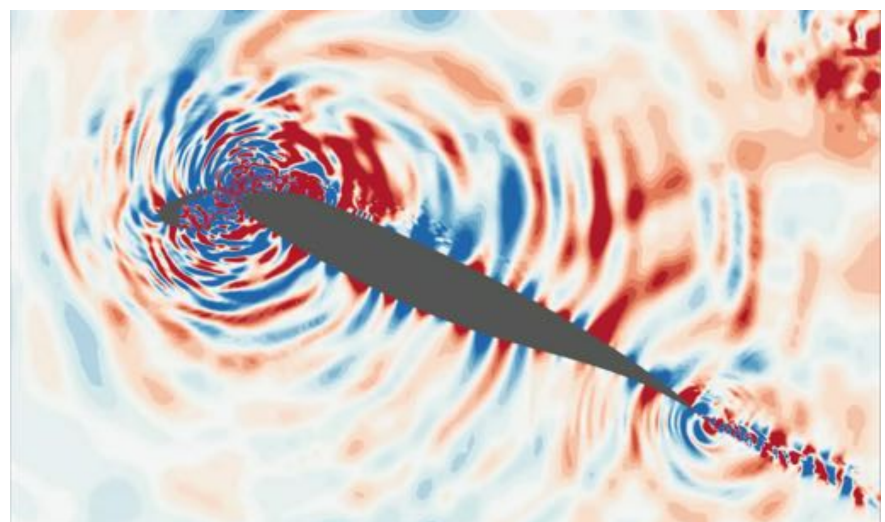


7th order accurate in span

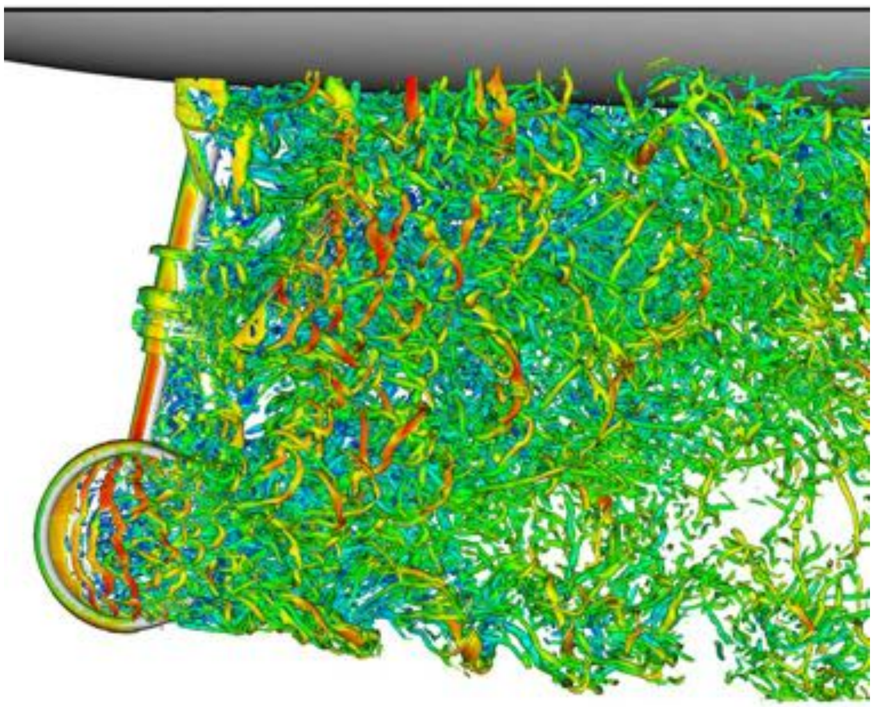


Blended Upwind/Central

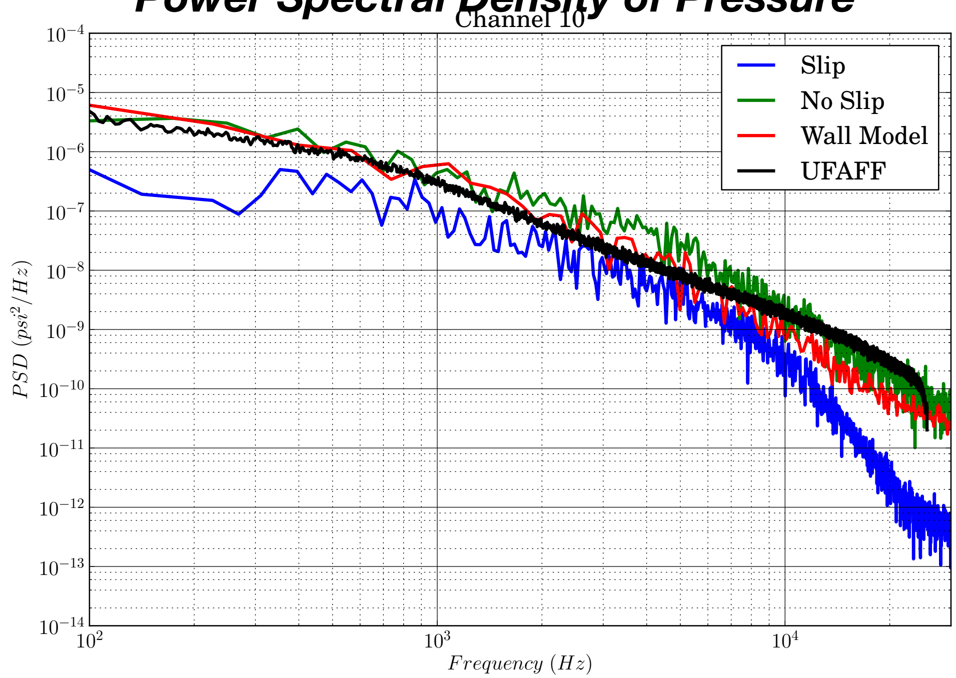




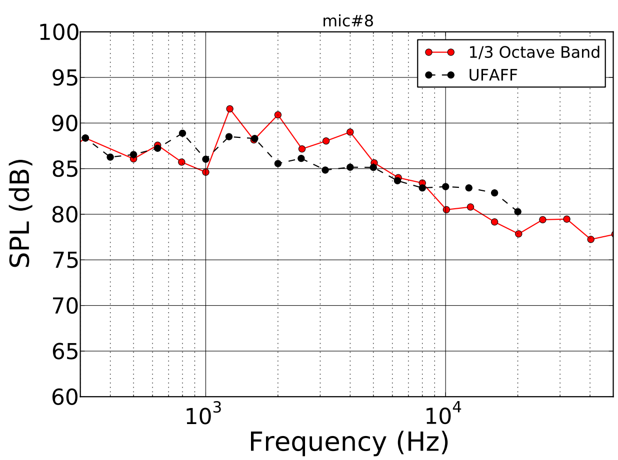
TTT - Gulfstream Landing Gear (AIAA BANC III)



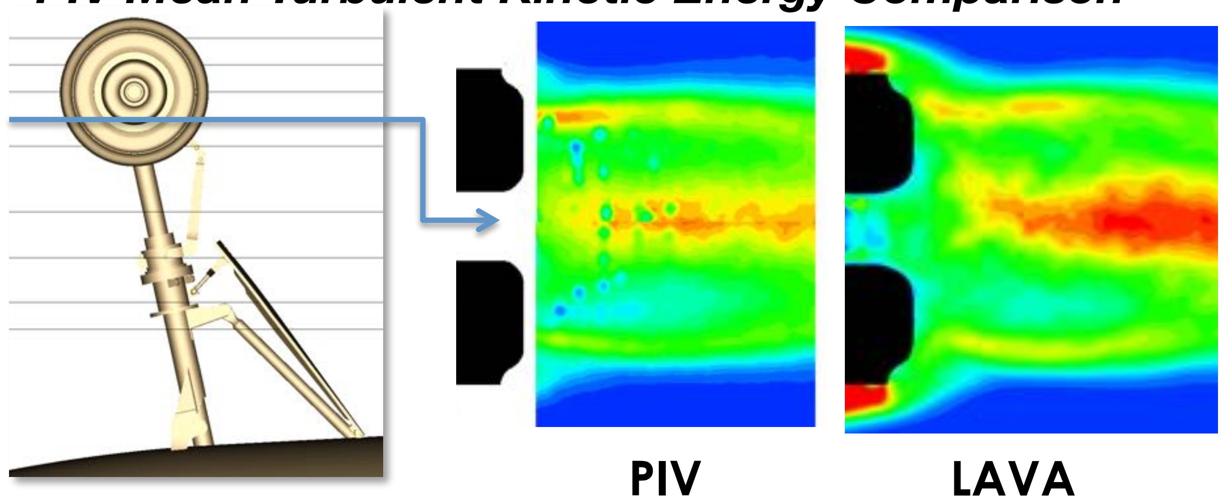
Power Spectral Density of Pressure



Far Field Acoustic SPL

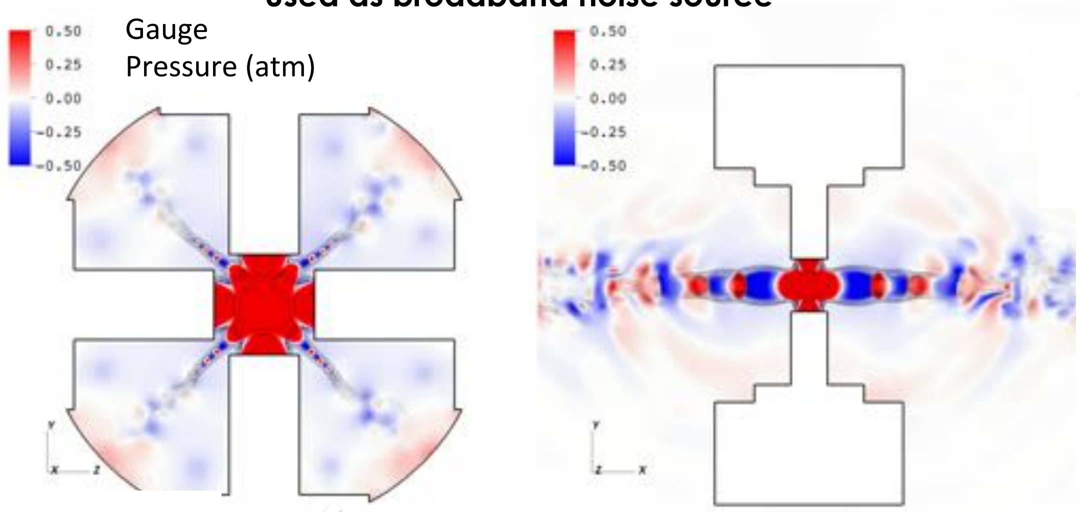


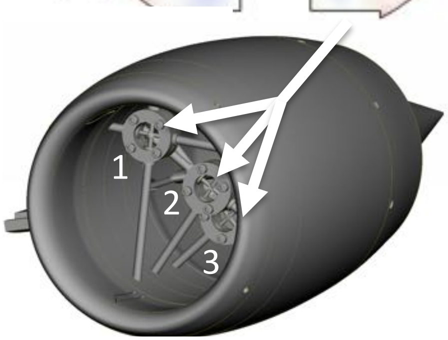
PIV Mean Turbulent Kinetic Energy Comparison



ERA - Hybrid Wing Body Engine Noise Emulator

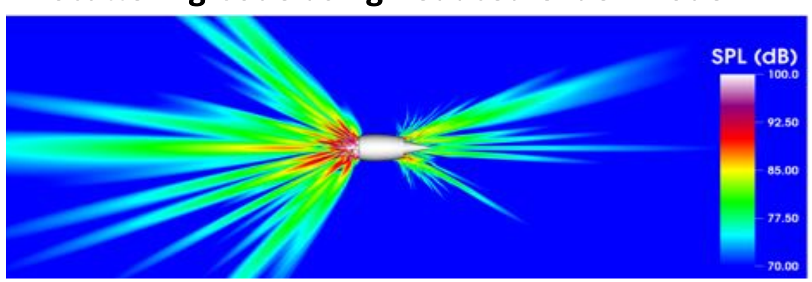
High fidelity CFD simulation of Four-Jet-Impingement device that is used as broadband noise source





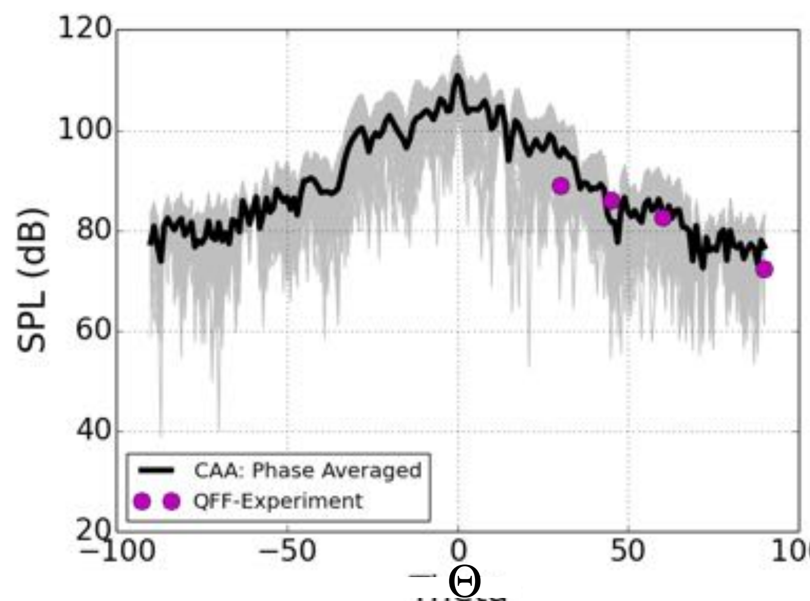
Experimental Setup to emulate Broadband Engine Noise

Sound Pressure Level Obtained with Linear Acoustic Scattering Code using Reduced Order Model



Engine placement study is performed using linear acoustic scattering code

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



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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:

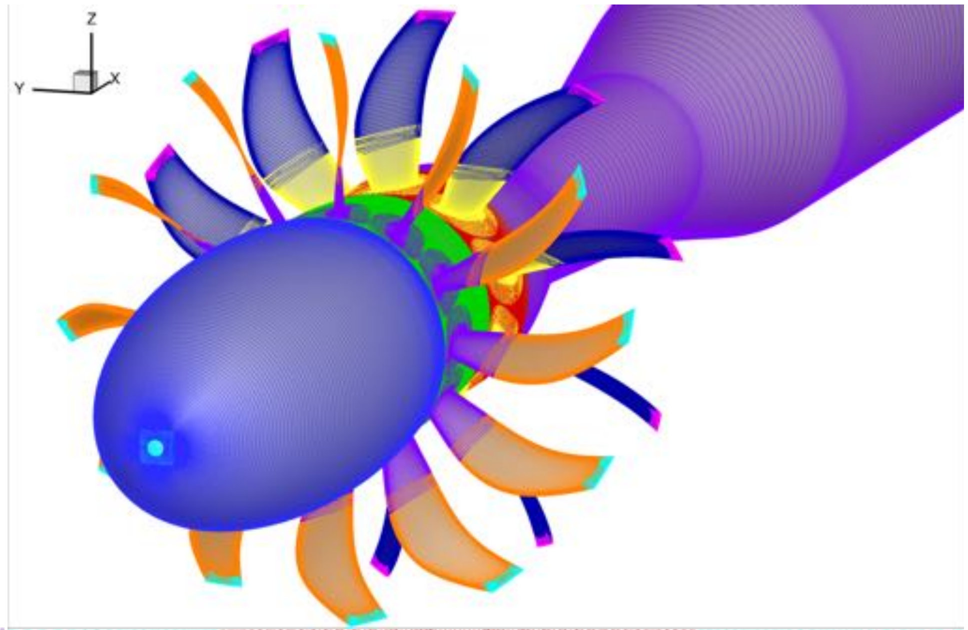
- Mach = 0.78
- Rotation speed = 6848 [RPM]
- Pressure = 101325.353 [Pa]
- Velocity = (265.4709, 0.0, 0.0) [m/s]
- Temperature = 288.15 [K]
- Condition for blades: fwd @ 64.4, aft @ 61.8 degrees
- Sound field measured at 0.43, 0.51, 0.69, 0.87, 1.16 [m]
- Initial runs have no plate or wind-tunnel geometry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

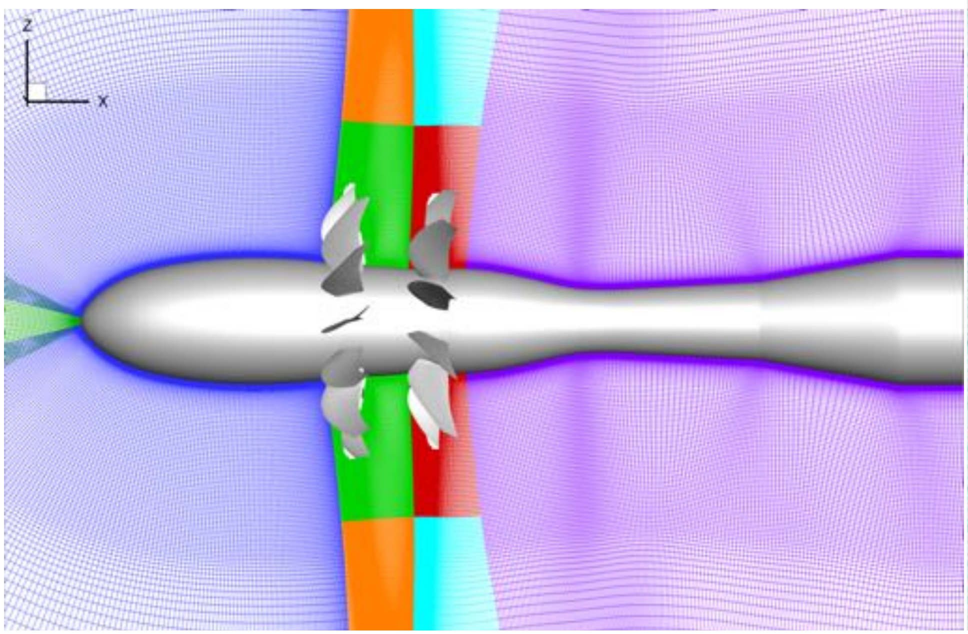
LAVA Overset - Computational Approach

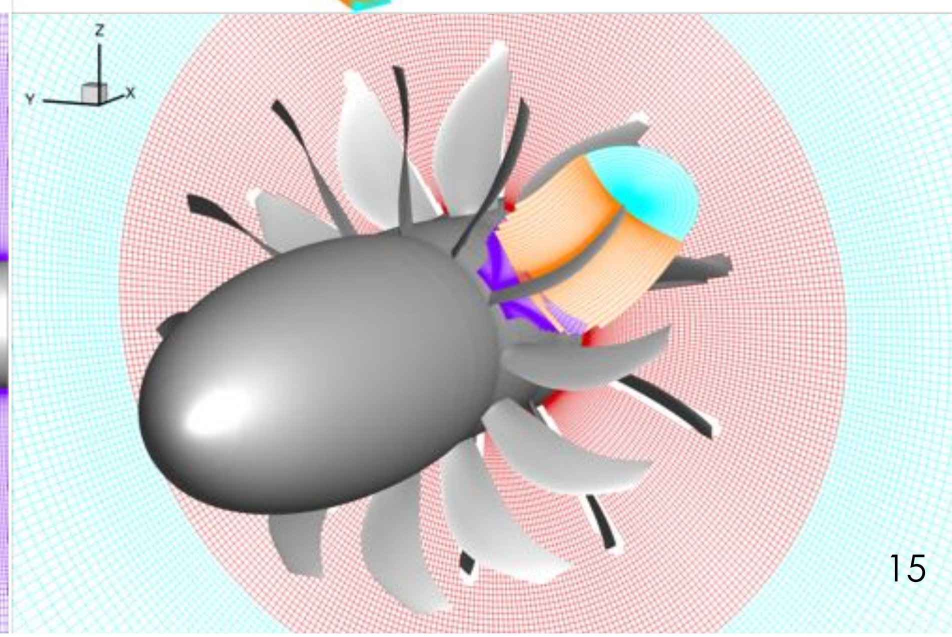
- 3-D Structured Overset Curvilinear Navier-Stokes Solver
- Hybrid RANS/LES using Spalart-Allmaras
- Modified Roe convective flux – 5th order WENO reconstruction
- 2nd order central differencing for viscous fluxes
- 2nd order backward differencing in time (dt = 1.2e-05 s – ½ deg.)
- Implicit dual-time stepping (CFLloc = 10, CFLTloc = 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. ≈ 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

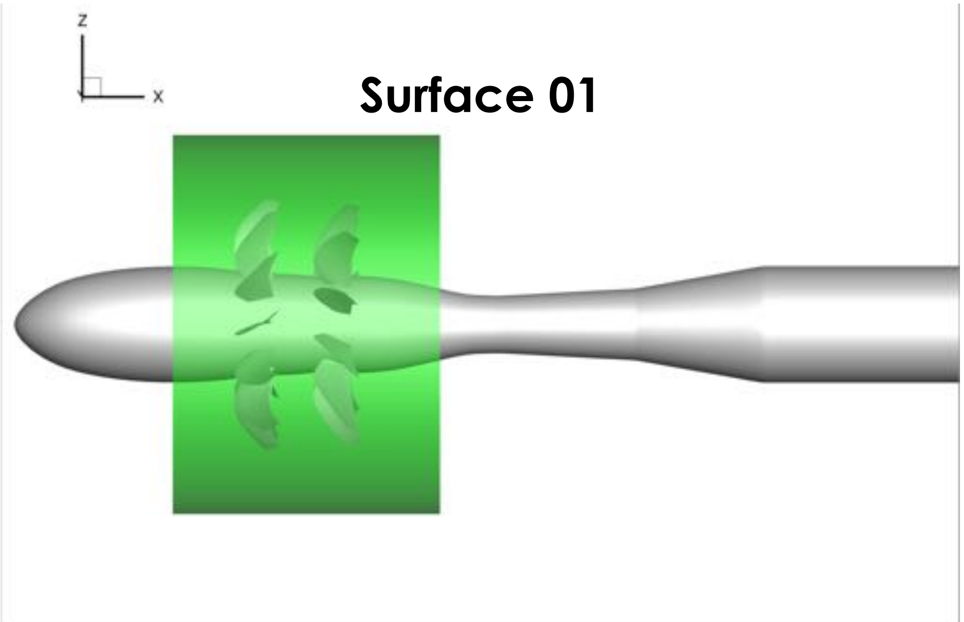
- 123 zones and 164.6 M grid points
- Triple fringe with 0 orphans
- Grid script required < 2 days to make
- Blade deflection angle parameterized
- Grid generation + connectivity 7-10 min.
- Computed y+ 4-5 at blade tip
- $\Delta\theta$ = 6mm Δr = 7mm near blade tip



