Open Rotor Computational Aeroacoustic Analysis with an Immersed Boundary Method

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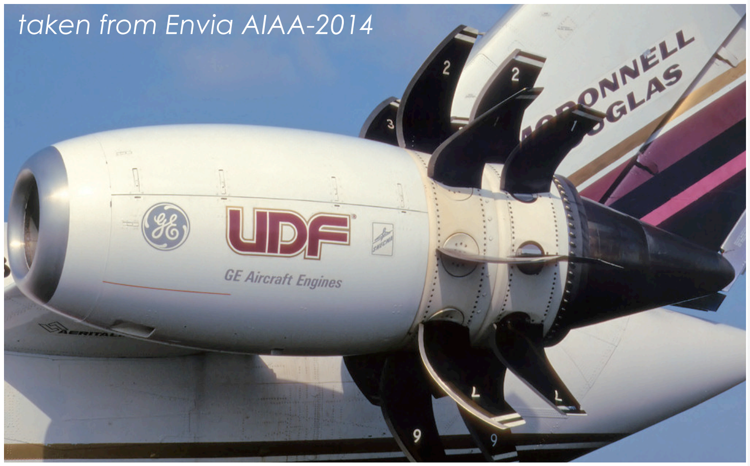
Outline

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. Pylon Installed Low Speed Case
7. Summary

Introduction – The Big Picture



GE36-UDF propfan demonstrator engine installed on MD-81 test bed aircraft (8x8)

Modern contra-rotating open rotor engine design from CFM (12x10)

- 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 a 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

Introduction – Previous Work

- ❑ NASA initiated several efforts that successfully addressed the noise prediction aspects for CROR mainly in free air

- ❑ There are two different approaches for modeling CROR noise
  a) Empirical models (cheap but lacks generality)
  b) Fully resolved CFD (general but expensive)

- ➢ Model source region (hydrodynamics) separate from acoustic propagation

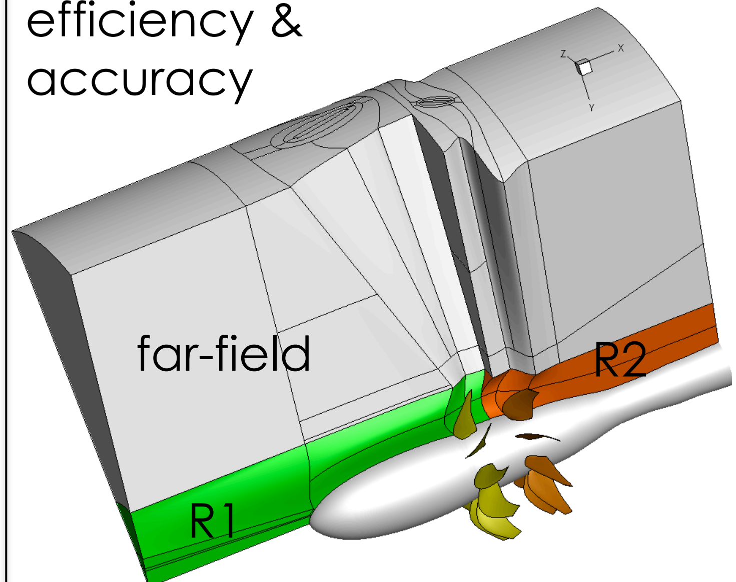
- ❑ Various tools are already available
  Acoustic: ASSPIN/ASSPIN2, FW-H_{pds}, FSC, LINPROP, QUADPROP, etc.
  Aerodynamics: SBAC, UBAC, FUN3D, OVERFLOW, LAVA, etc.