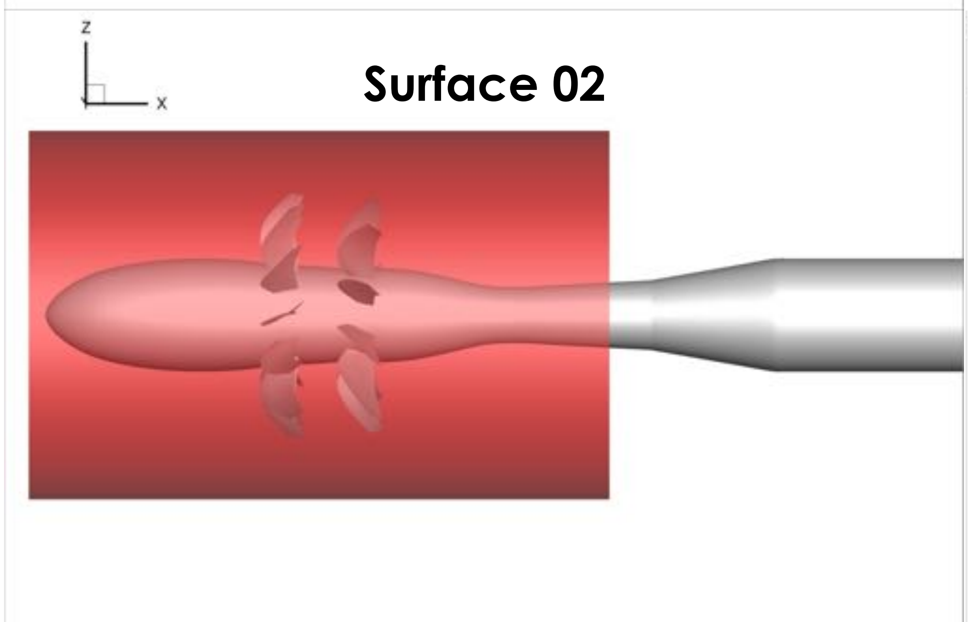


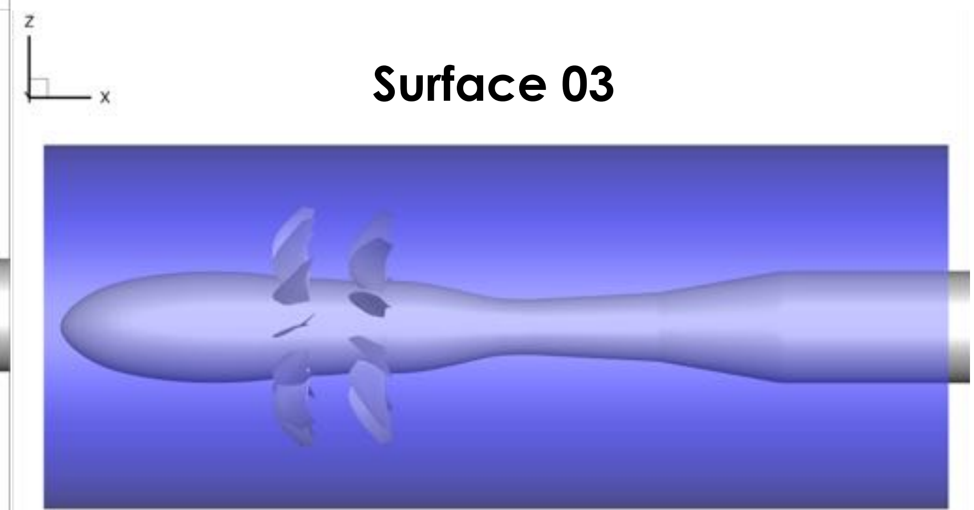


Acoustic Propagation Surface



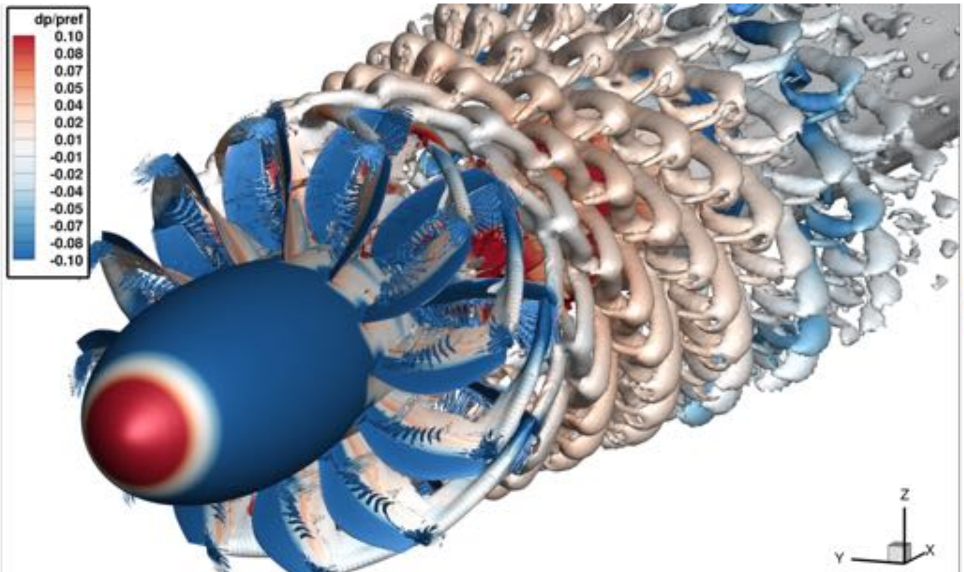
- 3 closed surface triangulations were generated to store unsteady CFD data for acoustic propagation
- An edge length 8.65 mm is used
- Triangulation is labeled with component IDs allowing various combinations of surfaces to be included in propagation

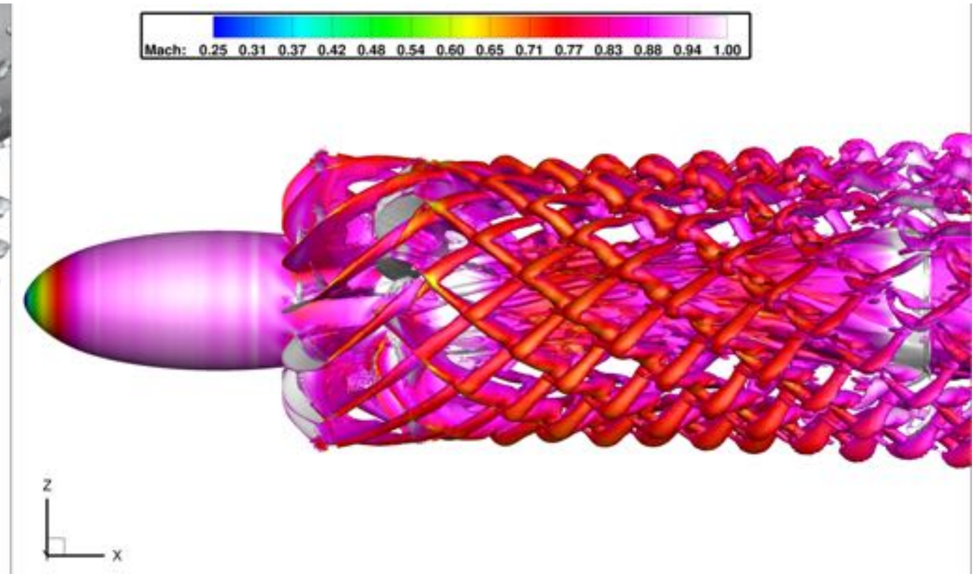


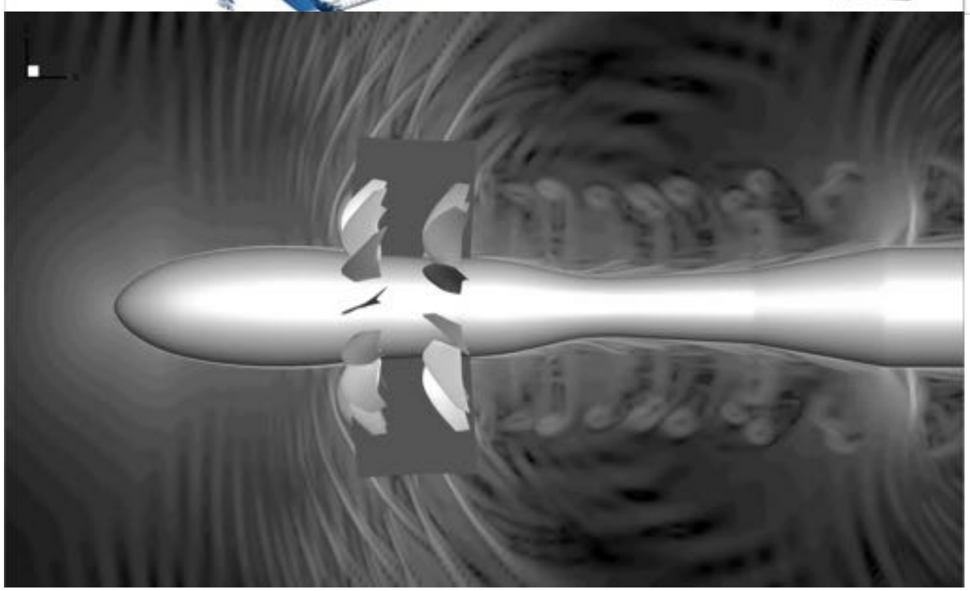


Overset Grids – Flow Visualization

Iso-contour of vorticity magnitude colored by pressure



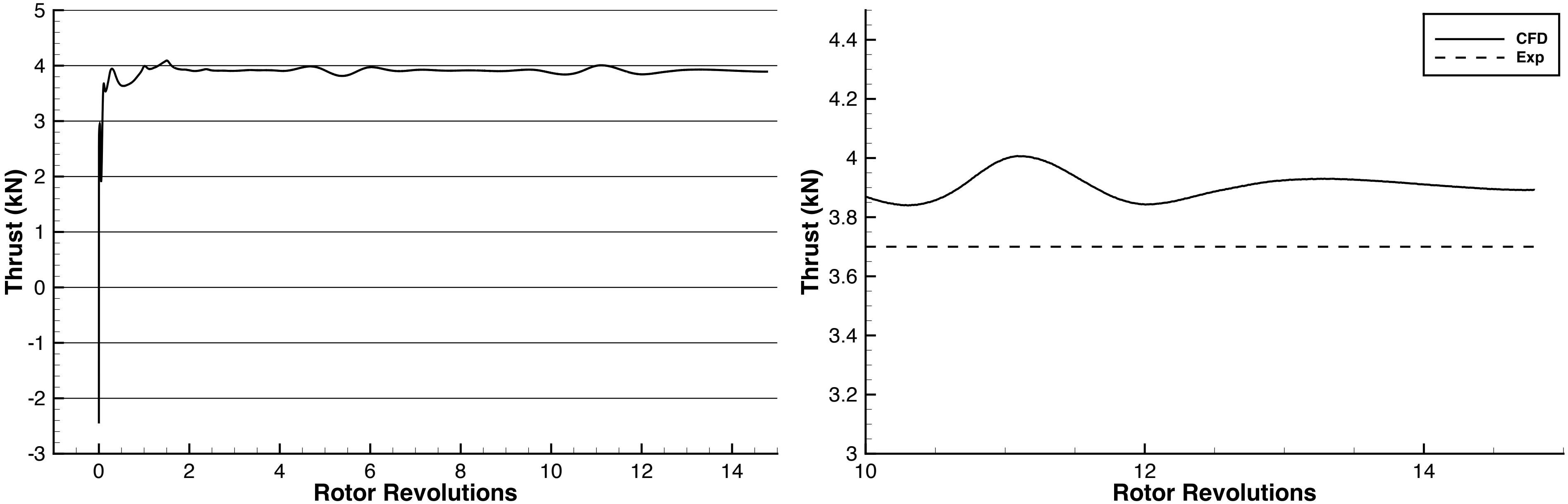




Magnitude of Density Gradient

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

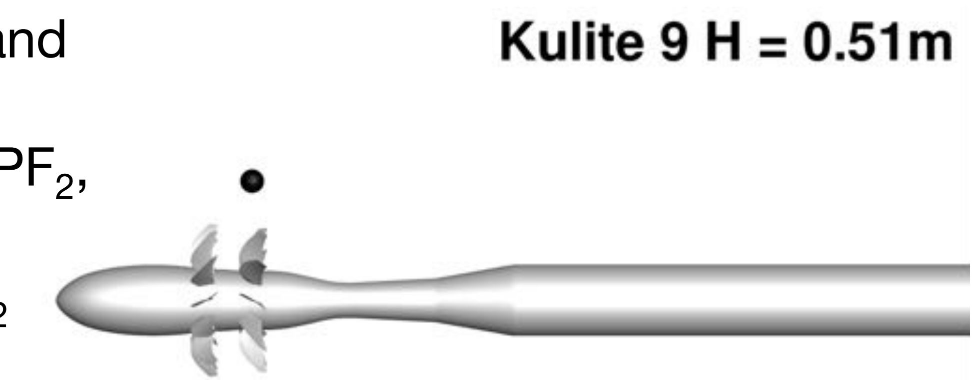
Overset – Time History of Thrust

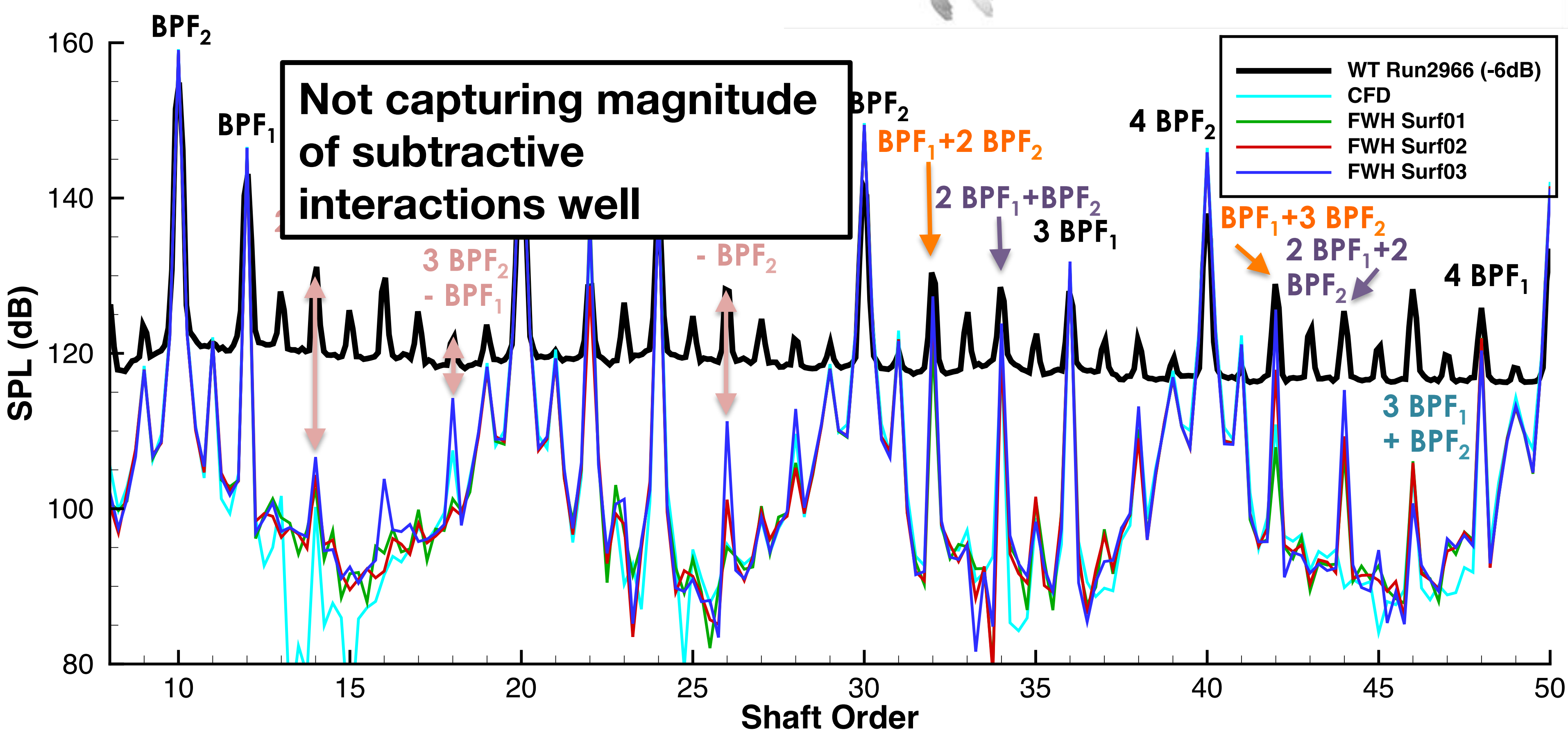


- Time-averaged thrust appears slightly larger than the WT data
- Computed y+ near the blade tips are between 4 and 5 causing an under-prediction of the viscous contribution leading to larger thrust
- Small oscillations appearing every 4.5 to 5 rotor revolutions is caused by inflow boundary condition reflection effects (these effects have been reduced using highly stretched far-field grid and non-reflecting BCs)

Overset – SPL Spectral Comparison

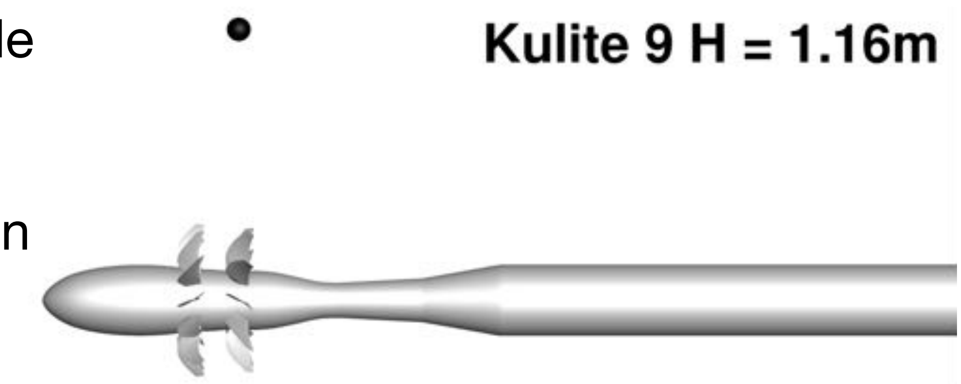
- Capturing nBPF$_1$ and nBPF$_2$ (n ≤ 4 and higher)
- Capturing BPF$_1$ + BPF$_2$, BPF$_1$ + 2 BPF$_2$, 2 BPF$_1$ + BPF$_2$, and BPF$_1$ + 3 BPF$_2$
- Loss of magnitude at 3 BPF$_1$ + BPF$_2$

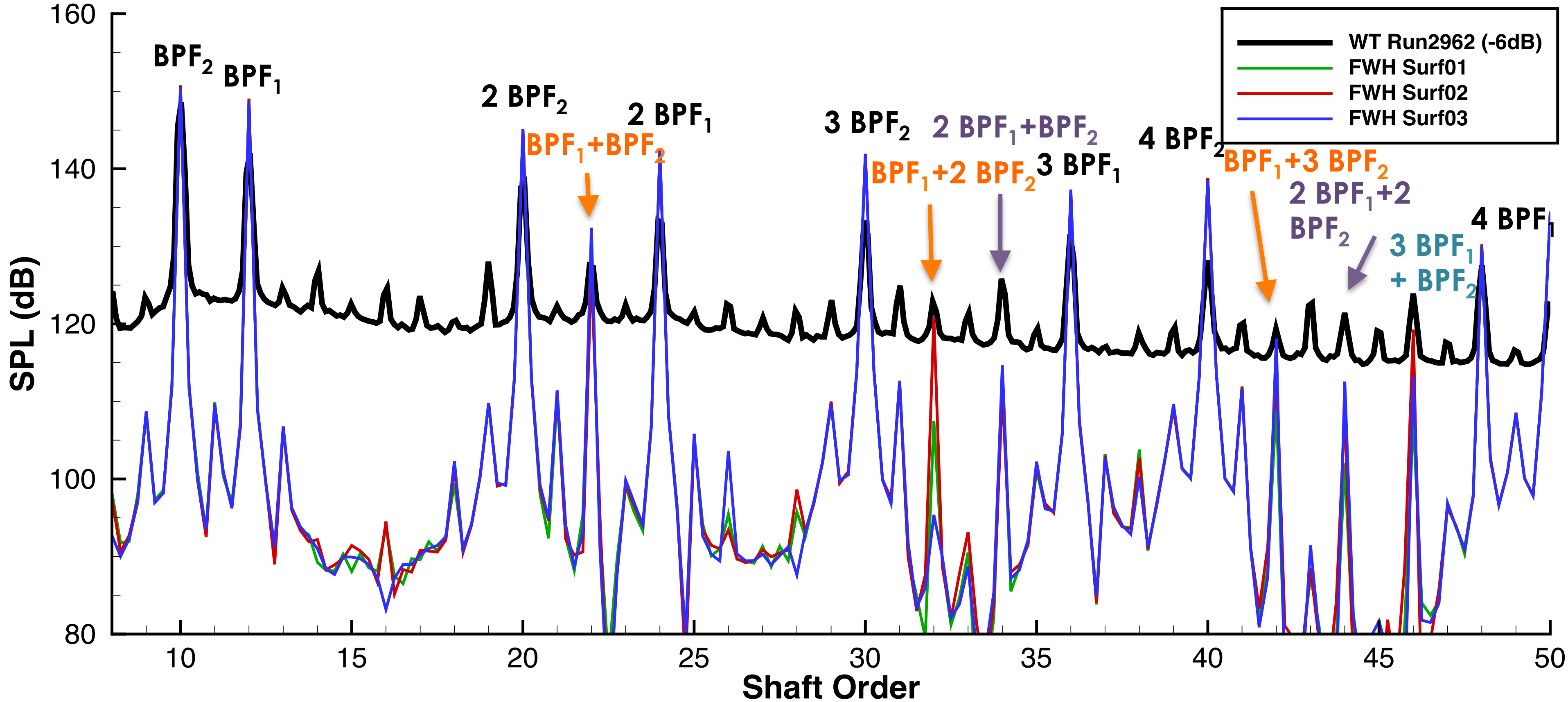




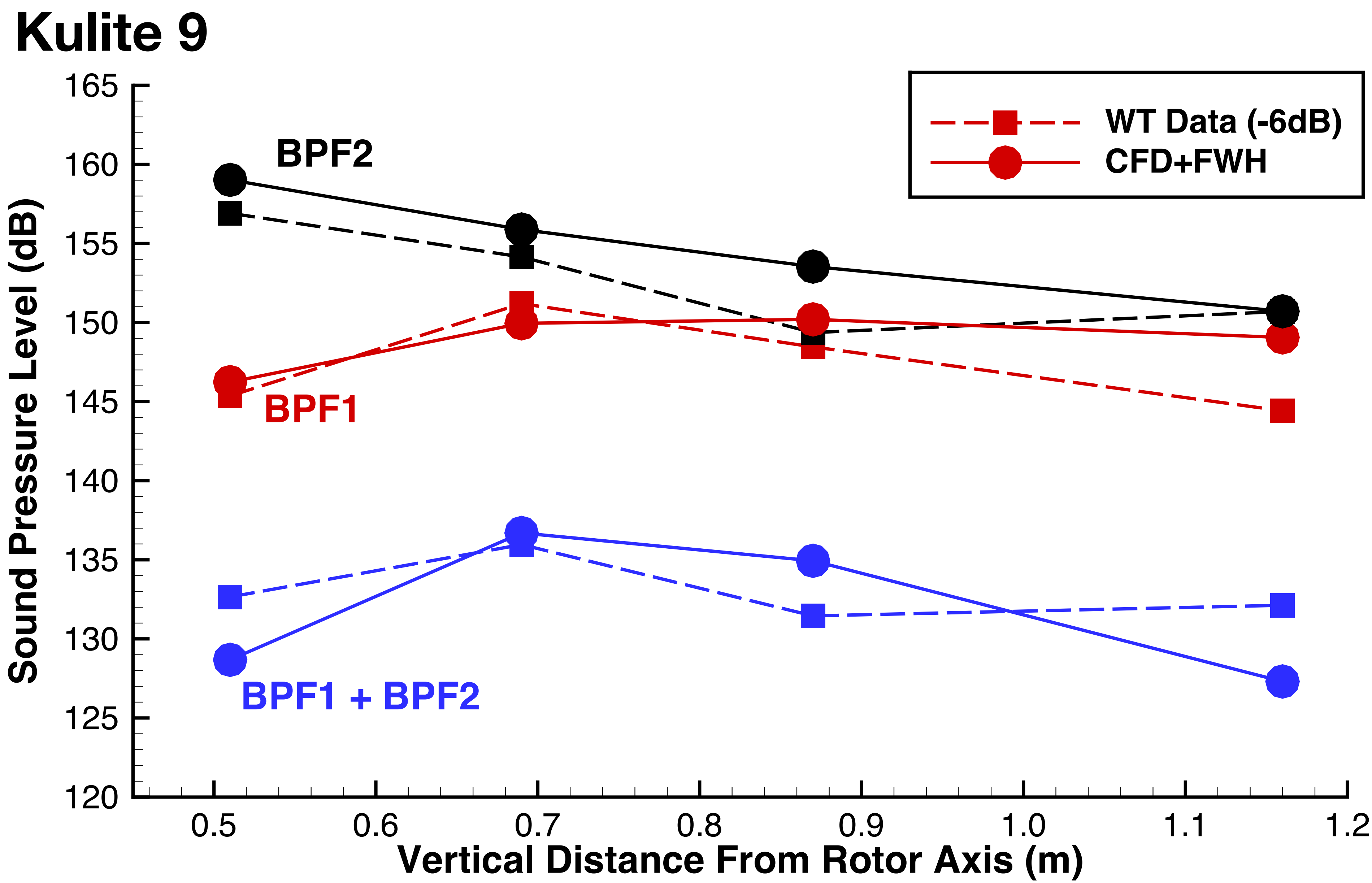
Overset – SPL Spectral Comparison

- Acoustic surface 2 appears to provide the best comparison at interaction frequencies
- $2BPF_1+2BPF_2$ and greater interaction amplitudes not well captured





Overset – SPL Tone Comparison

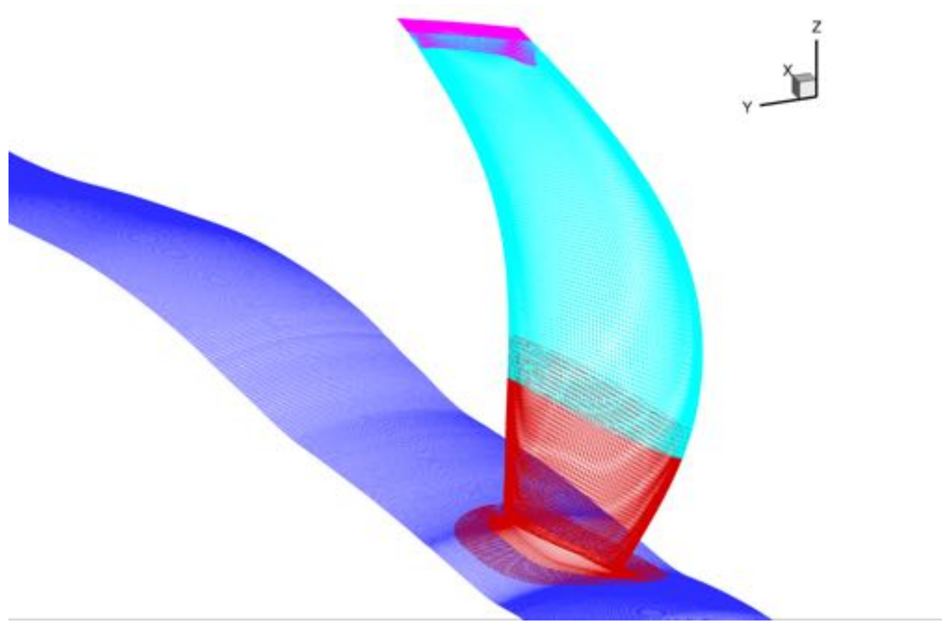


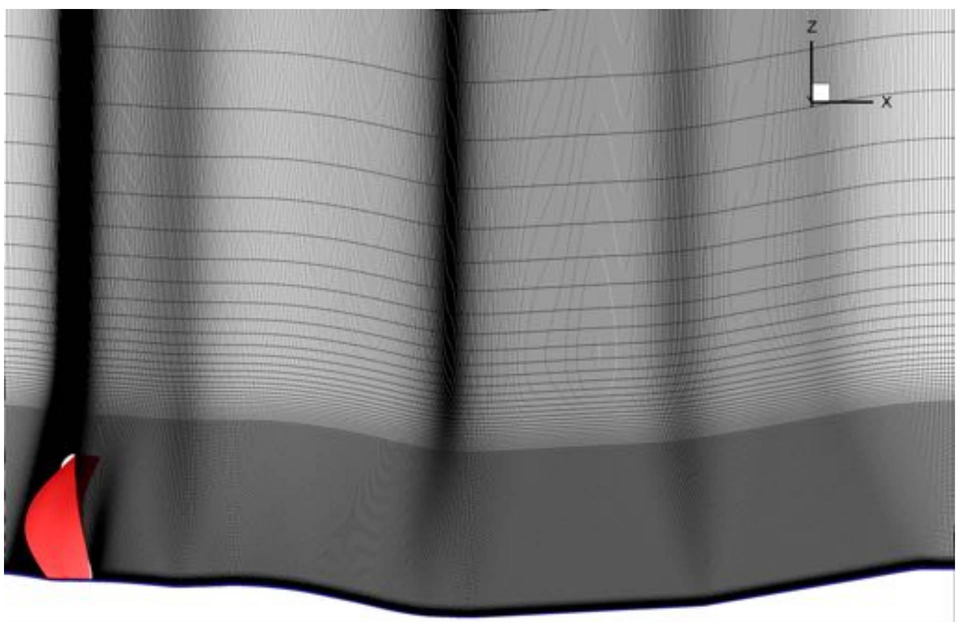
Overset - Time-step resolution study

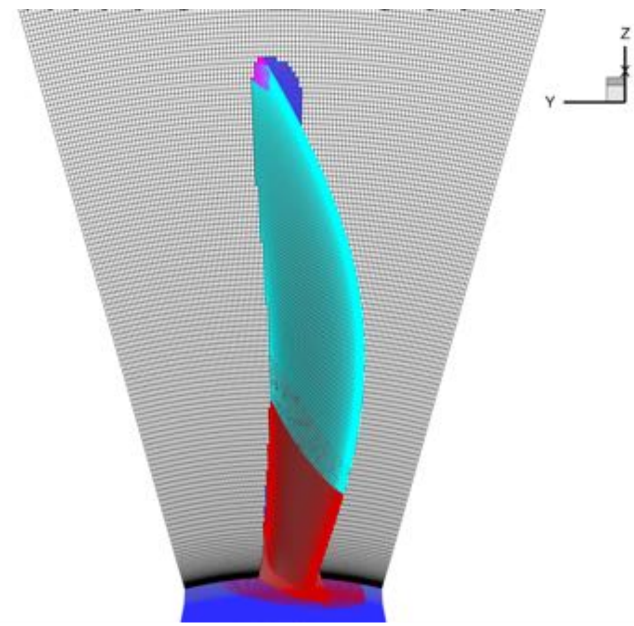
- Curvilinear solver utilized implicit 2nd order backward differencing in time allowing large time-steps to be utilized while maintaining stable solutions with viscous meshes
- When utilizing high-resolution spatial discretizations, temporal error discretization may dominate if too large a time-step is used
- A time-step resolution study for a single forward rotor (modeling 1/12th 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)







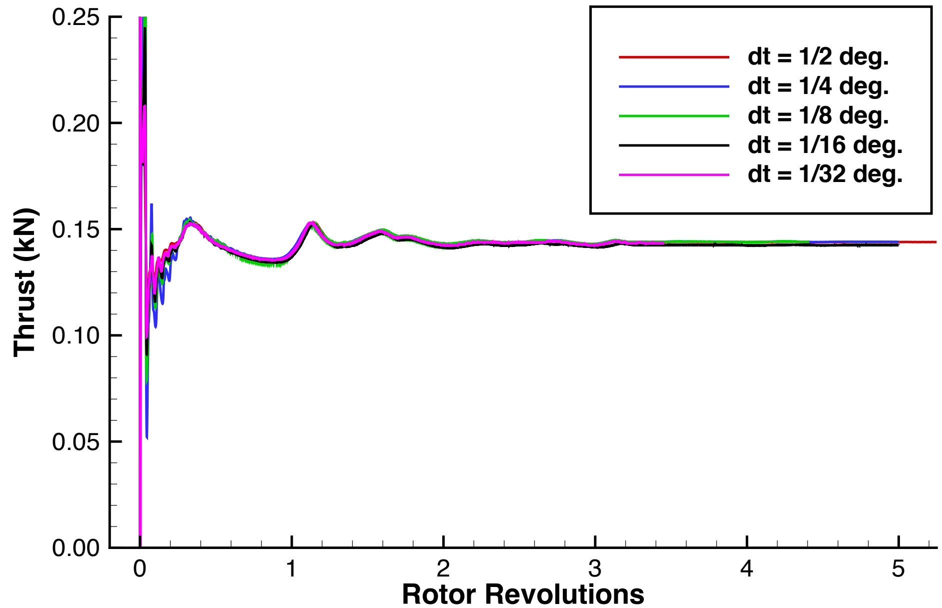
Discretization and Solver Parameters

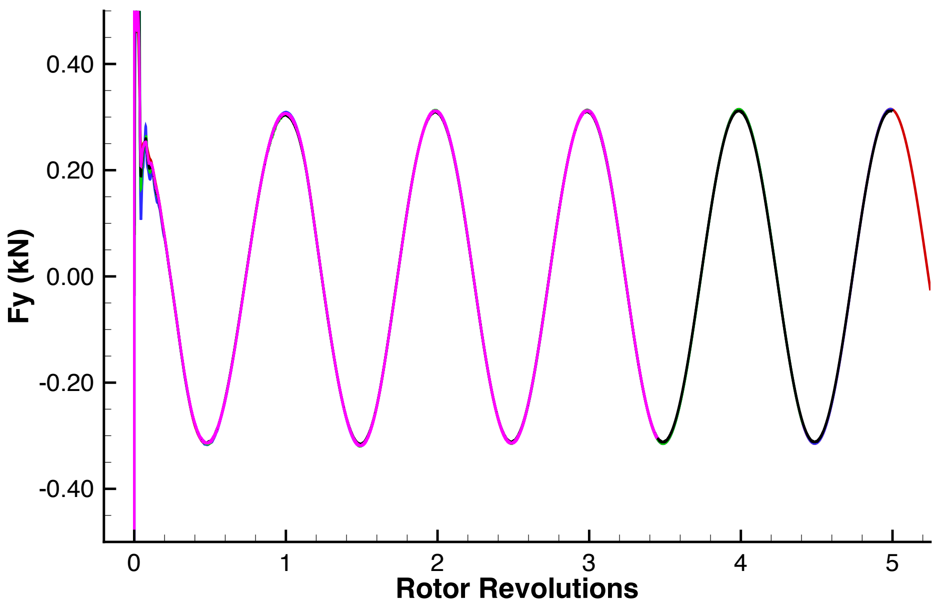
- LAVA structured overset grid curvilinear Navier-Stokes solver
- Hybrid RANS/LES using Spalart-Allmaras
    - Unsteady Reynolds Averaged Navier-Stokes (URANS)
    - Manual specification of RANS/LES interface based on URANS
    - Delayed Detached Eddy Simulation (DDES)
- Modified Roe convective flux – 5^{th} order reconstruction
- 2^{nd} order central differencing for viscous flux
- 2^{nd} order backward differencing in time
    - dt = 1.217e-05 seconds (1/2 deg.)
    - dt = 6.085e-06 seconds (1/4 deg.)
    - dt = 3.042e-06 seconds (1/8 deg.)
    - dt = 1.521e-06 seconds (1/16 deg.)
    - dt = 7.606e-07 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