- ❑ Different aspects of CROR noise generation have been studied
  - ❑ Tonal noise is the dominant part in the spectrum
    (Envia IJA-2015, Envia CMFF12-2012, VanZante and Envia ASME-2014, Nasr et al. AIAA 2013-3800, Sharma & Chen AIAA 2012-2265, Bush et al. AIAA 2013-2202)
  - ❑ 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)

Introduction – Our Motivation

- A key challenge is to devise an efficient method that can capture installation effects
- Current approach:
  - Utilizing Cartesian AMR compressible Navier-Stokes solver within LAVA
  - Ffowcs-Williams and Hawkings (FWH) method for acoustic noise propagation
  - Comparison with experiments and Housman & Kiris (2016) utilizing LAVA's curvilinear-overset solver

State-of-the-art in terms of efficiency & accuracy



Non-linear harmonics FINE™/ Turbo simulations and acoustic model for propagation

Envia IJA-2015, Envia CMFF12-2012, VanZante & Envia ASME-2014

- **Objectives of this work:**

1. Develop moving boundary capabilities inside LAVA Cartesian
2. Validate LAVA Cartesian+FWH approach against experimental data
3. Analyze noise propagation for nominal takeoff and cruise conditions

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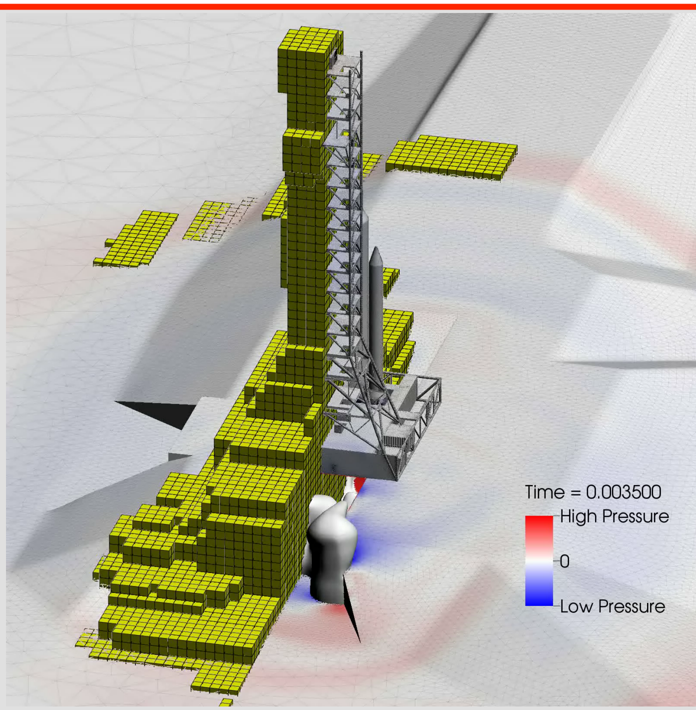
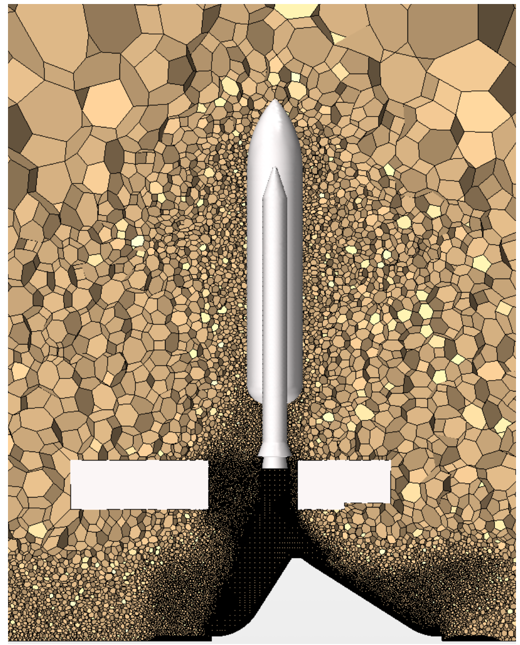
Launch Ascent & Vehicle Aerodynamics (LAVA)

LAVA is being developed at NASA Ames Research Center



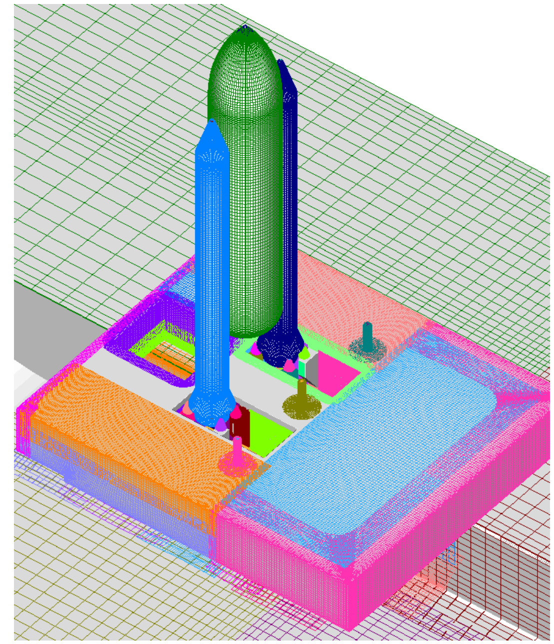
Cartesian AMR

- Essentially no manual grid generation
- Highly efficient Structured 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 partially automated
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods are yet to fully mature

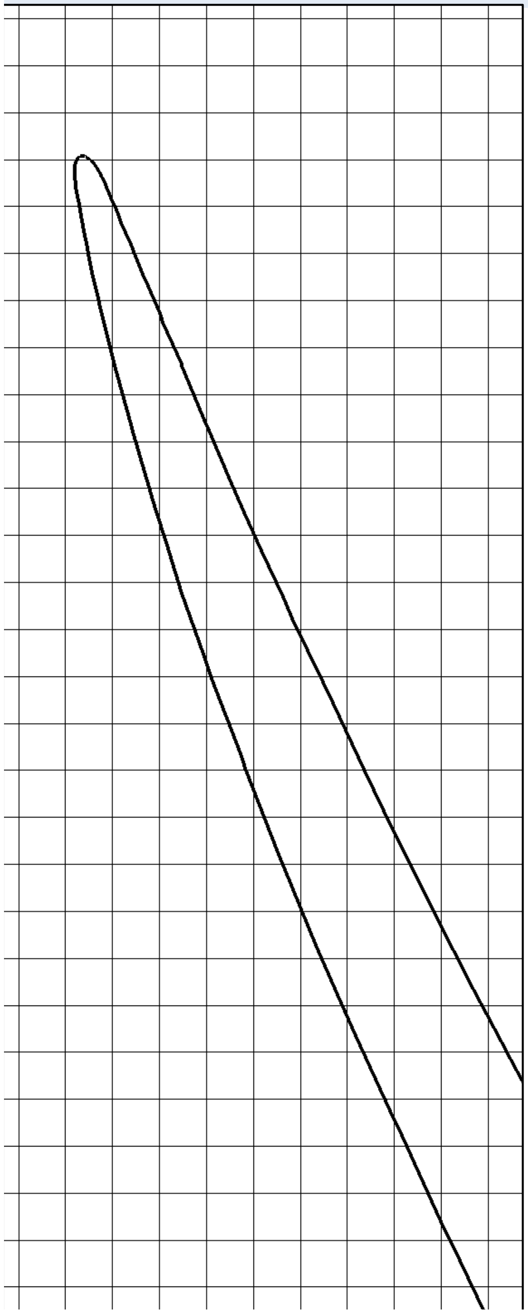


Structured Curvilinear

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

*Kiris et al.(2016), Sozer et al. (2014), Brehm et al. (2015)