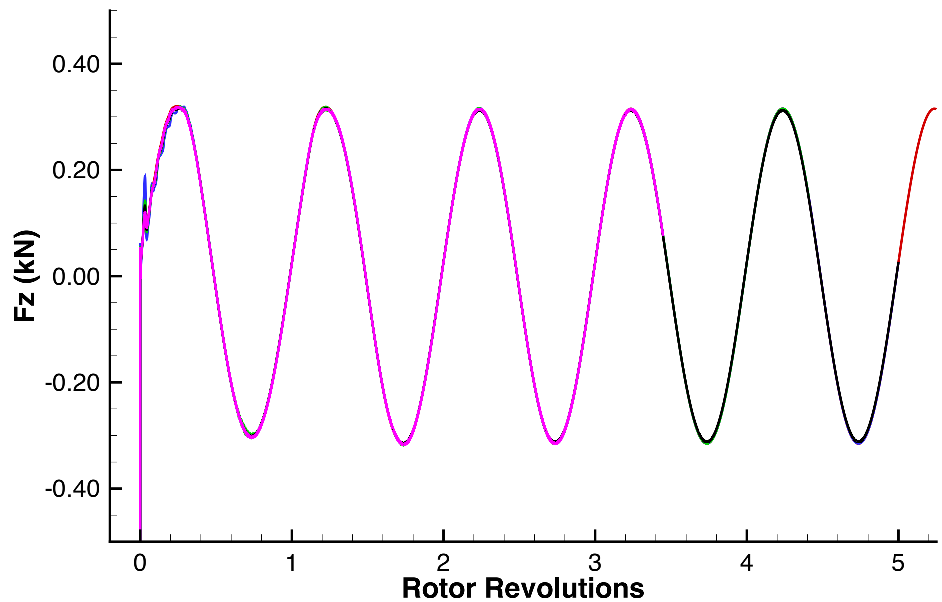
Time-step Resolution Results

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

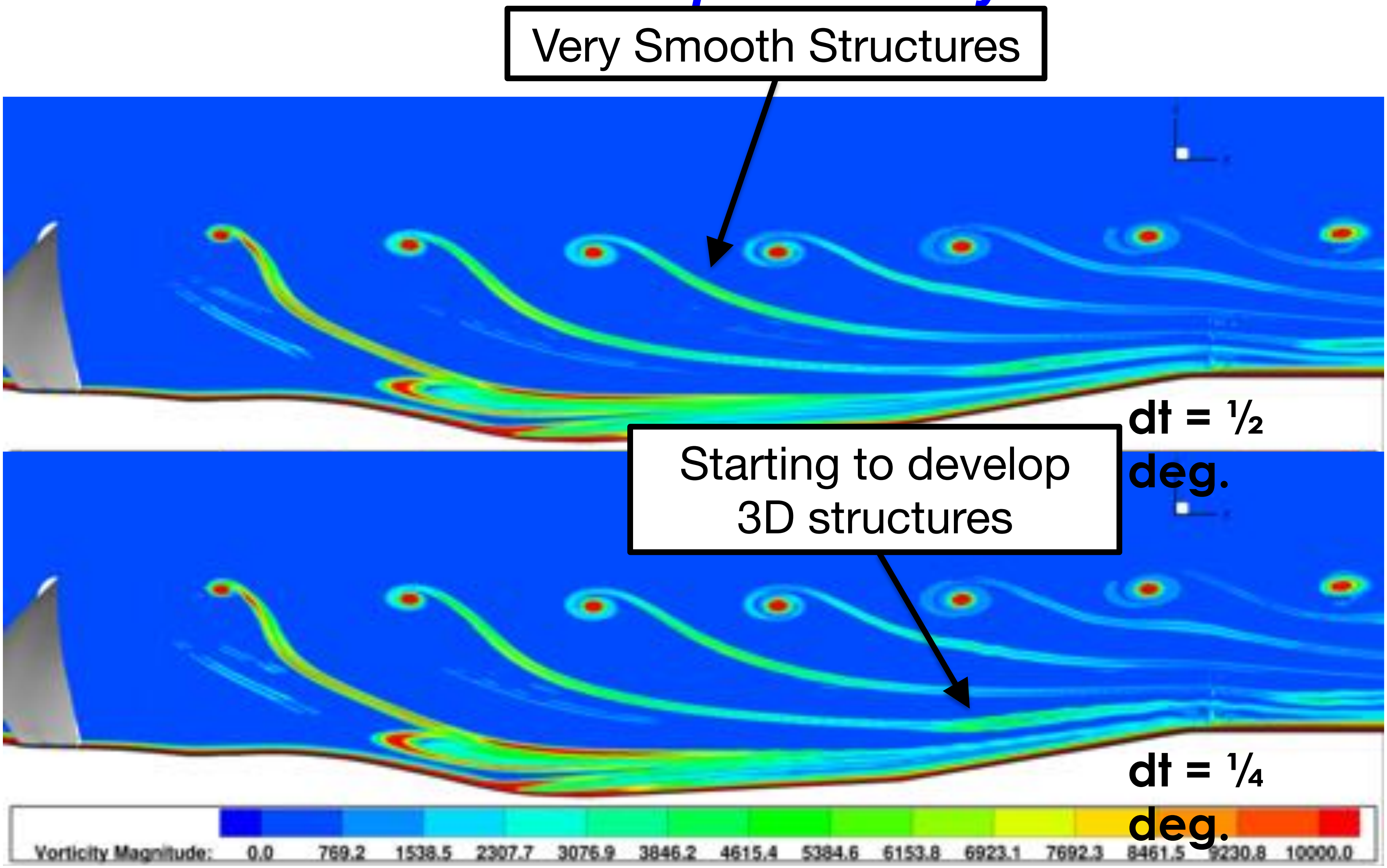






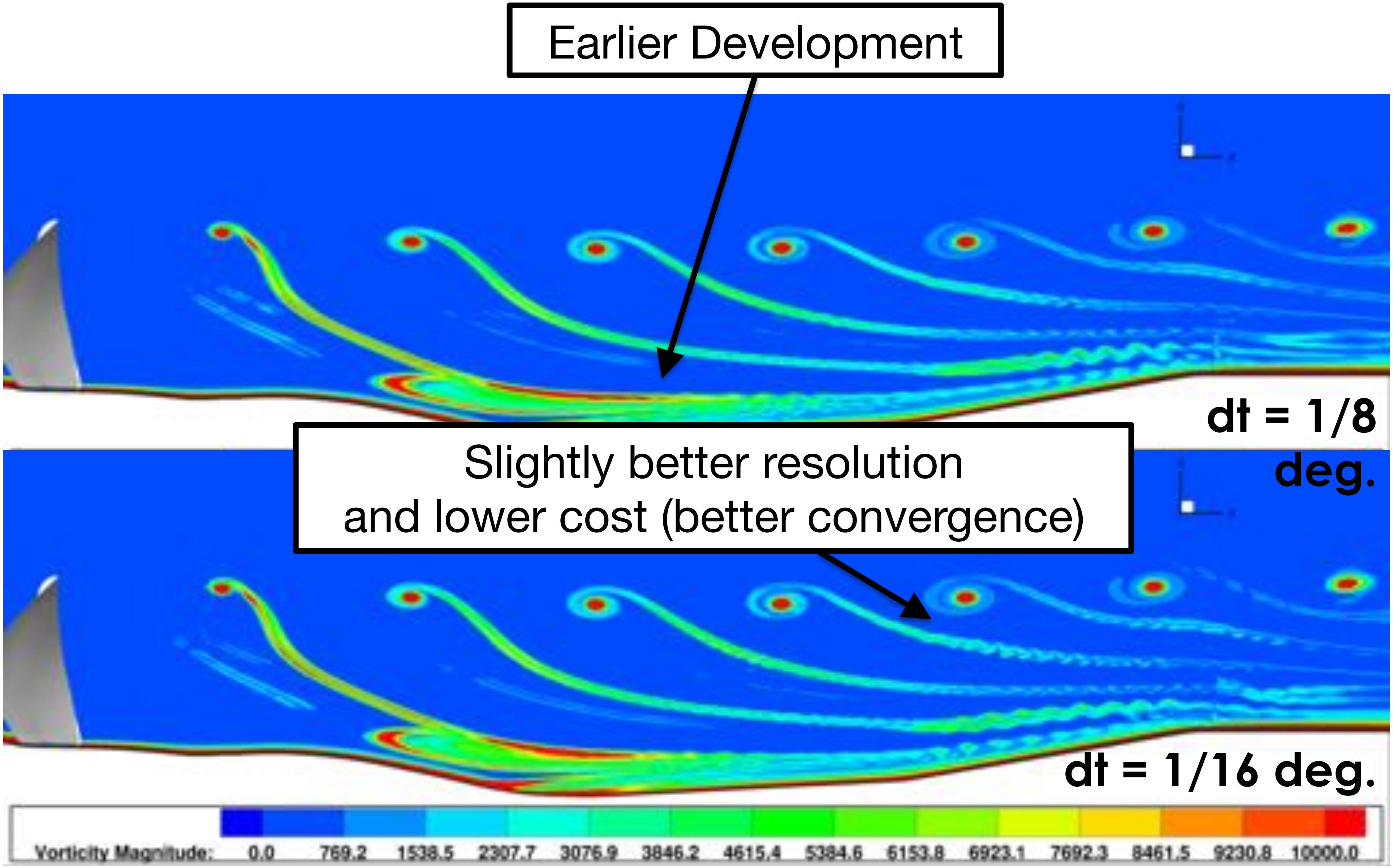
Time-step Resolution Results

Wake Resolution Time-Step Sensitivity



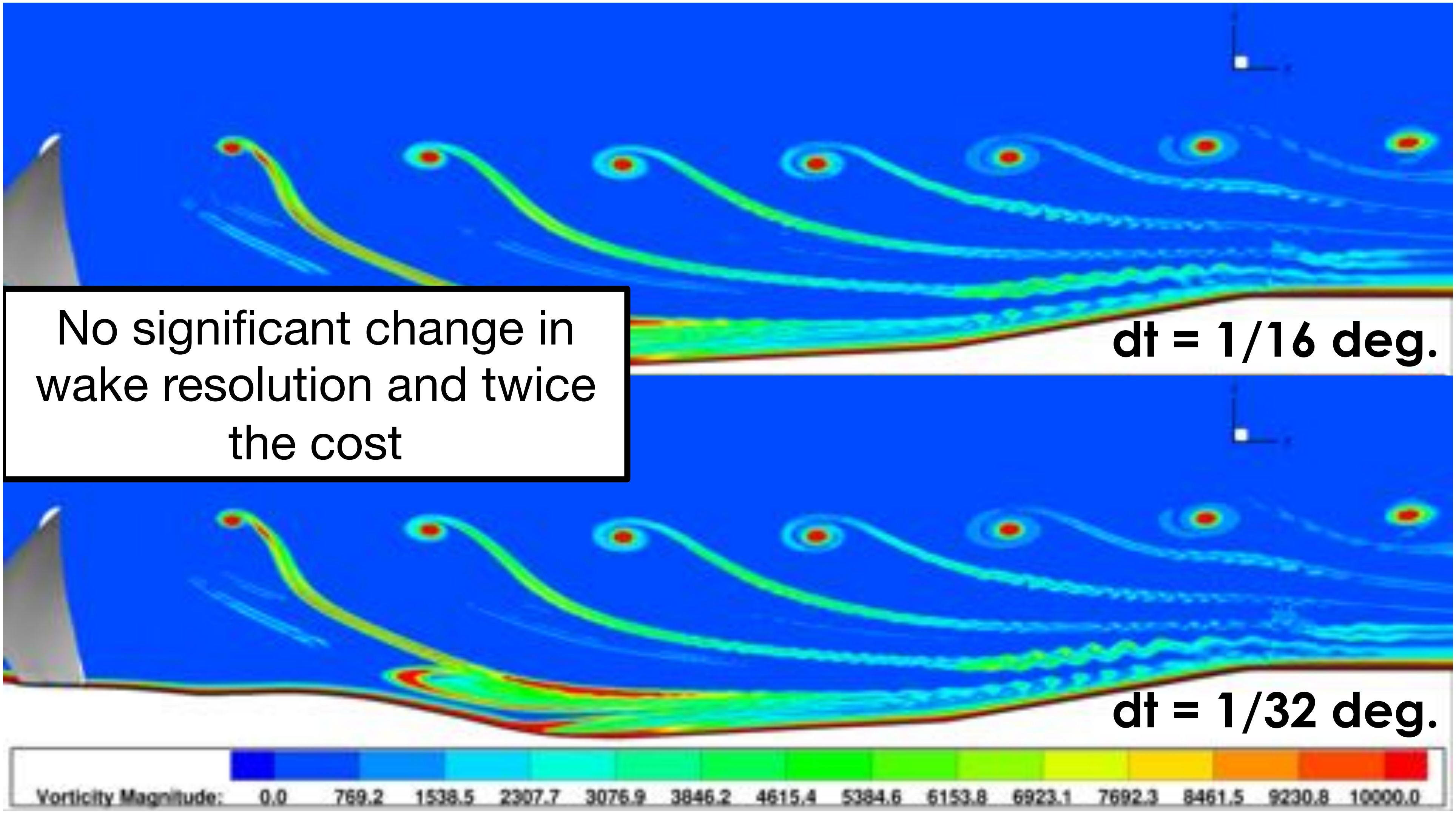
Time-step Resolution Results

Wake Resolution Time-Step Sensitivity



Time-step Resolution Results

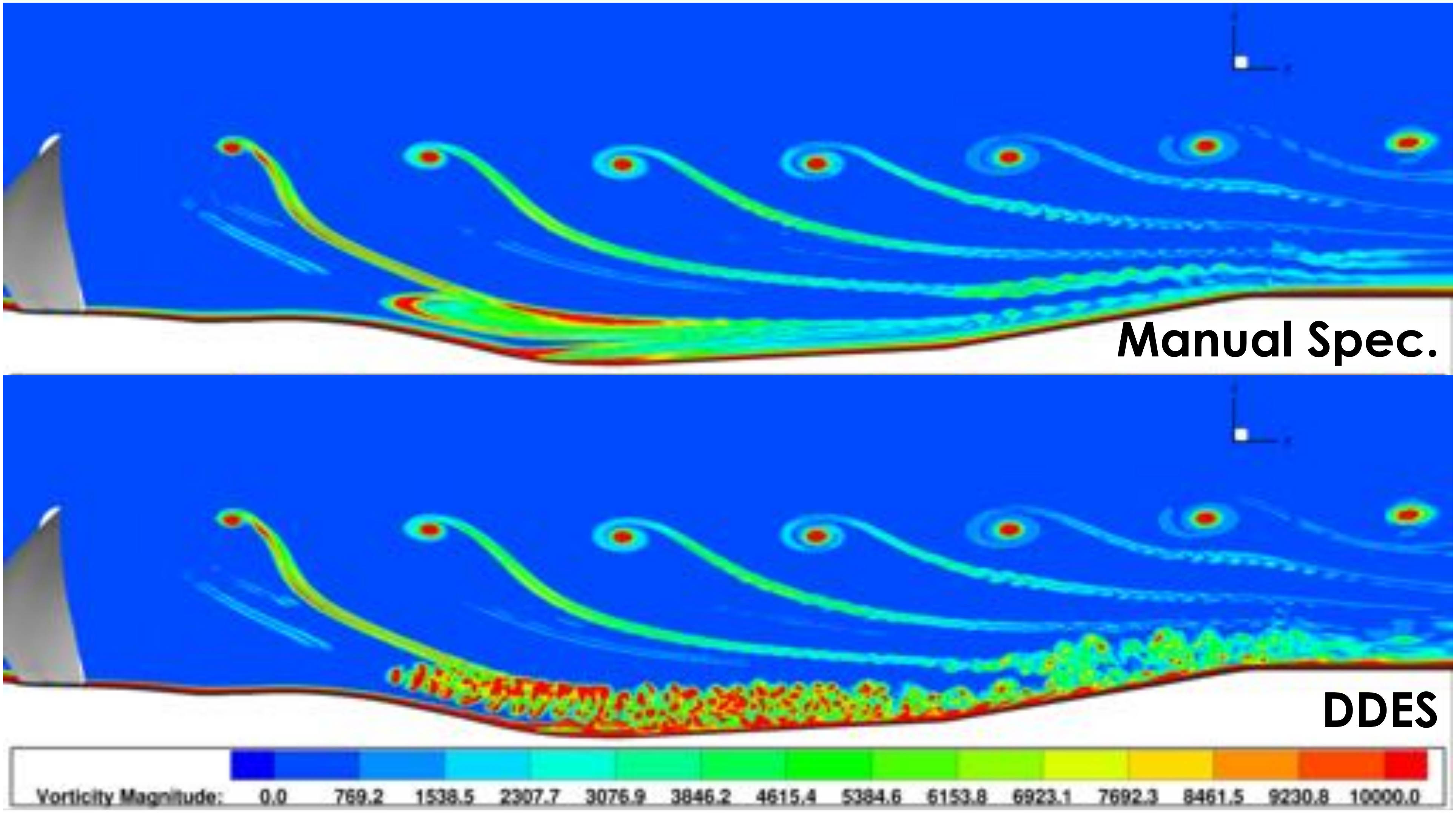
Wake Resolution Time-Step Sensitivity



No significant change in wake resolution and twice the cost

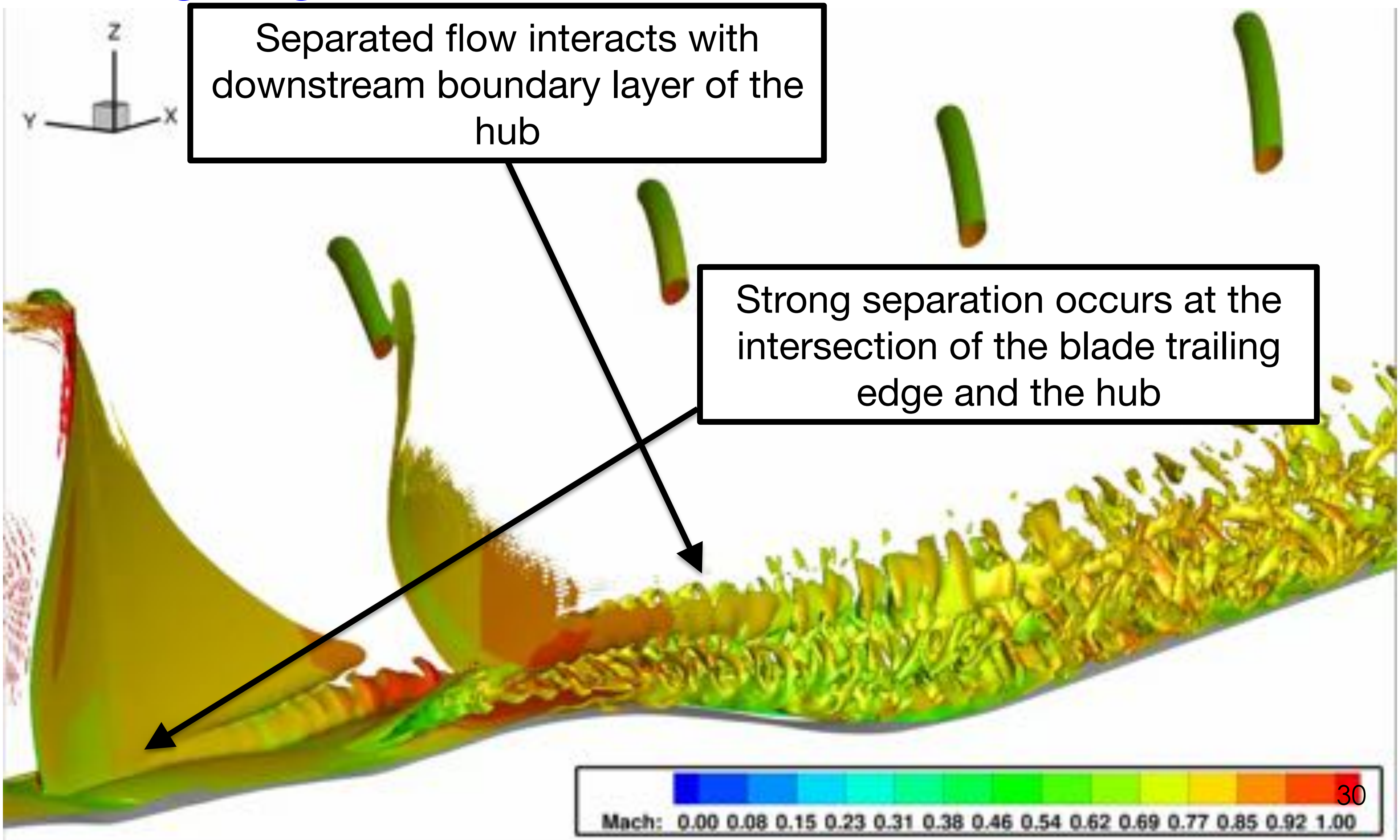
Time-step Resolution Results

Wake Resolution Turbulence Model Sensitivity (dt = 1/16 deg.)



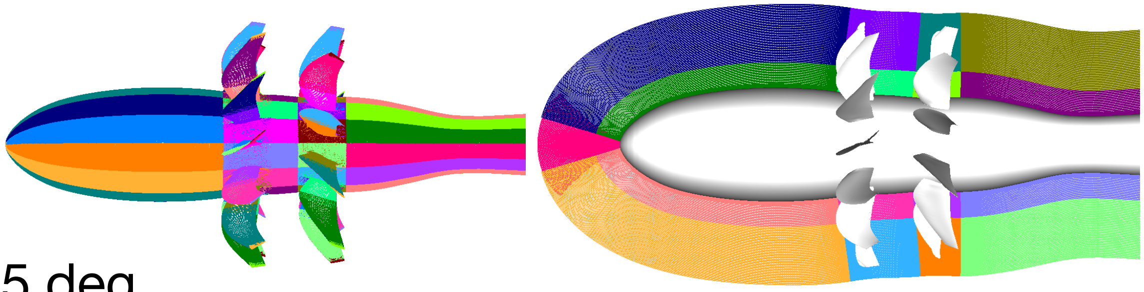
Time-step Resolution Results

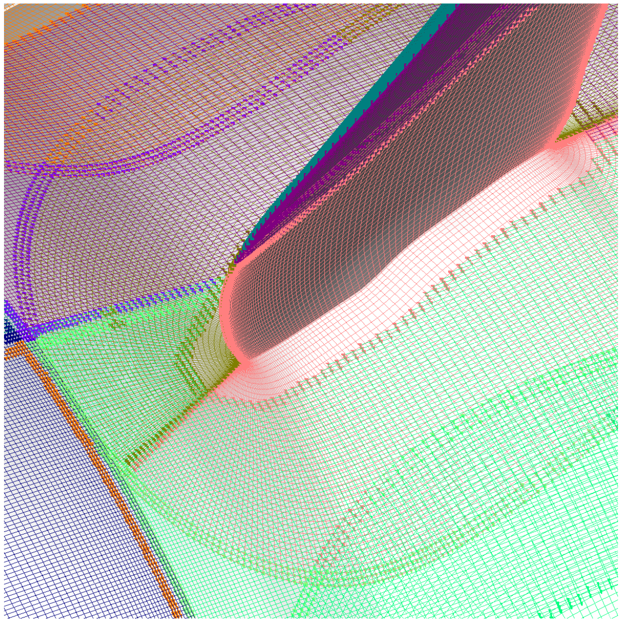
Trailing Edge/Hub Corner Separation

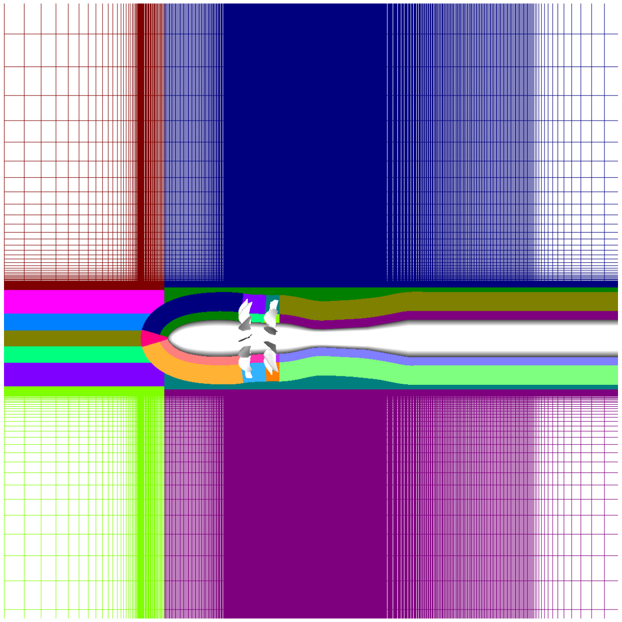


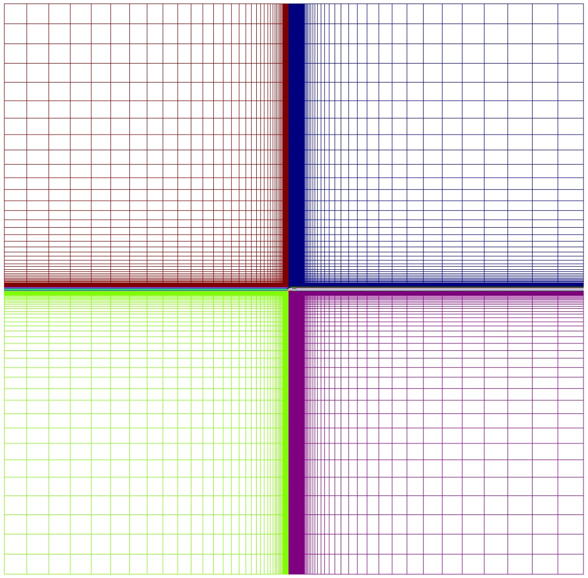
Fine Mesh Overset Grid System

- 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.

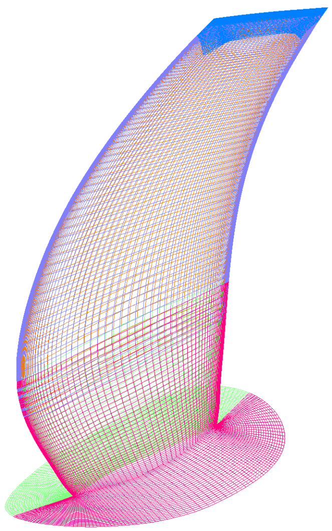




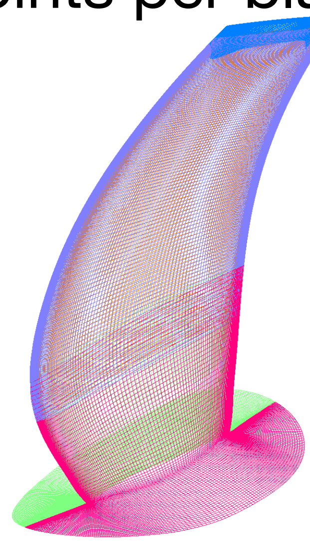


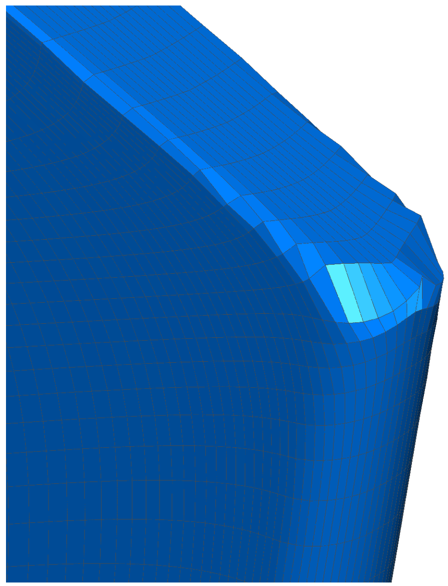


Fine Mesh Overset Grid System

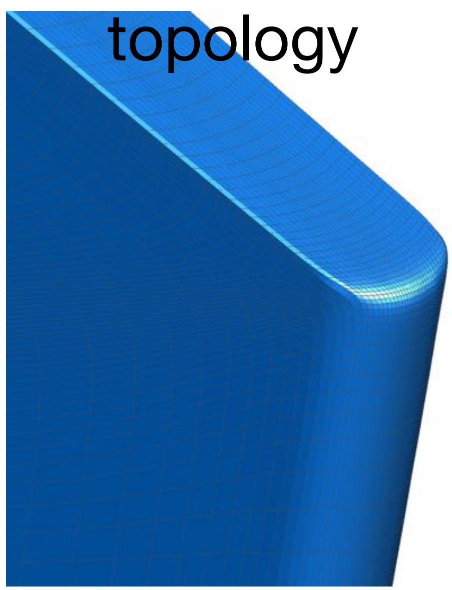


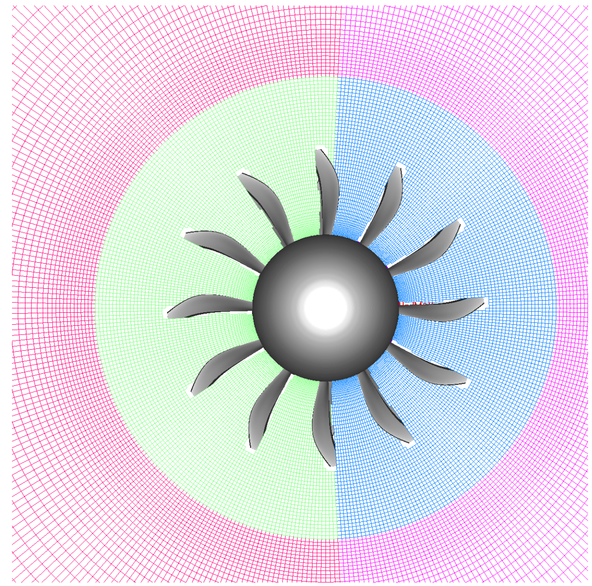
5.5 M to 10.6 M points per blade





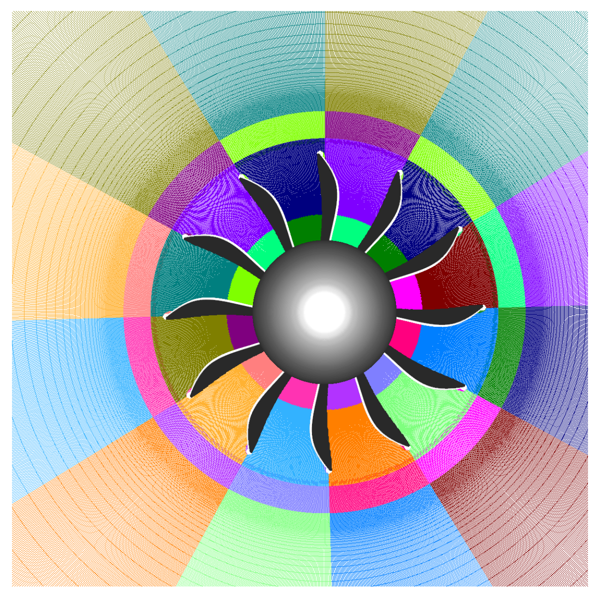
Improved topology





Old

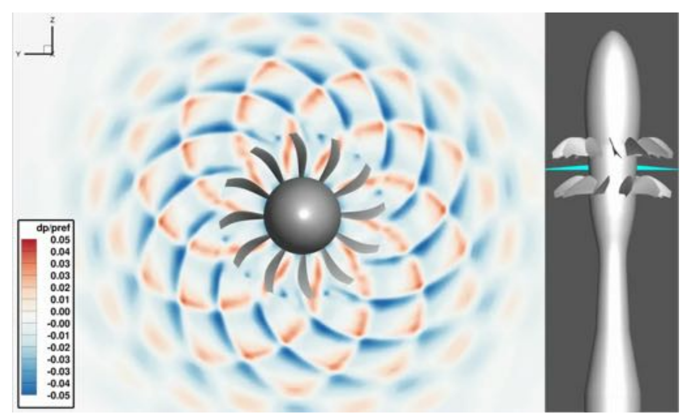
Highly Refined



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

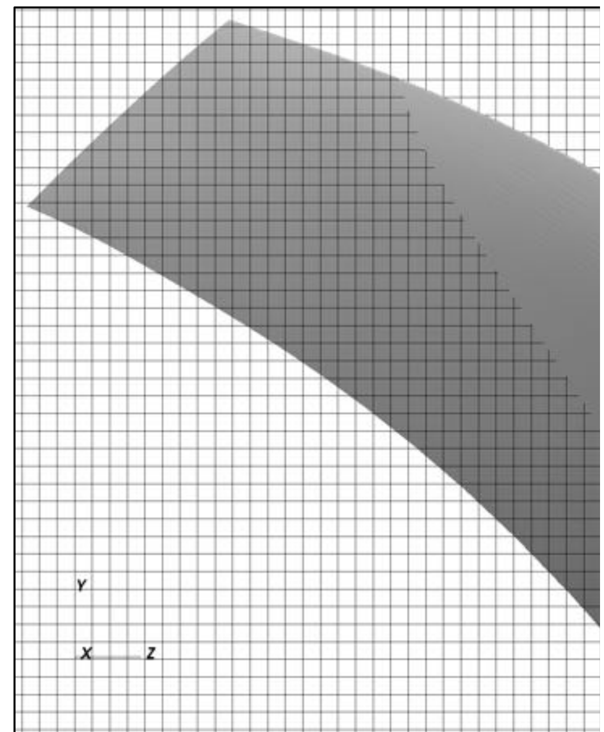
- *LAVA (Launch Ascent Vehicle Aerodynamics)*
  - *Introduction*
  - *Acoustics Related Applications*
- *LAVA Applications to Open Rotor*
  - *Structured Overset Grids*
  - *Cartesian Grid with Immersed Boundary*
    - *High Speed Case*
    - *High Speed Case with Plate*
    - *Low Speed Case*

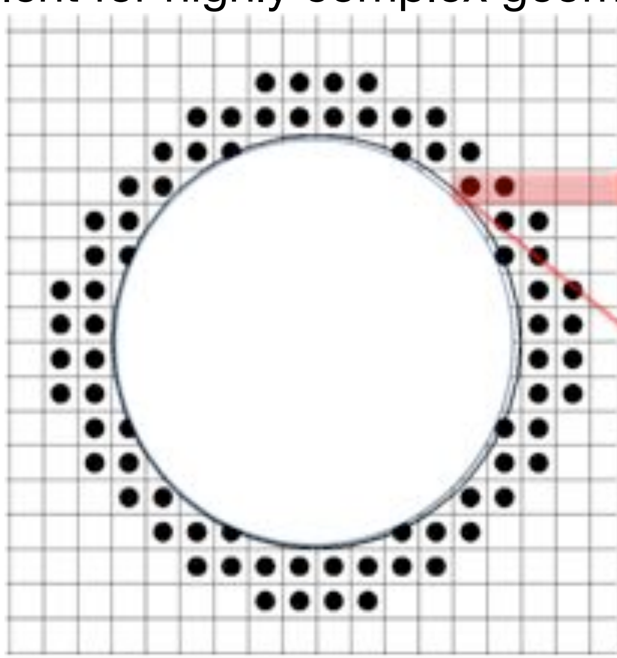
LAVA Cartesian

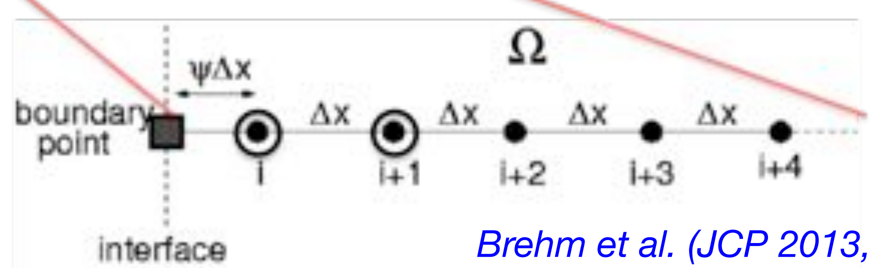
- *Computational Approach:*
- 3D Cartesian Navier-Stokes Solver
- 5^{th} and 6^{th} order WENO spatial discretization
- Higher-order immersed boundary method
- 4^{th} order explicit Runge-Kutta time stepping (dt = 1/16 degree)
- Rotor revolutions are simulated from an impulsive start using free-stream 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







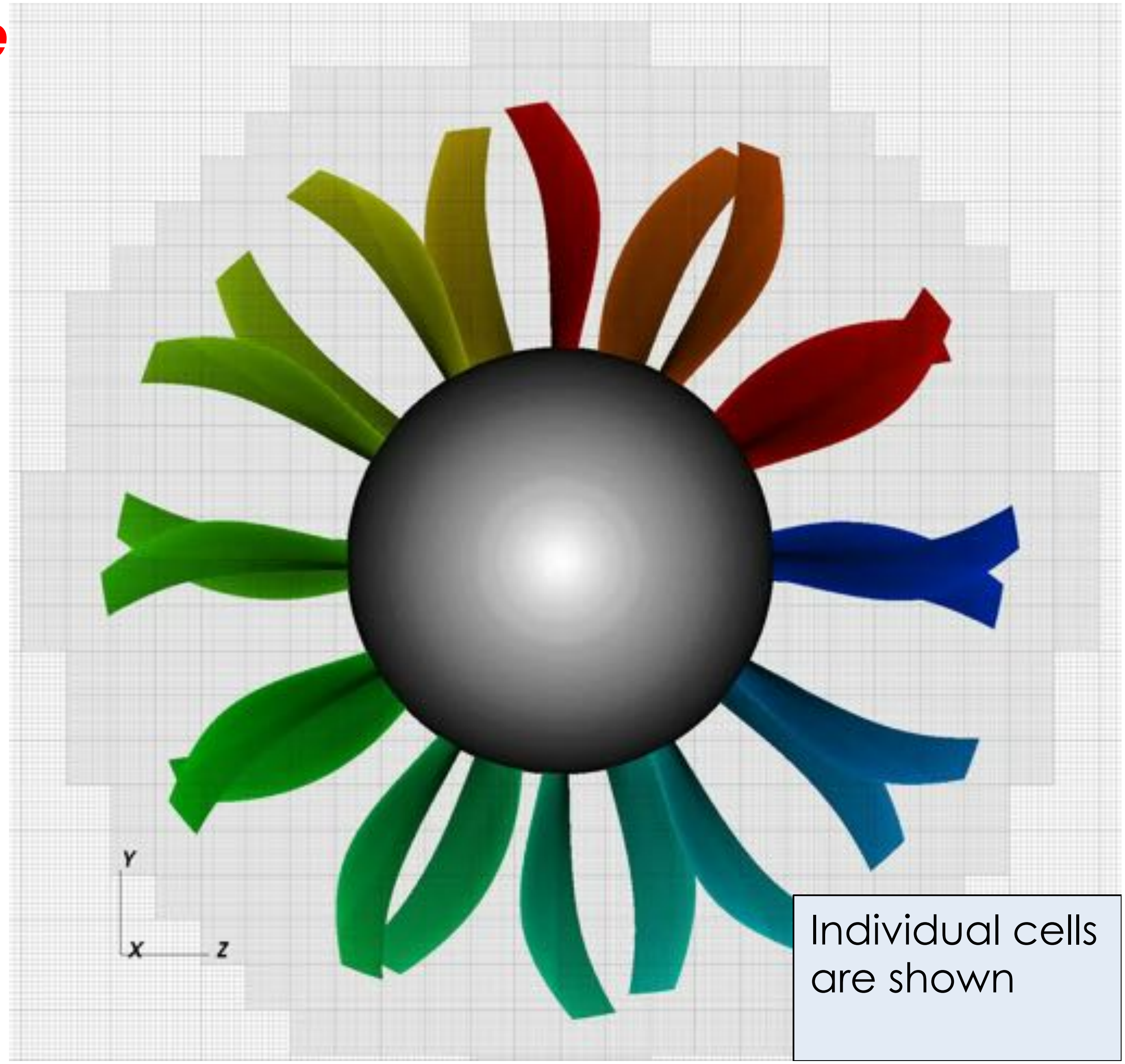
Brehm et al. (JCP 2013,2015)

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
- Δx = 2mm near blades, Δx = 4mm in wake region



Cartesian Grid with Moving OR Geometry

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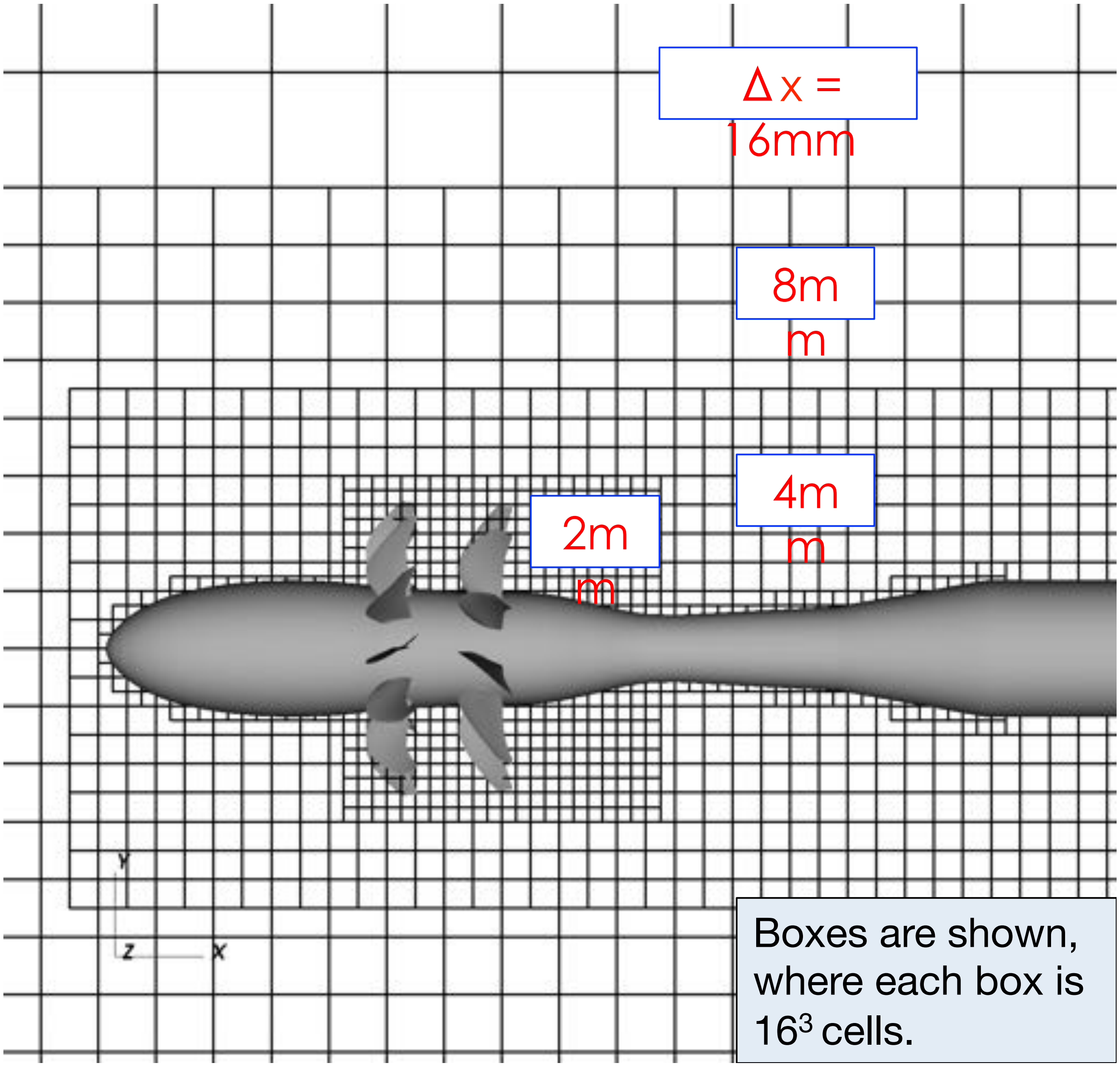
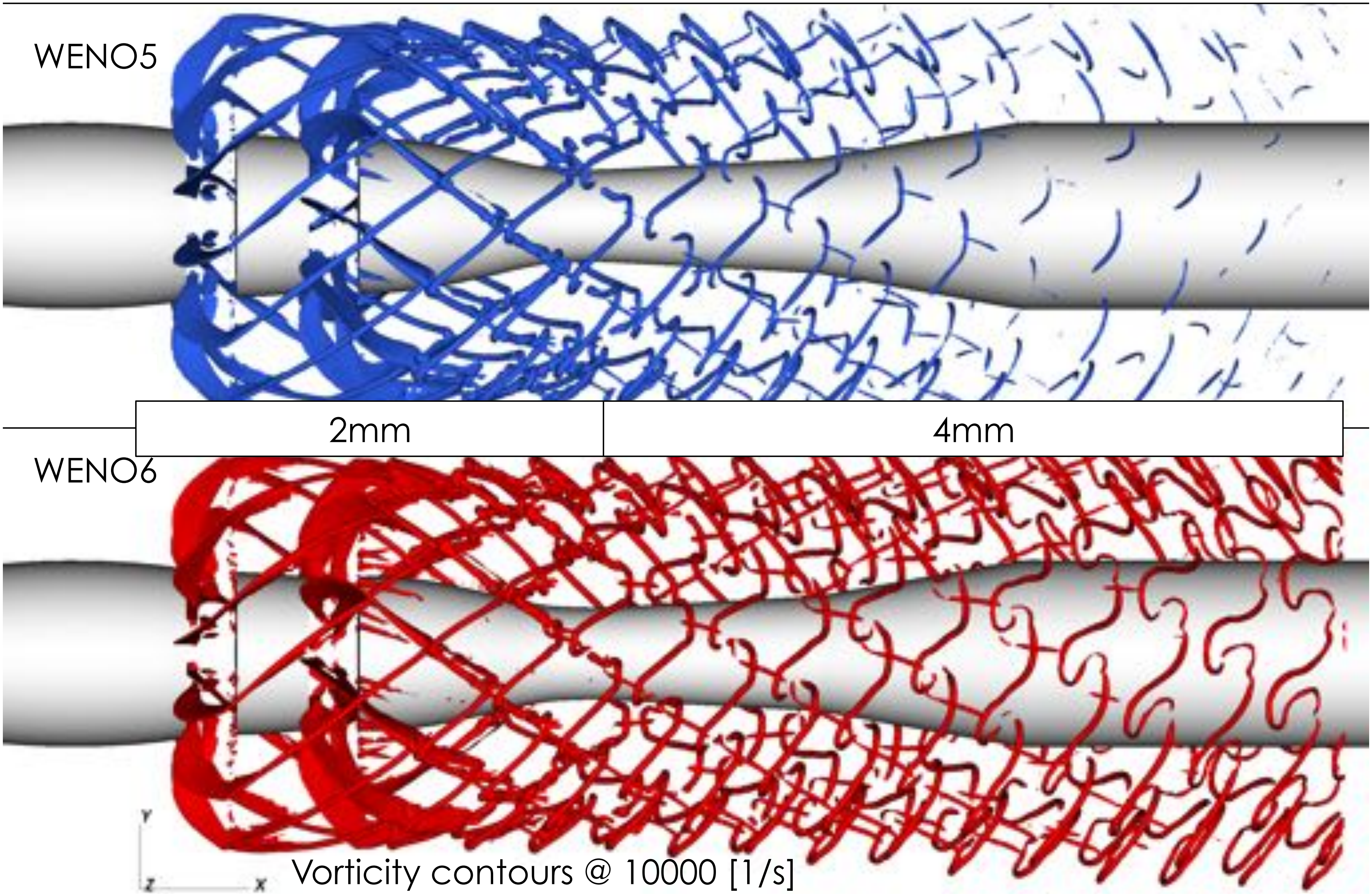


Boxes are shown, where each box is 16^3 cells.

LAVA Cartesian : WENO5 vs WENO6



LAVA Cartesian : WENO6 Vorticity

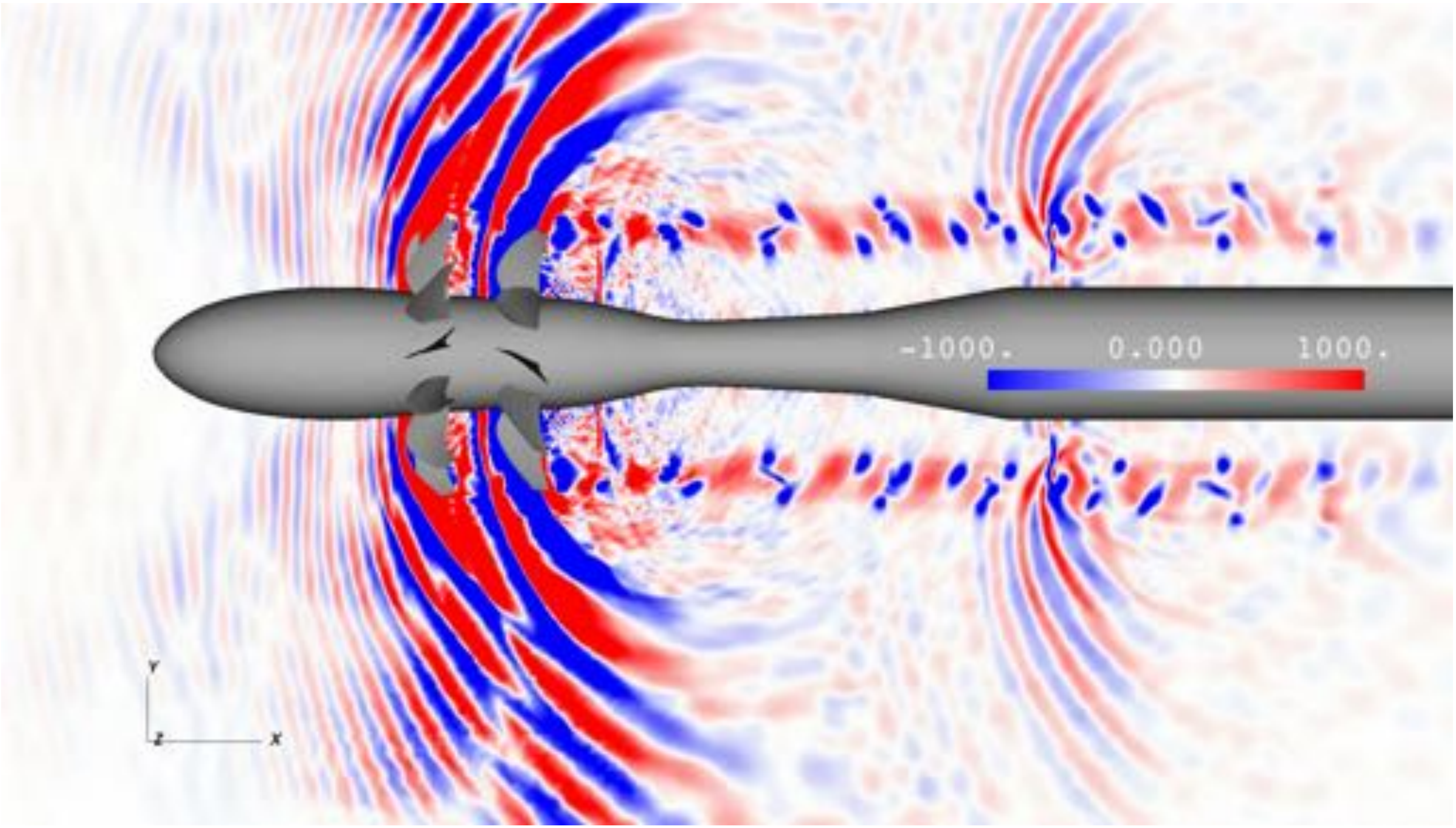
Vorticity contours @ 10000 [1/s], colored by pressure

LAVA Cartesian : Passive Particles

Passive particles seeded at trailing edges of blades: red is fwd, blue is aft seeding

LAVA Cartesian – WENO5

Disturbance Pressure



P' = P – P_ave

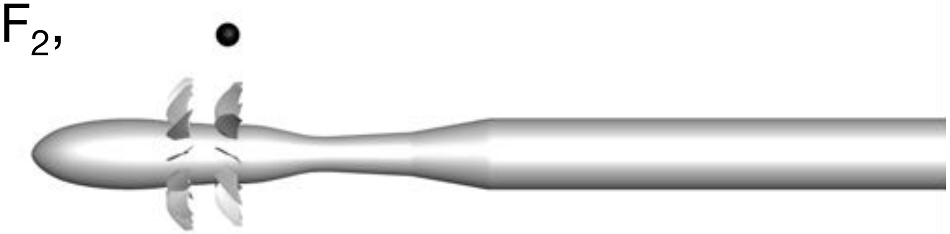
LAVA Cartesian – WENO5

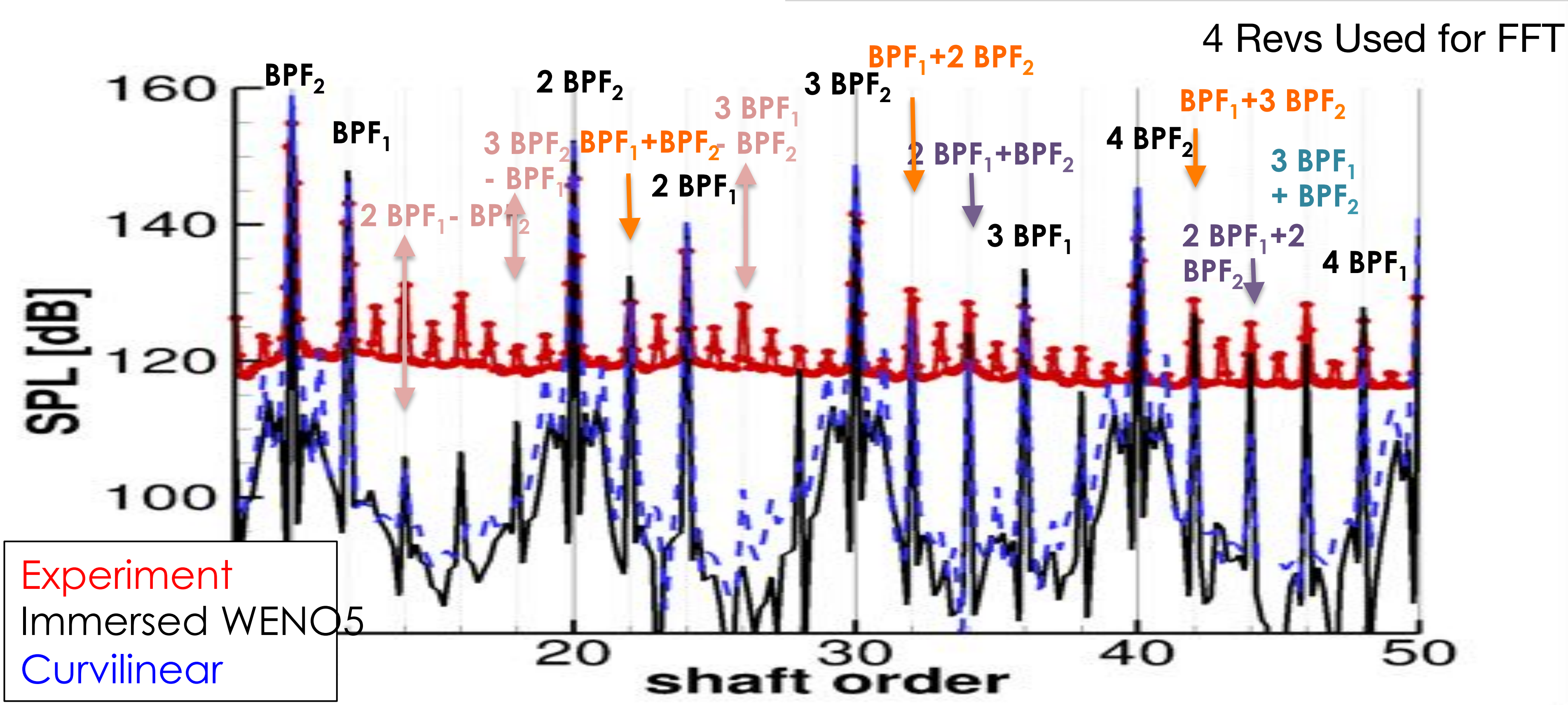
Density Gradient

SPL Spectral Comparison

- Capturing $nBPF_1$ and $nBPF_2$ ($n \leq 4$ 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





SPL Spectral Comparison

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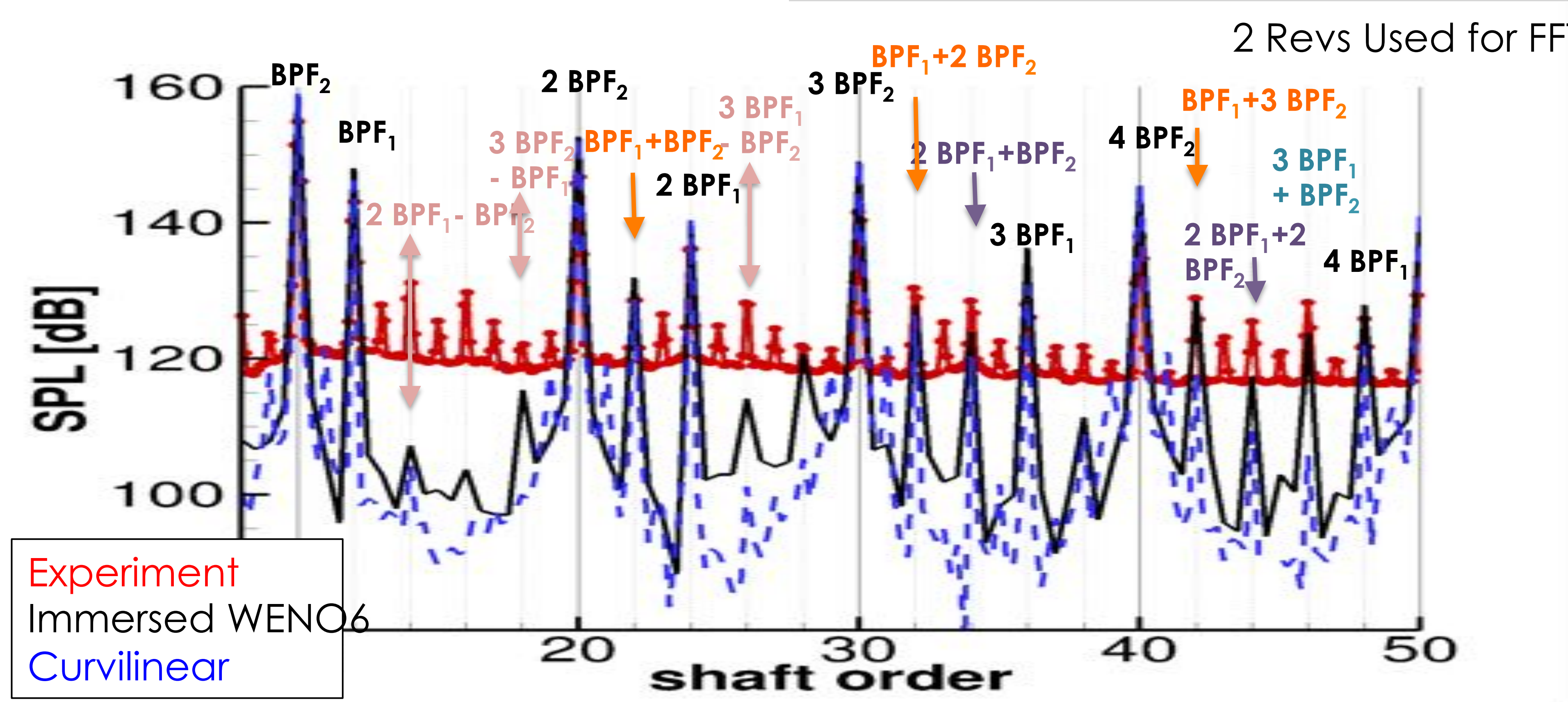
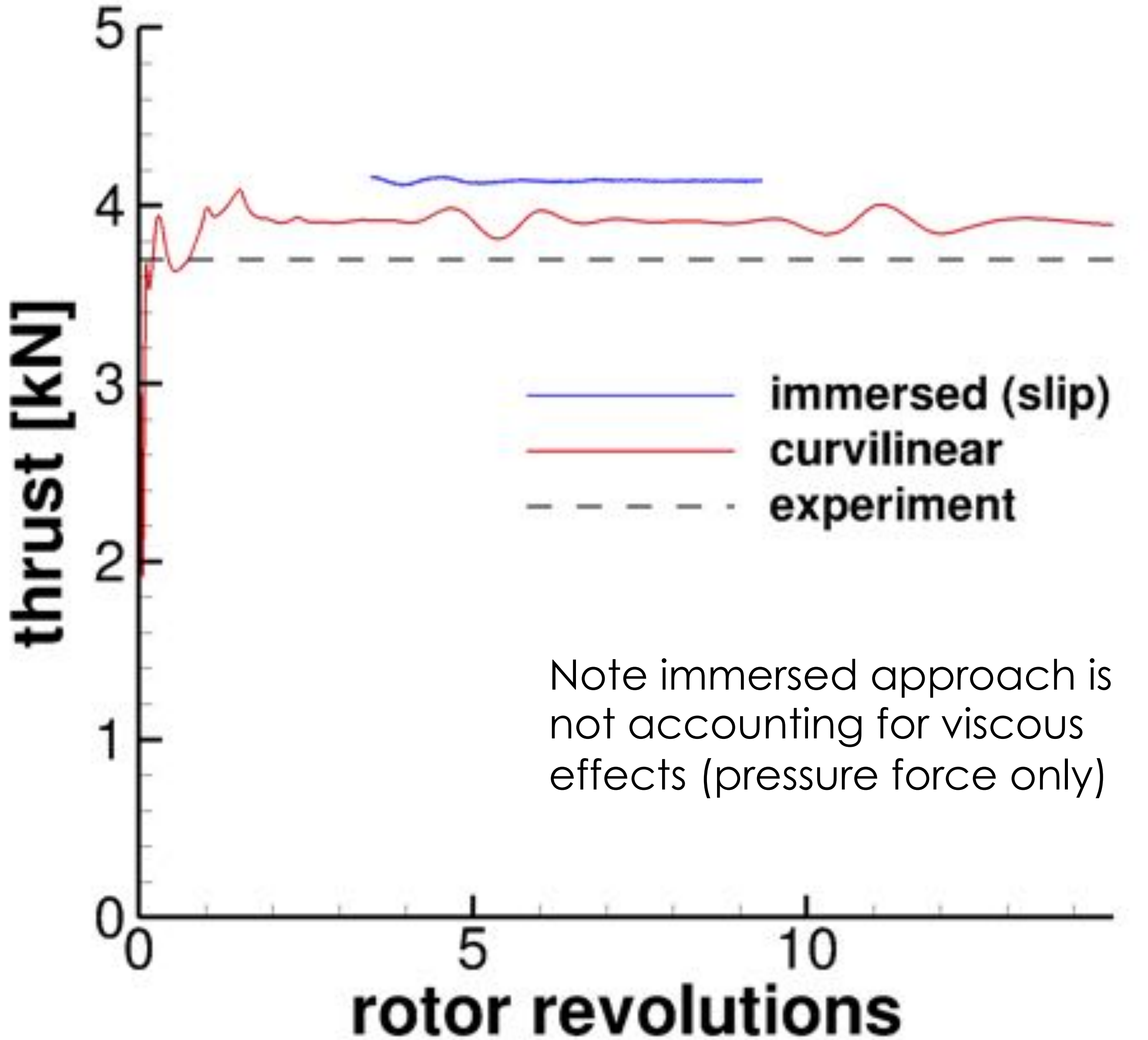
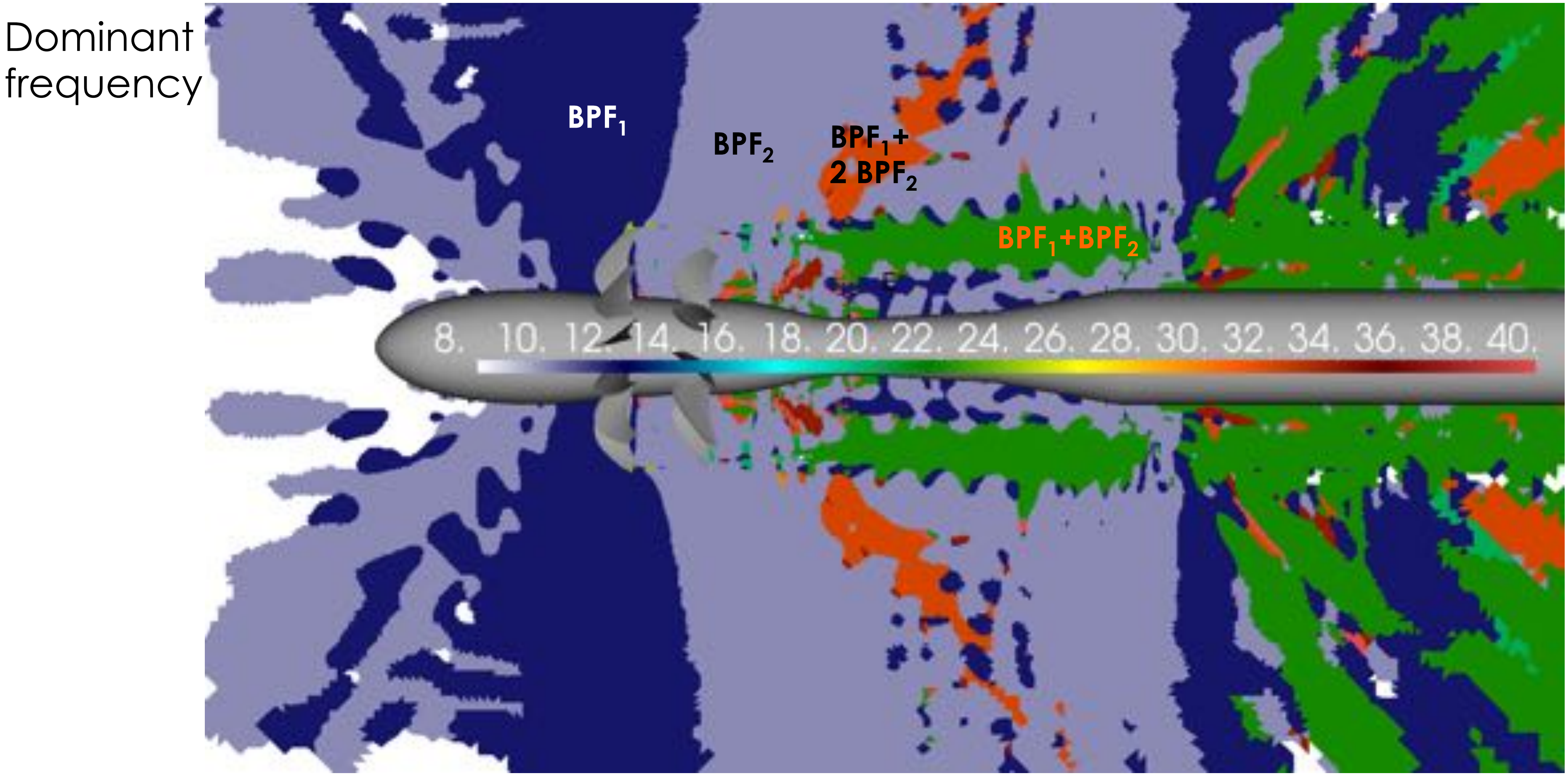
Kulite 9 H = 0.51m