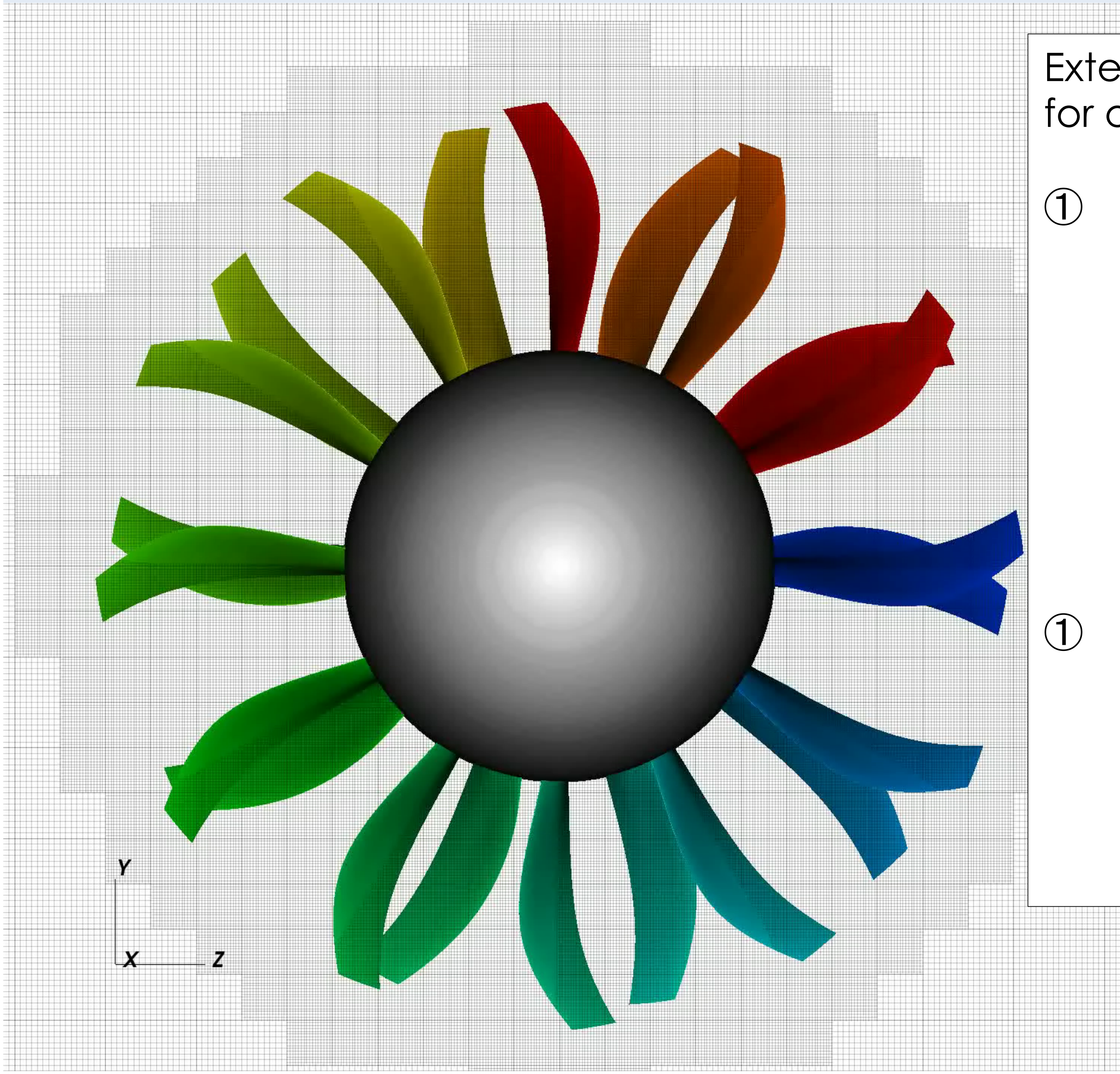
Immersed Boundary Method (IBM) Introduction