Thrust Comparison



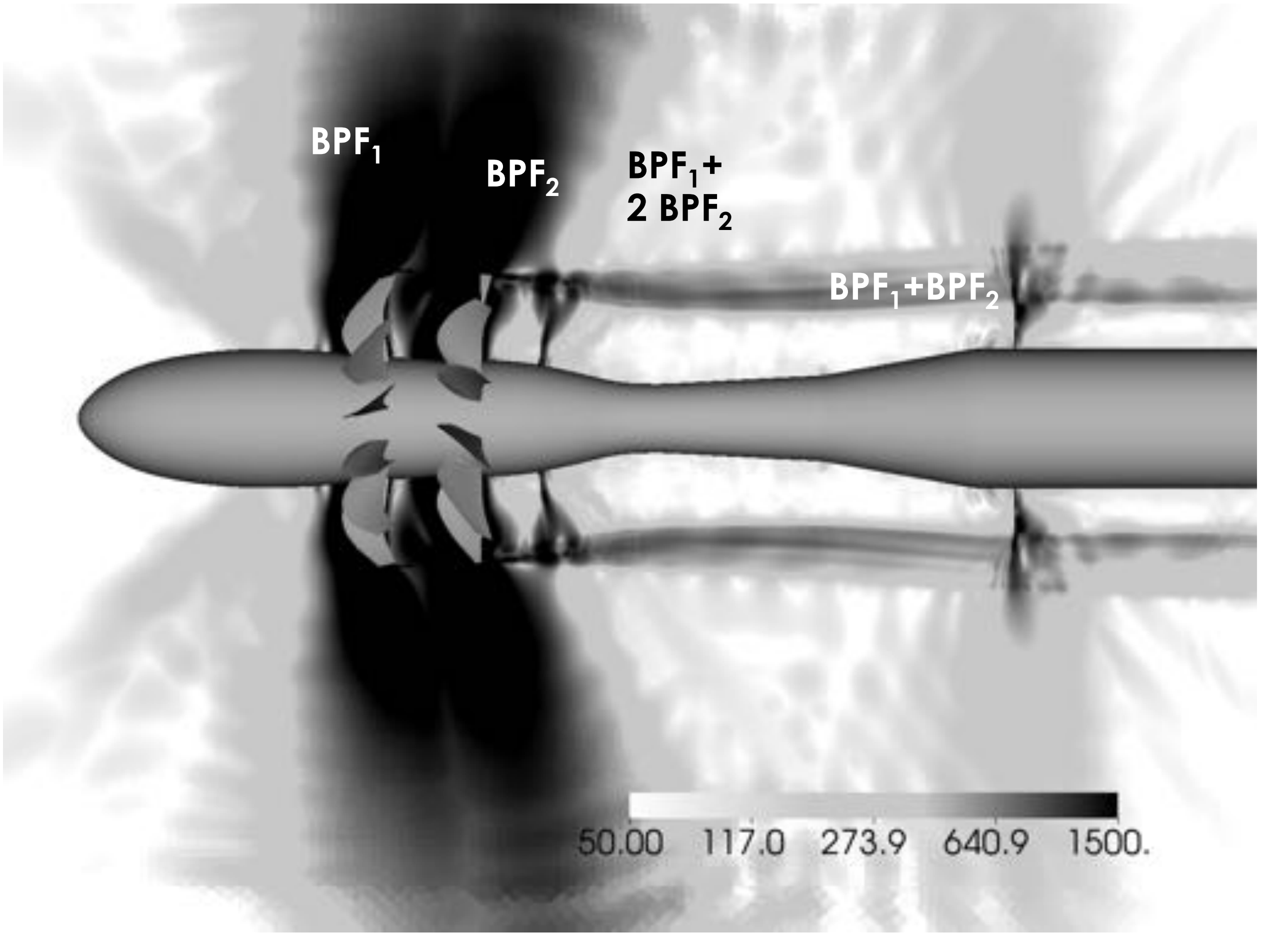
Temporal FFTs: Immersed WENO5



- **Different noise generation mechanisms are dominating different parts of the flow field**

Temporal FFTs: Immersed WENO5

Maximum amplitude

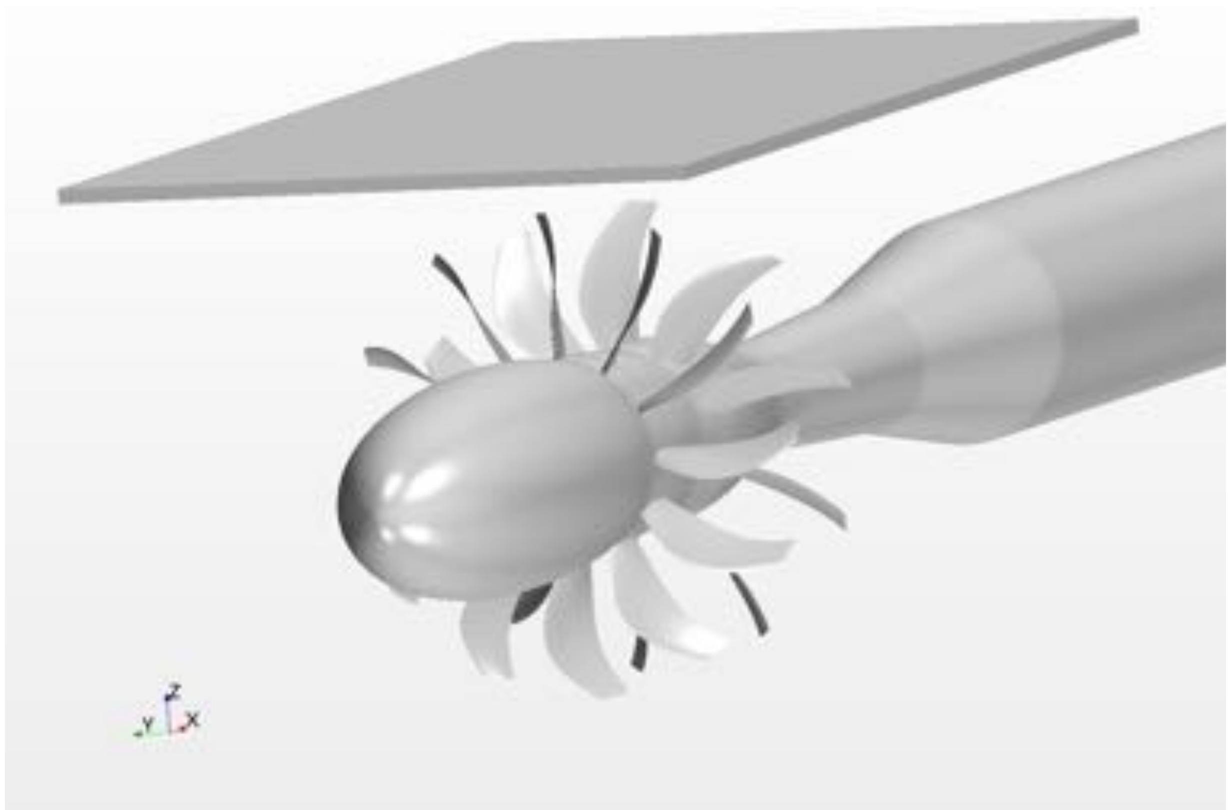


- **Different noise generation mechanisms are dominating different parts of the flow field**

LAVA Cartesian : Plate Effects

Inserted plate into existing Cartesian (WENO5) simulation.
Preliminary results:

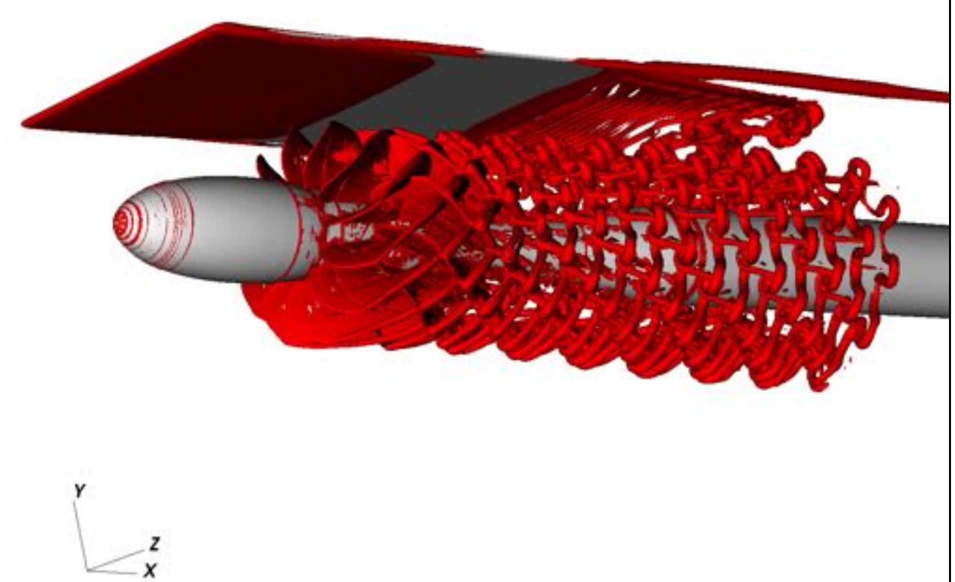
- Additional grid points for plate
- Elevated velocity/CFL occurred at leading and trailing edge
- Plate trailing edge has unsteady wake shedding



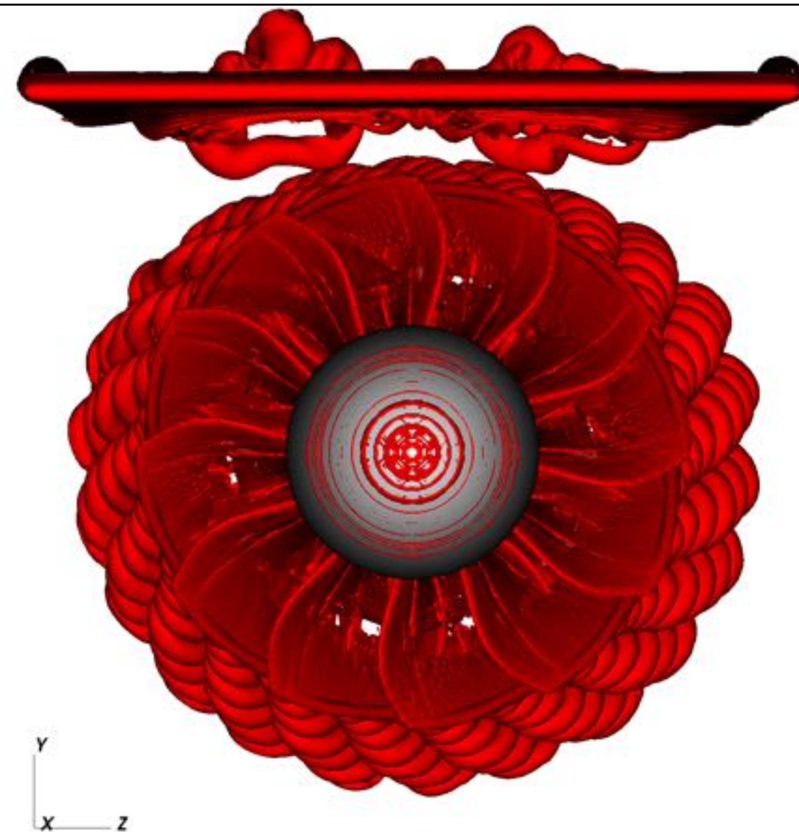
LAVA Cartesian : Plate Effects

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)



Oblique view showing plate wake



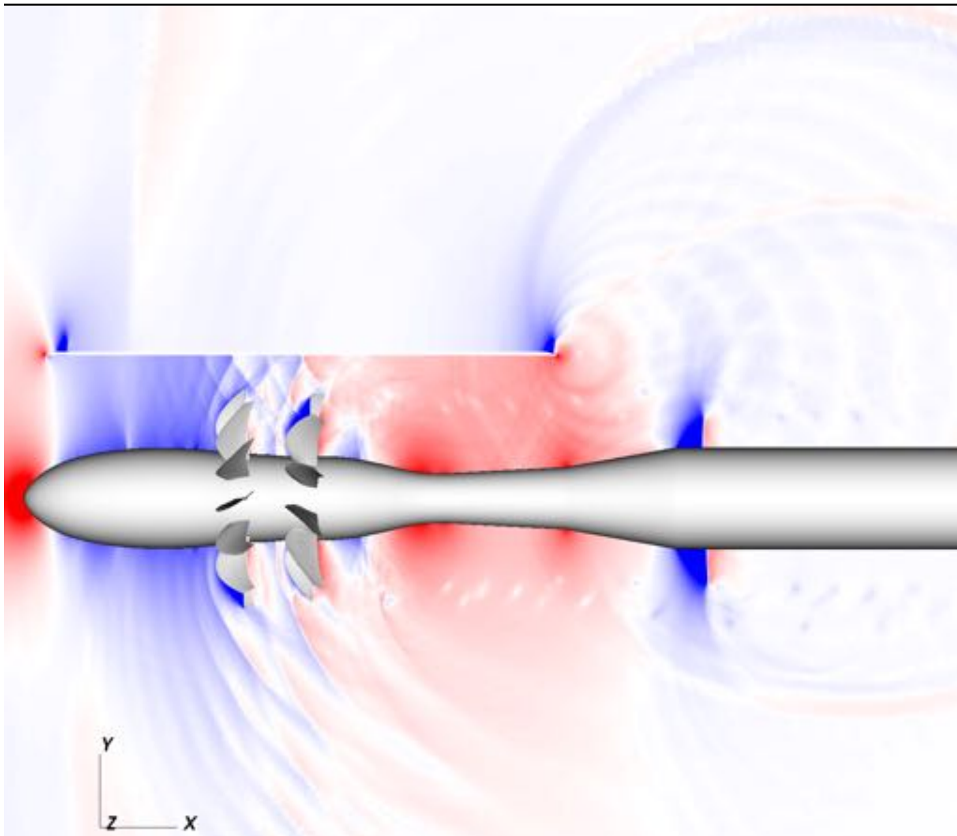
Asymmetry of vorticity “web”

Vorticity level 2000 [1/s] contoured

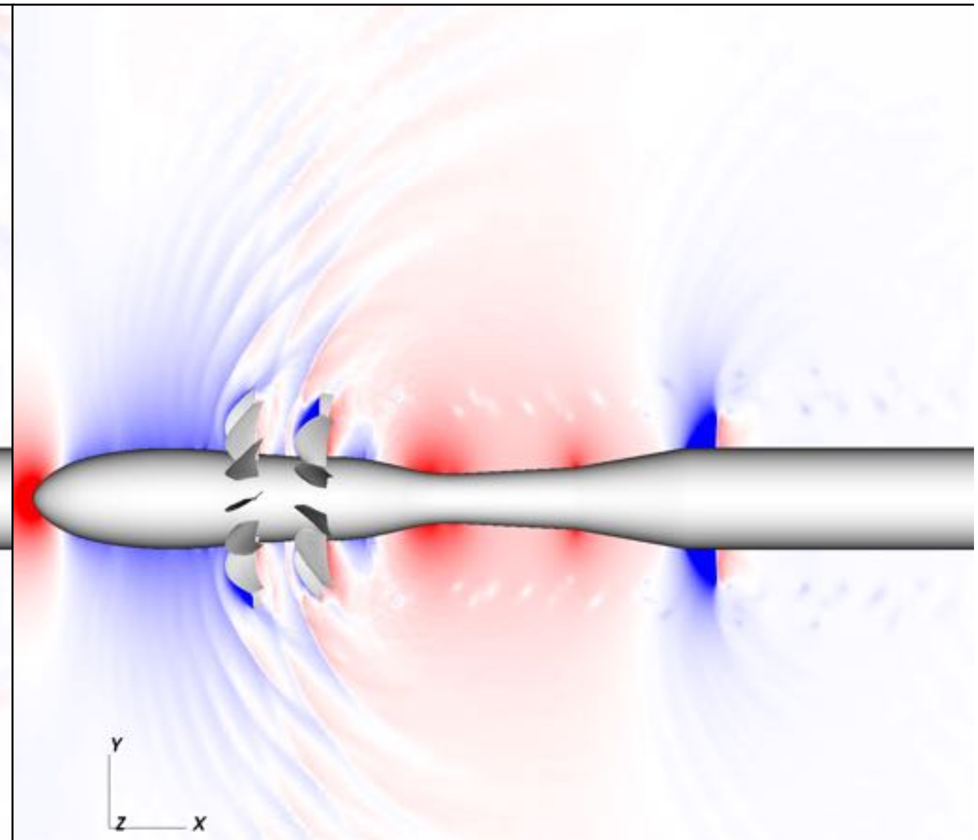
LAVA Cartesian : Plate Effects

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



With sampling plate at 43cm

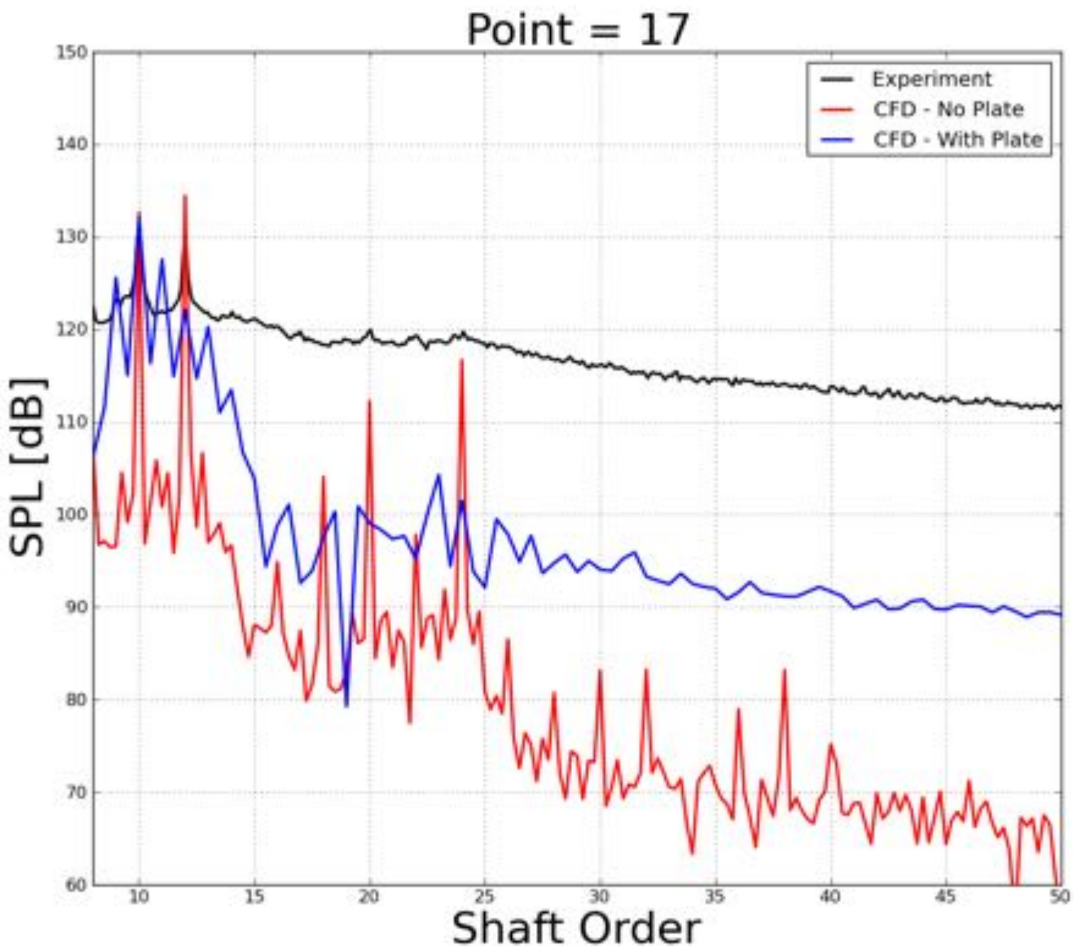


Without sampling plate

LAVA Cartesian : Plate Effects

Comparisons show that the plate (@43cm) introduces flow differences:

- Elevated broadband levels
- Finer grid resolution should further improve broadband content

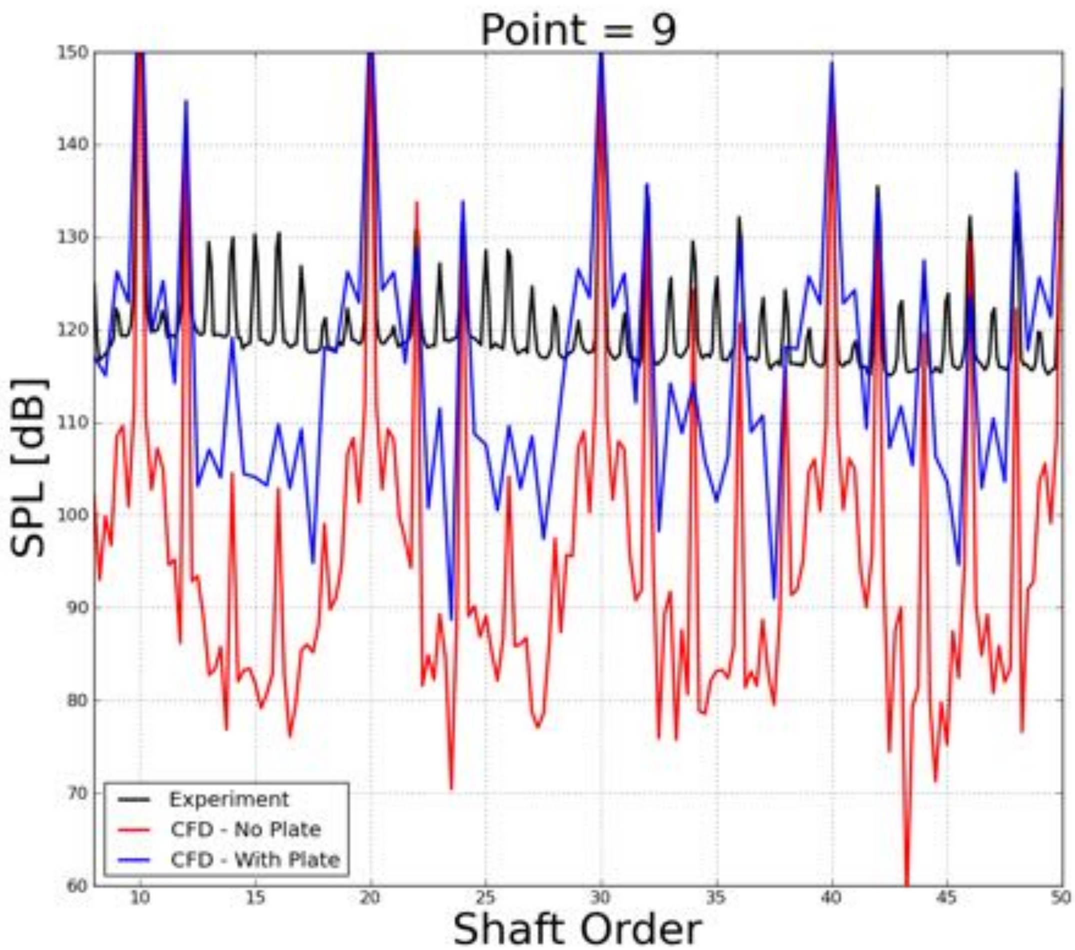


Point 17 (upstream)

LAVA Cartesian : Plate Effects

Comparisons show that the plate (@43cm) introduces flow differences:

- Elevated broadband levels
- Finer grid resolution should further improve broadband content

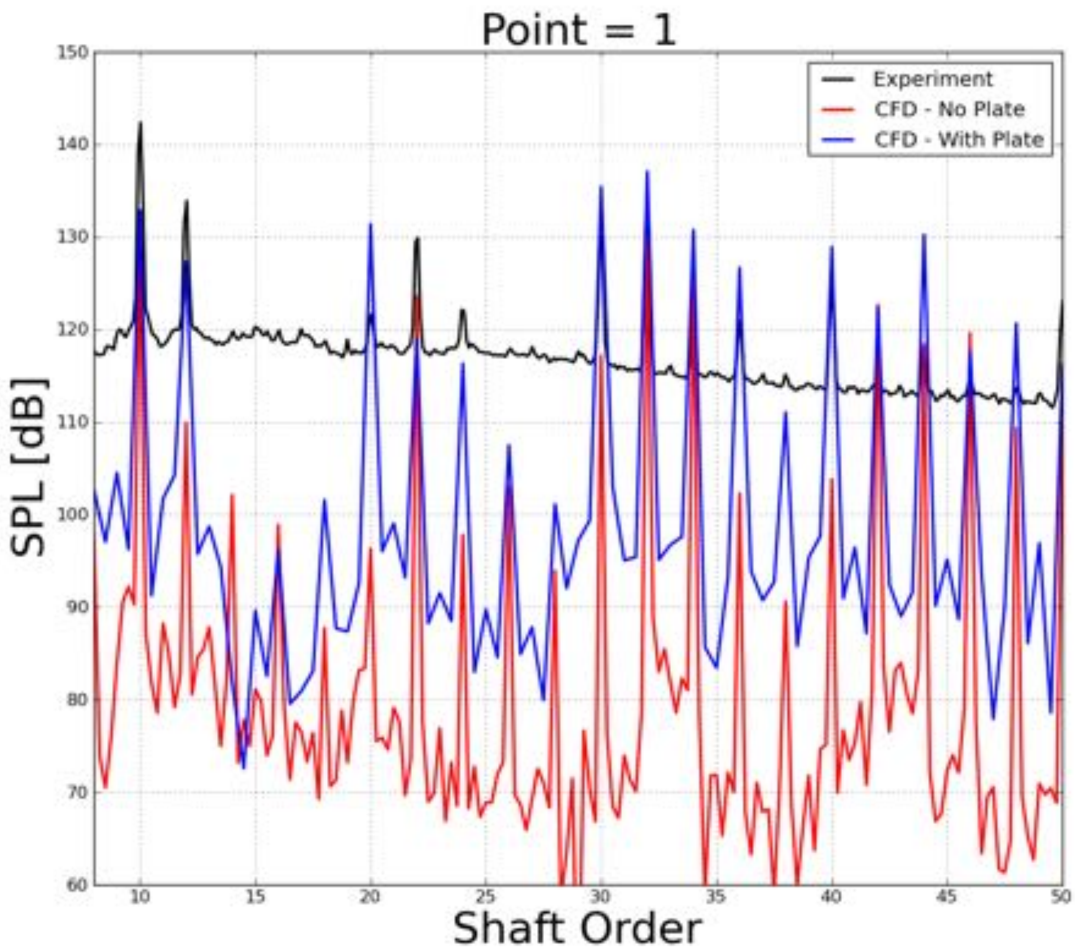


Point 9 (center)

LAVA Cartesian : Plate Effects

Comparisons show that the plate (@43cm) introduces flow differences:

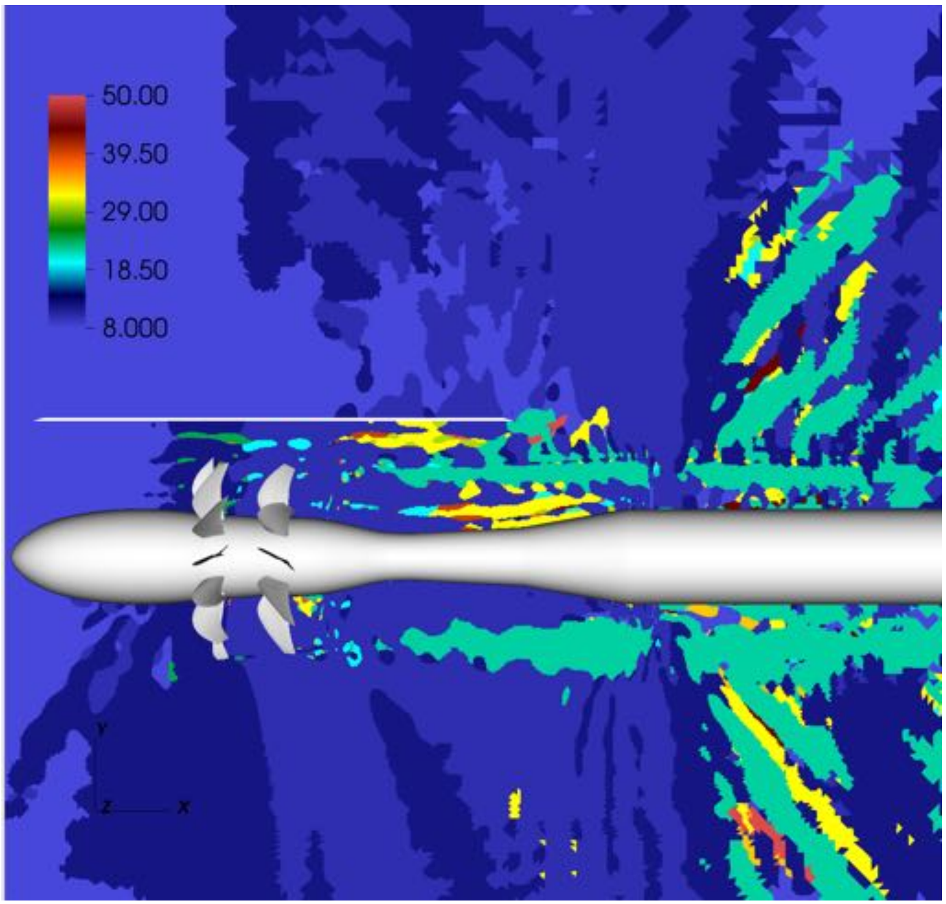
- Elevated broadband levels
- Finer grid resolution should further improve broadband content



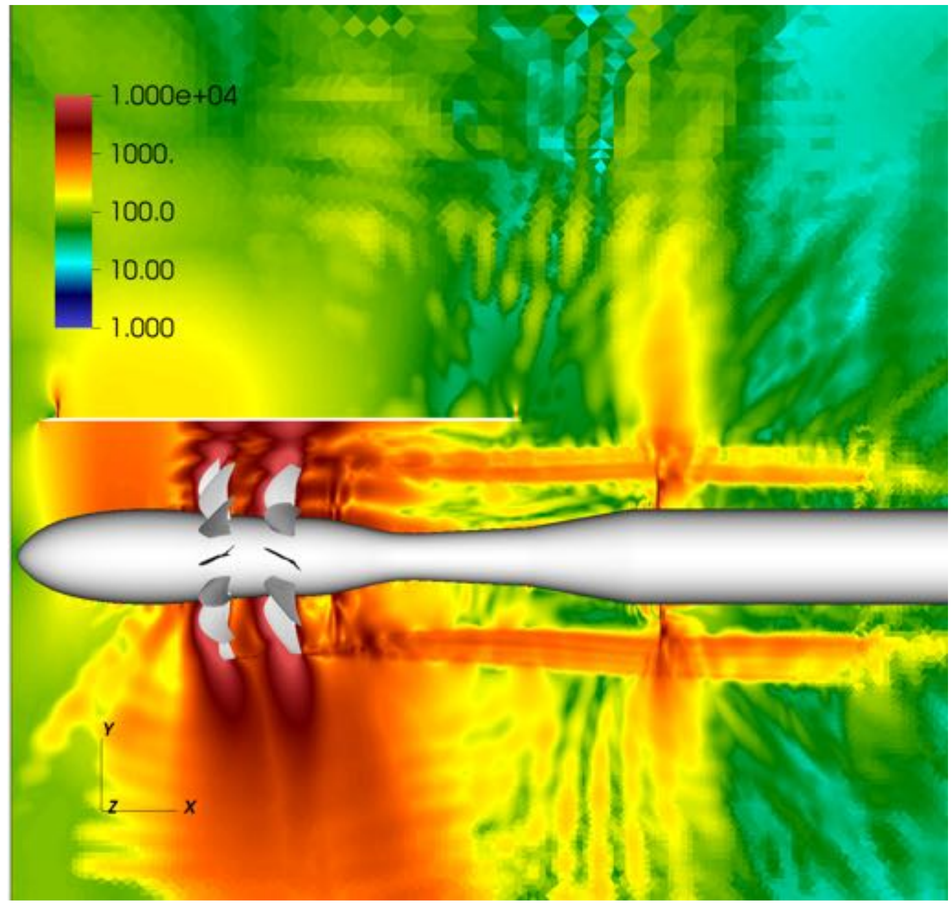
Point 1 (aft)

LAVA Cartesian : Plate Effects

Frequency at peak amplitude [shaft orders]



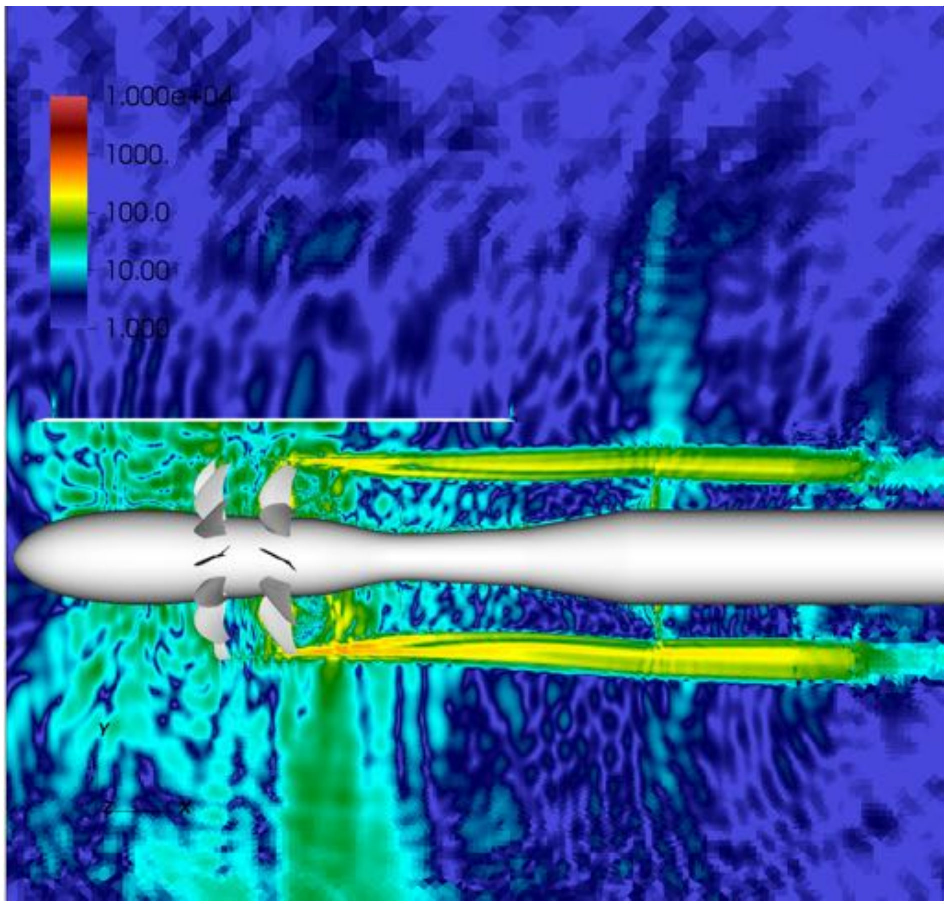
Amplitude at peak frequency



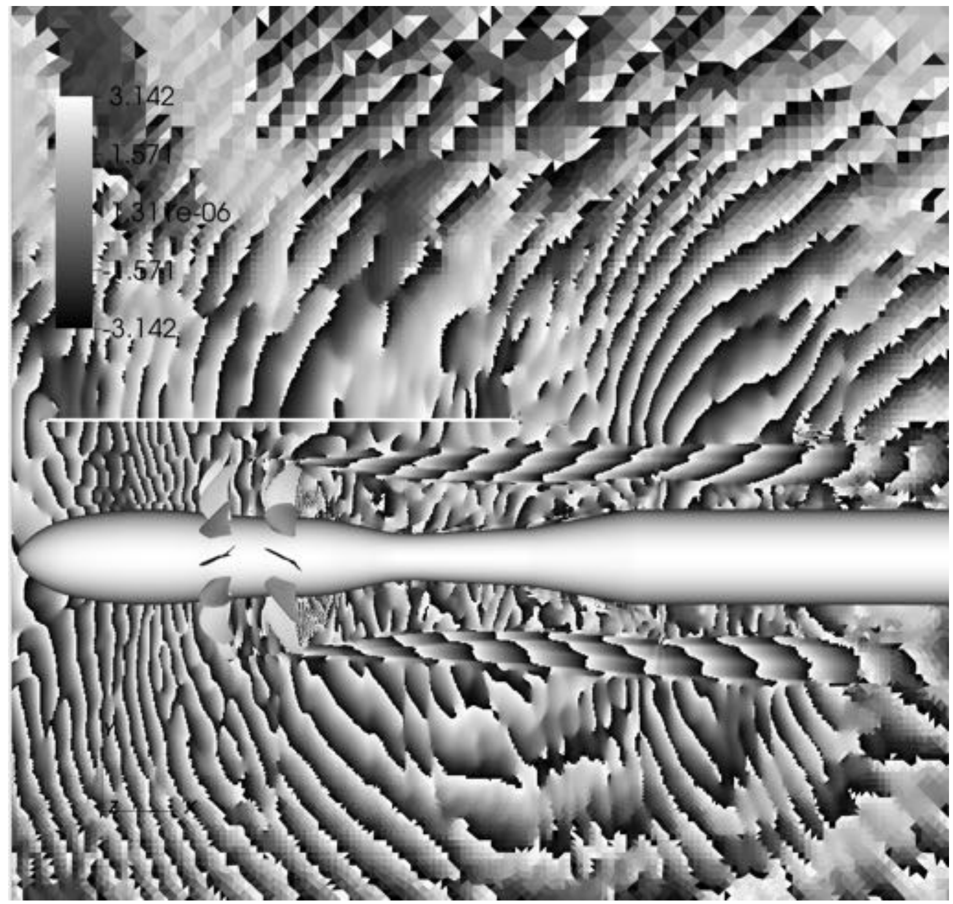
LAVA Cartesian : Plate Effects

Shaft Order = 14 (2 x BPF_1-BPF_2)

Amplitude



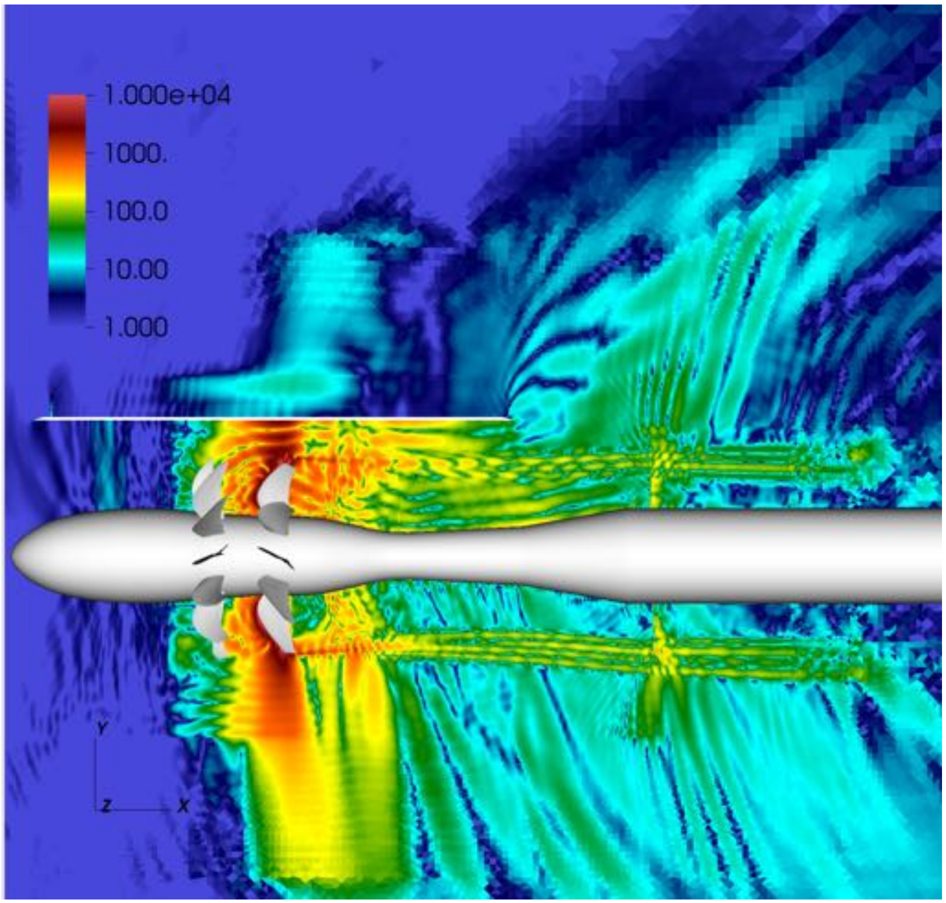
Phase



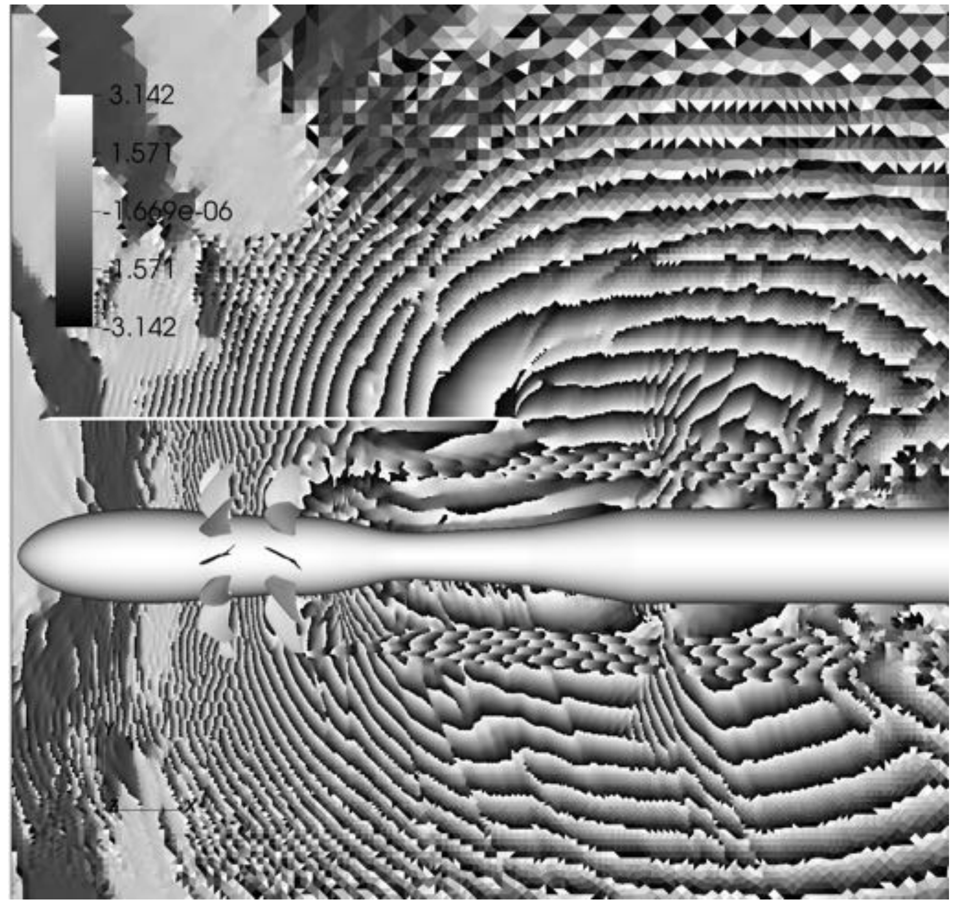
LAVA Cartesian : Plate Effects

Shaft Order = 30 (3 x BPF_1)

Amplitude



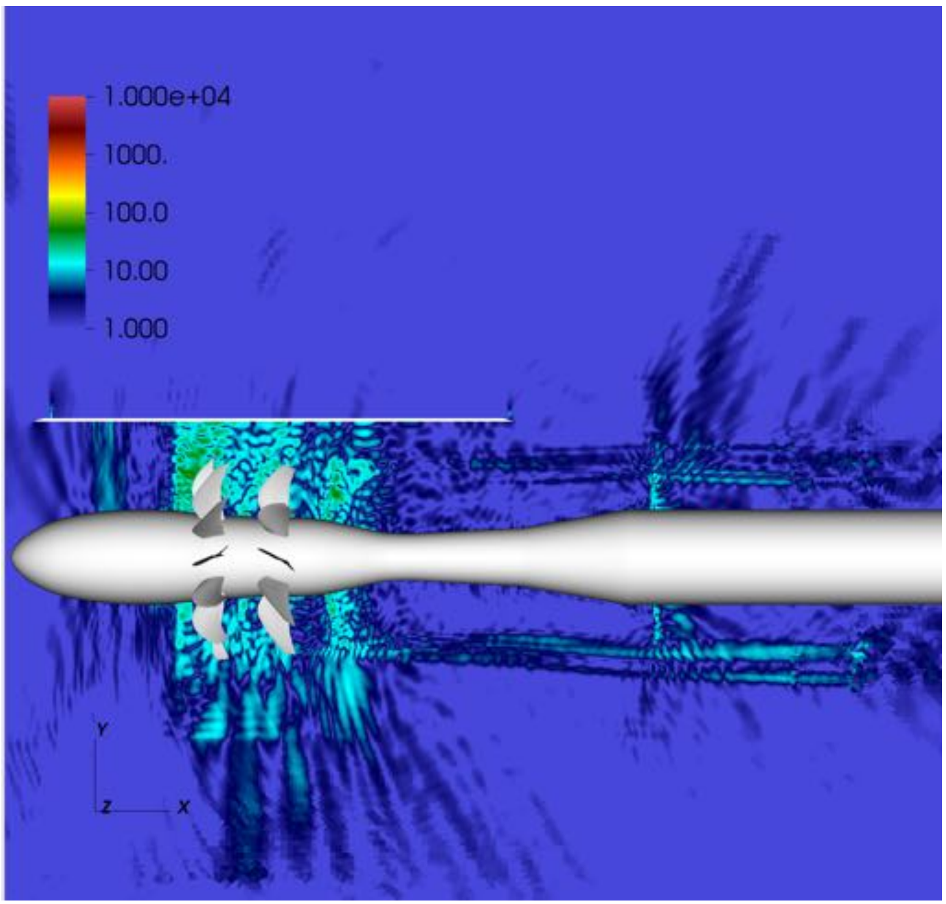
Phase



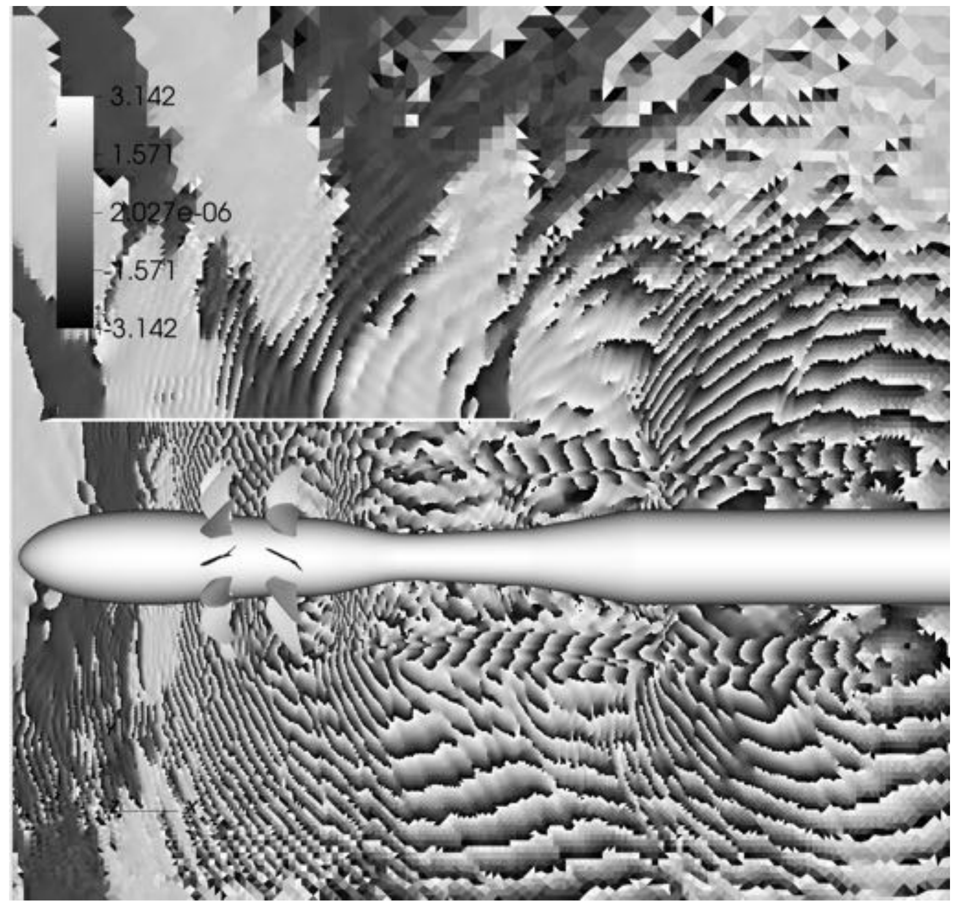
LAVA Cartesian : Plate Effects

Shaft Order = 33

Amplitude



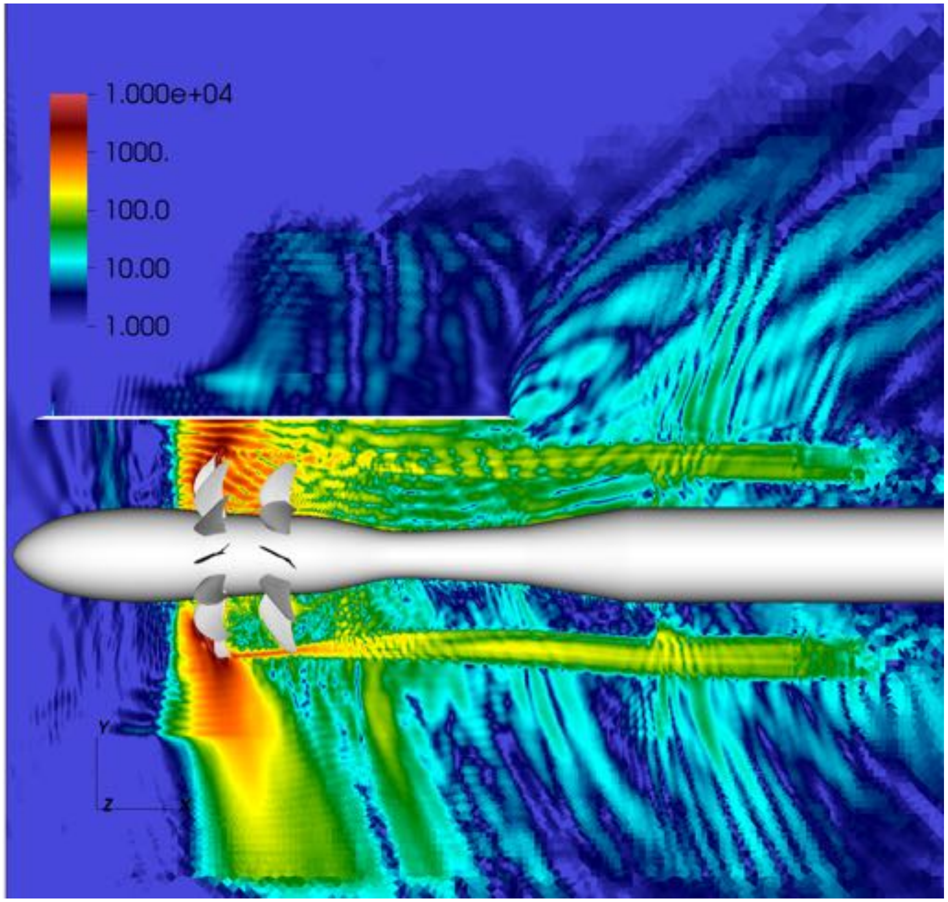
Phase



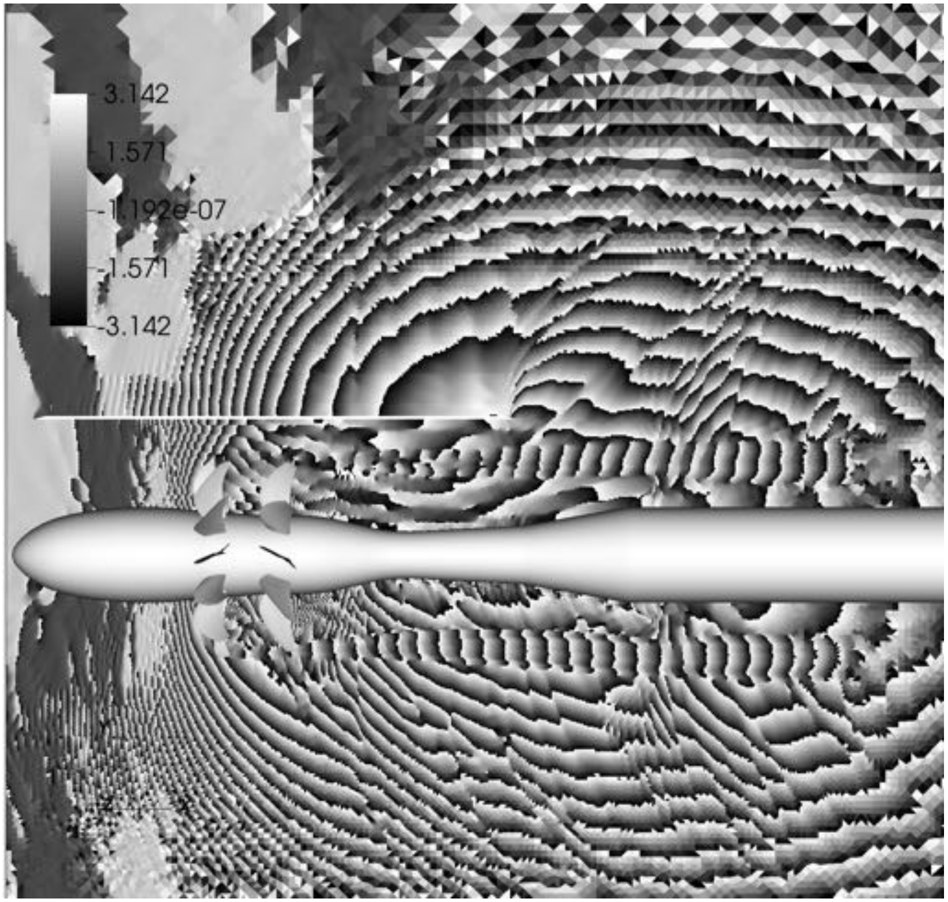
LAVA Cartesian : Plate Effects

Shaft Order = 36 (3 x BPF_2)

Amplitude



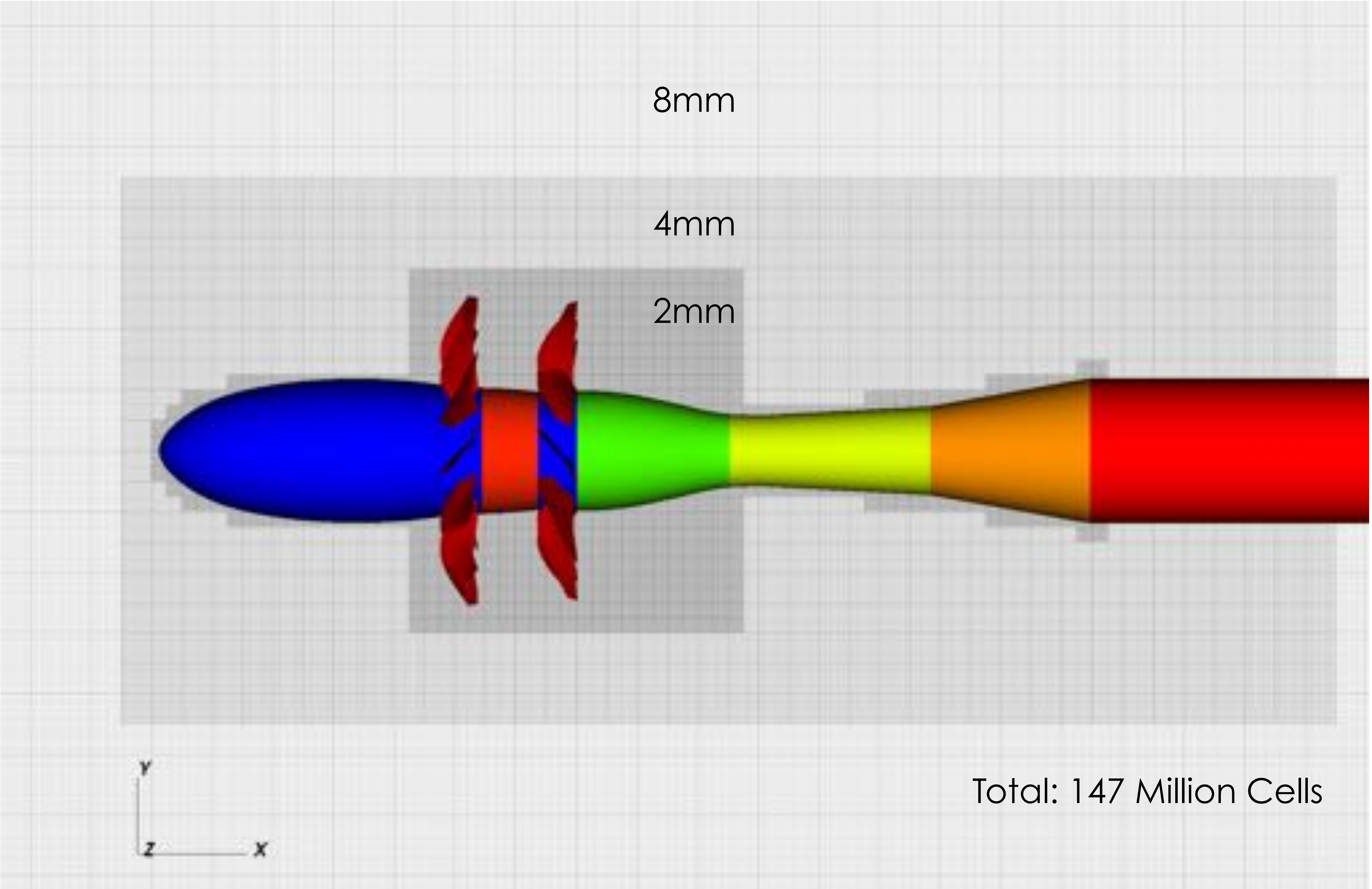
Phase



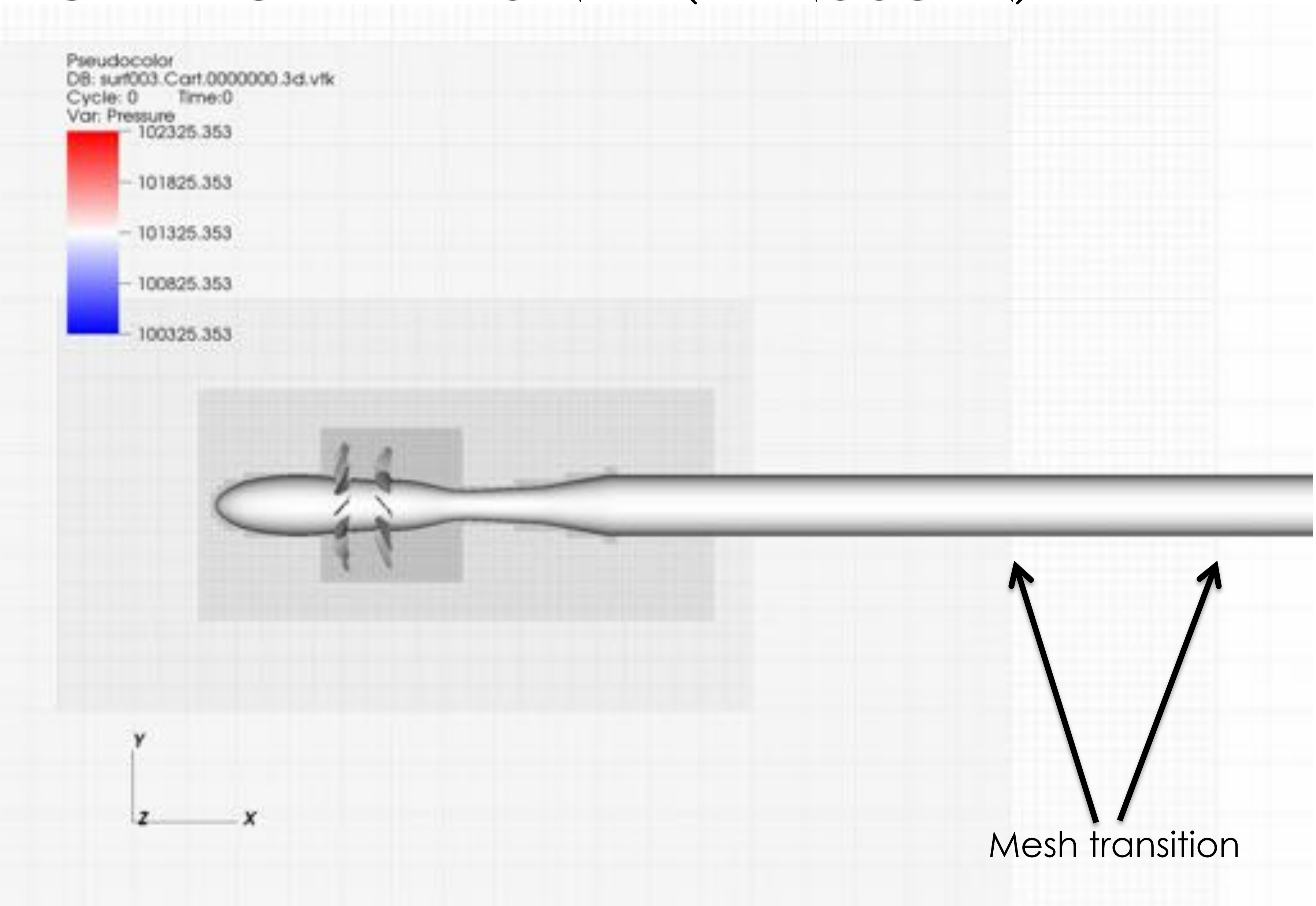
Low Speed Case Setup

- *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

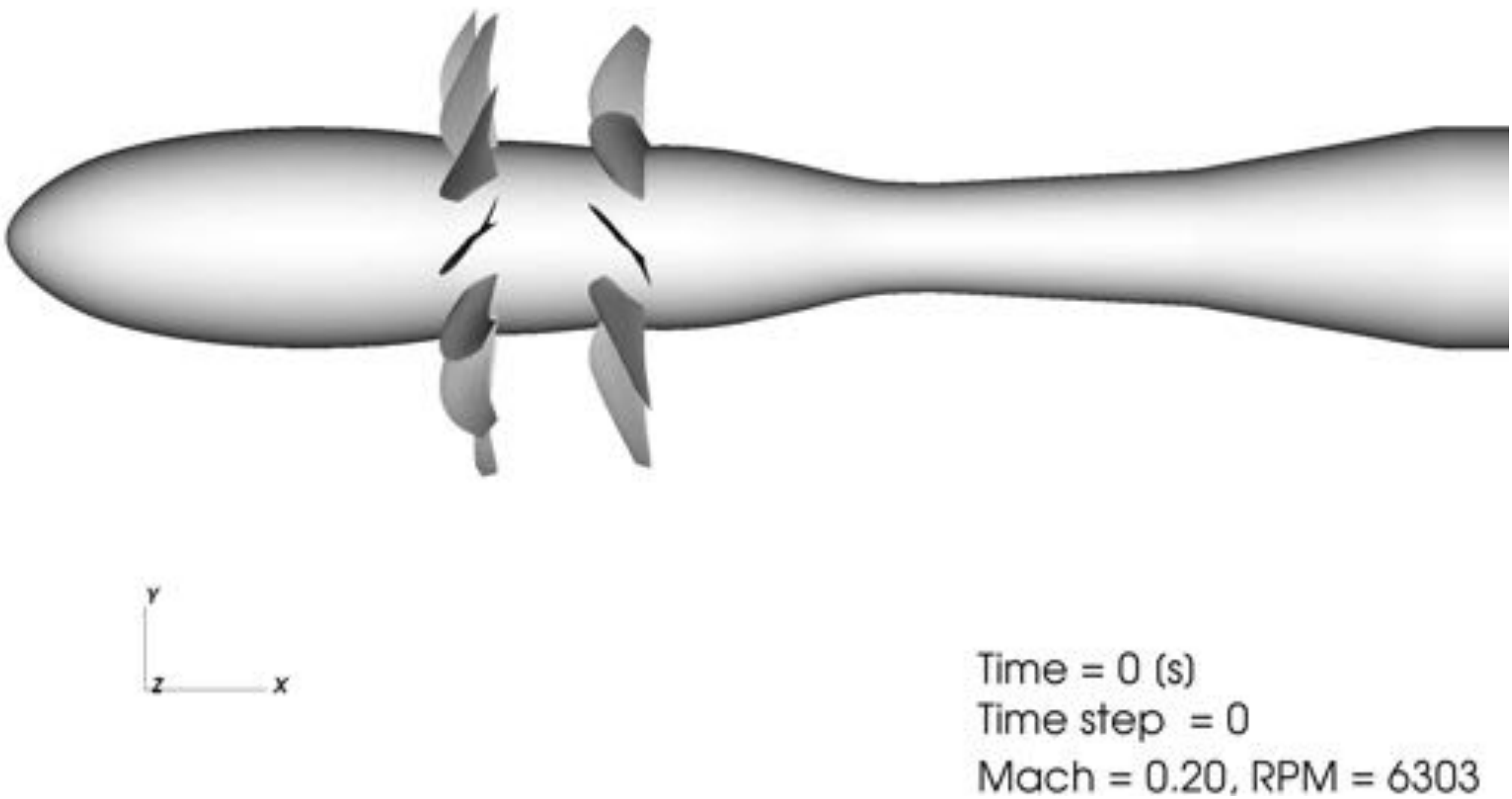
Cartesian Immersed Boundary: Mesh



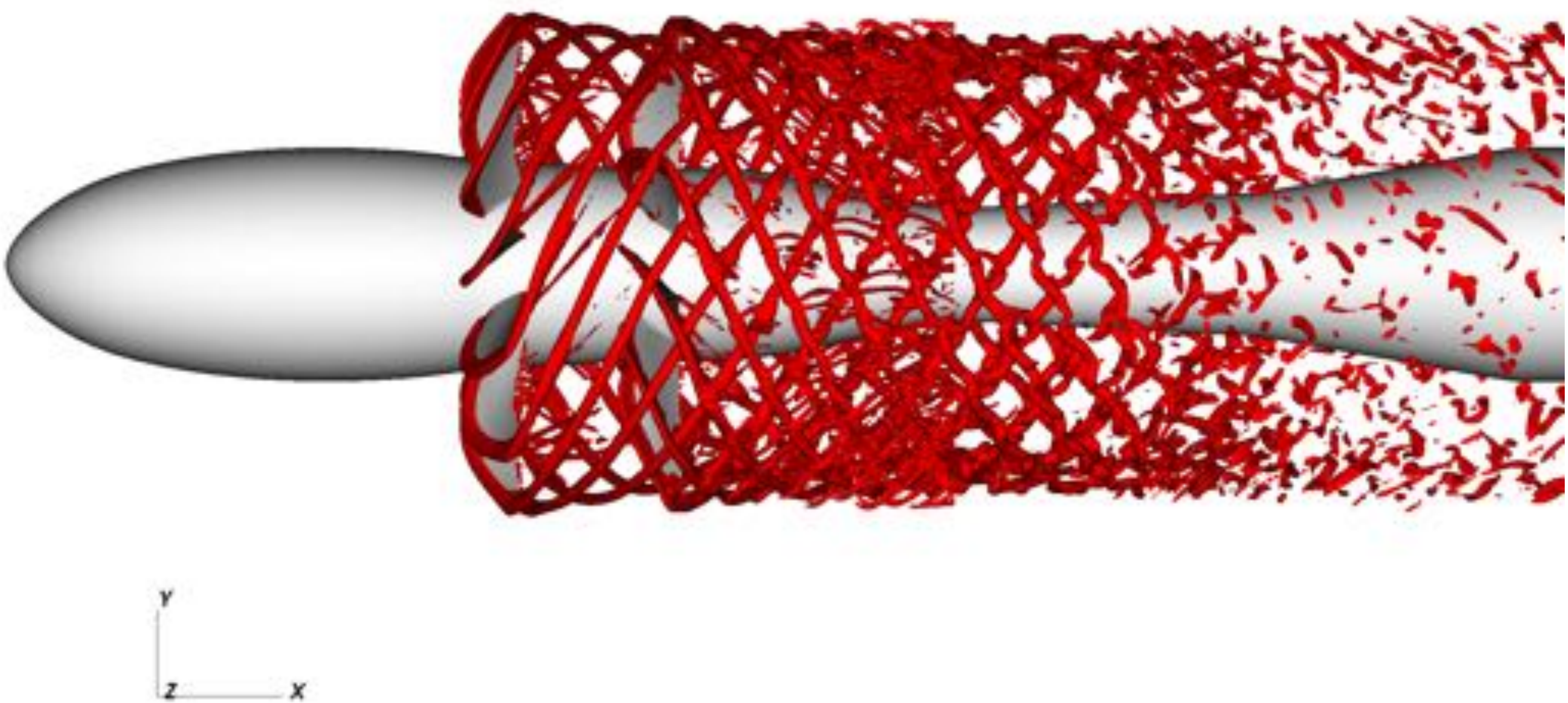
Cartesian Immersed Boundary Startup Transient (Pressure)



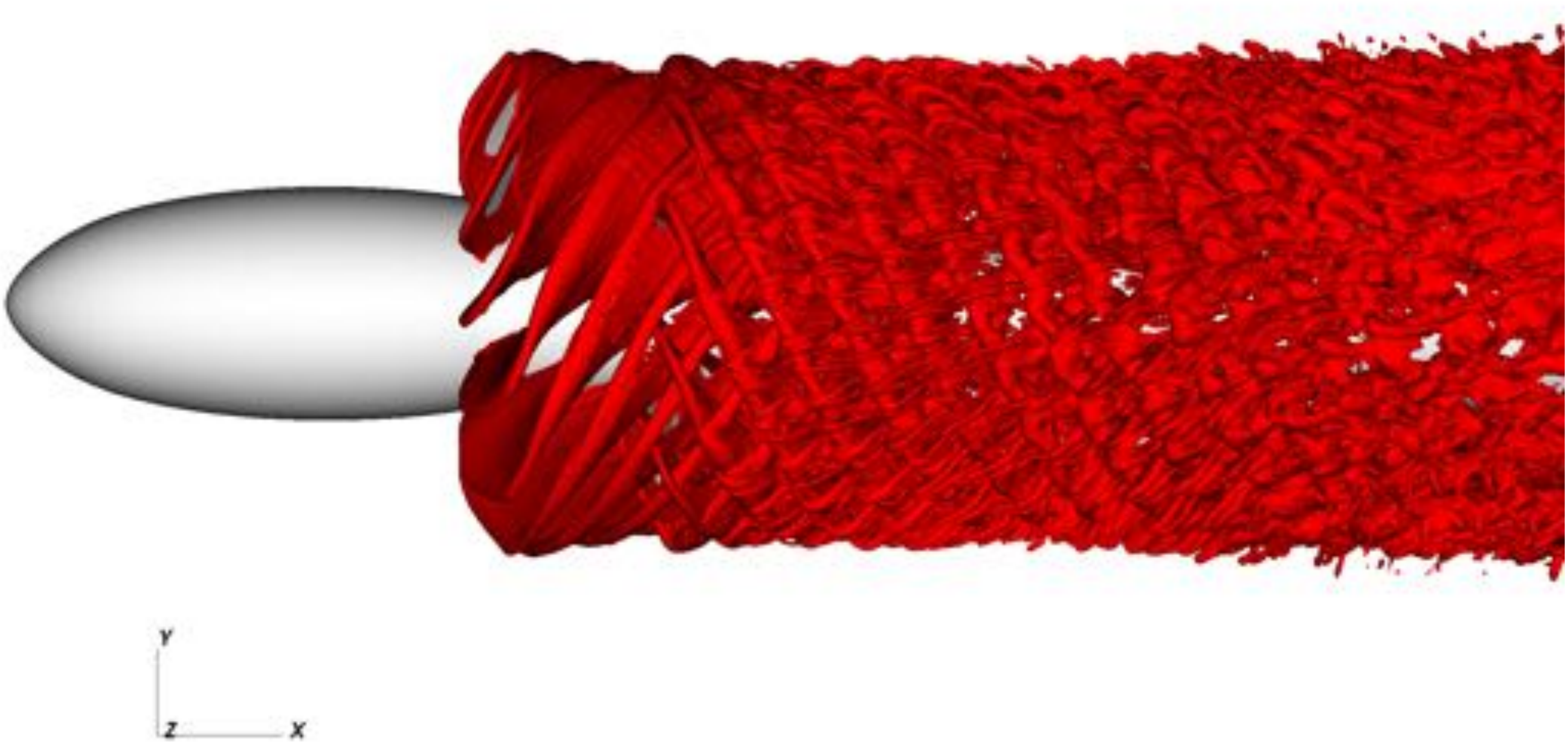
LAVA Cartesian - Pressure Movie



LAVA Cartesian - Vorticity @ 5000 [1/s]

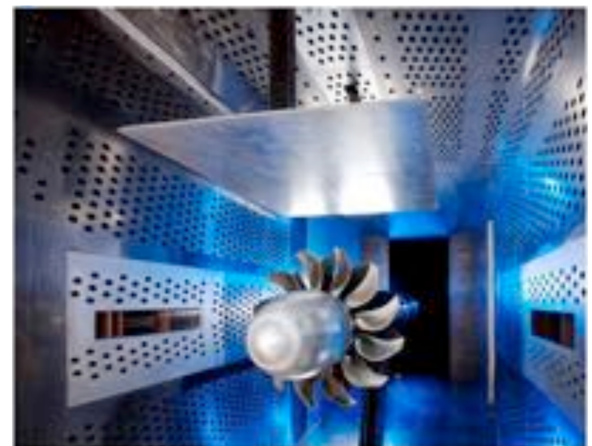


LAVA Cartesian - Vorticity @ 2000 [1/s]



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