- IBMs enable automatic volume mesh generation from water tight surface triangulation(s)
- For problems involving moving and deforming boundaries IBM provides clear advantages (for example no mesh deformation needed)
- Main disadvantage is that at high Reynolds numbers, IBMs become inefficient or require some type of wall model
- Most immersed boundary methods are only lower order accurate
- LAVA Cartesian has two different IBM methods available:

  1. Ghost cell based scheme (2010-present)
  2. Interior only, higher order accurate schemes (2015-present)

Extensions of IBM for Open Rotor



Extensions of IBM required for open rotor simulations:

① Optimizations for high-performance:
- Interior only scheme for thin geometry
- Geometry queries
- Re-computation of irregular stencils
- Many others

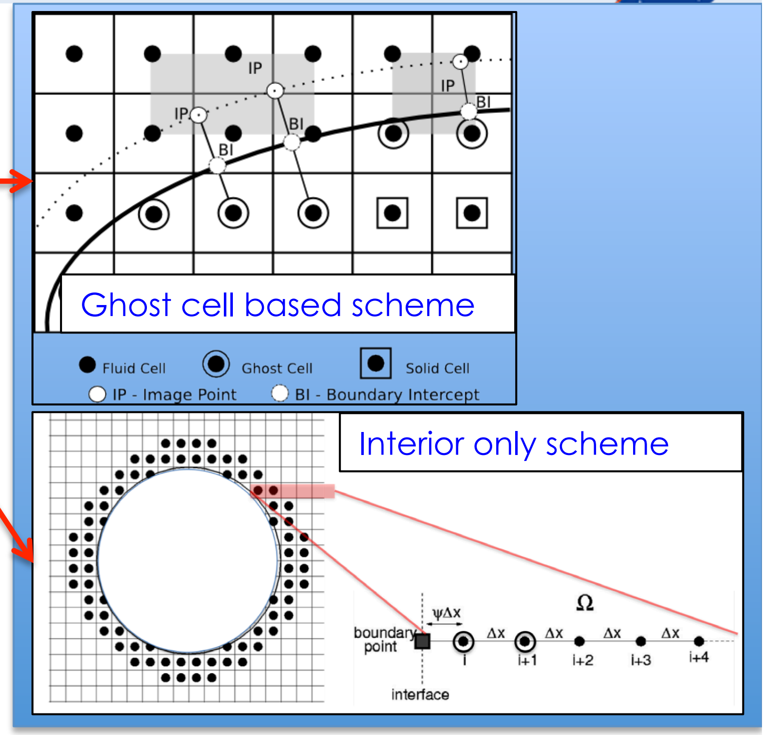
① Address accuracy challenges that are associated with IBM discretizations for moving geometry

IBM Performance Challenge: Thin Geometry

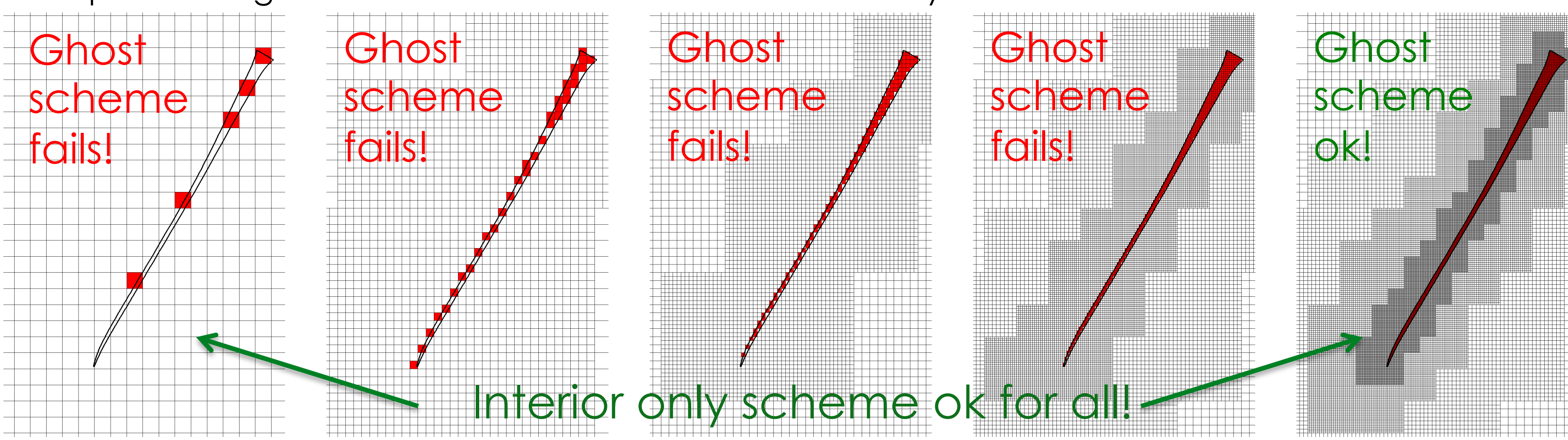
Interior only vs ghost cell based IBM:

- Ghost cell based schemes require filling cells in solid which are used by interior stencils
- Interior based schemes have stencils based only on points in fluid

For thin and/or under-resolved geometry, interior only based schemes are far superior!



Example showing Cartesian mesh refinement for a thin body:

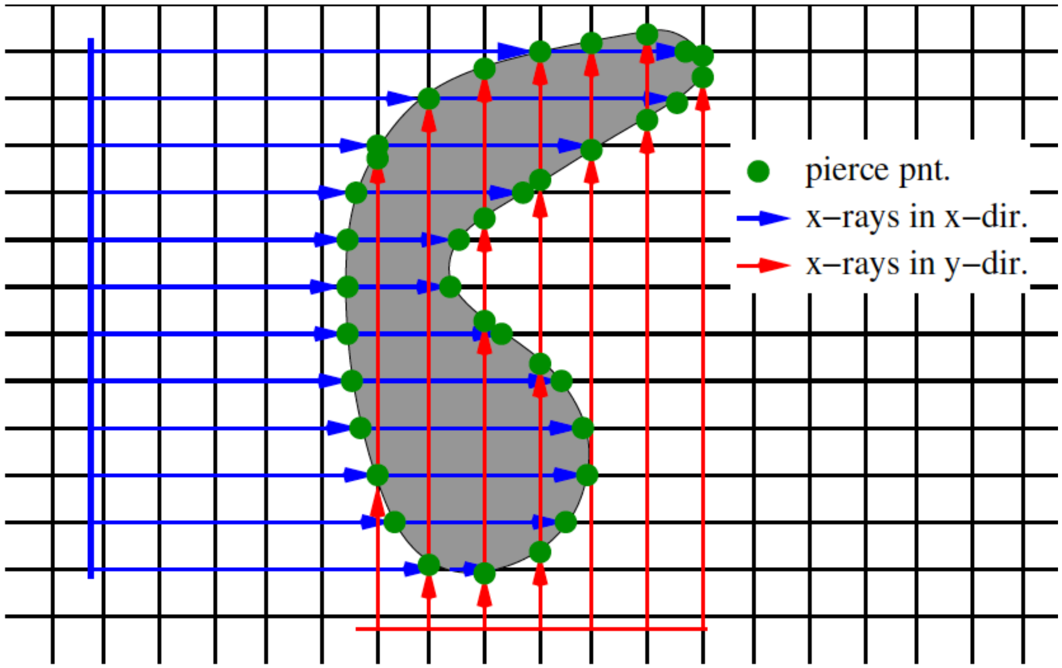


IBM Performance Challenge: Geometry Queries

- High-performance queries required for moving geometry:
  - Point inside/outside
  - Ray-surface intersection
  - Nearest point
  - Box-surface intersection

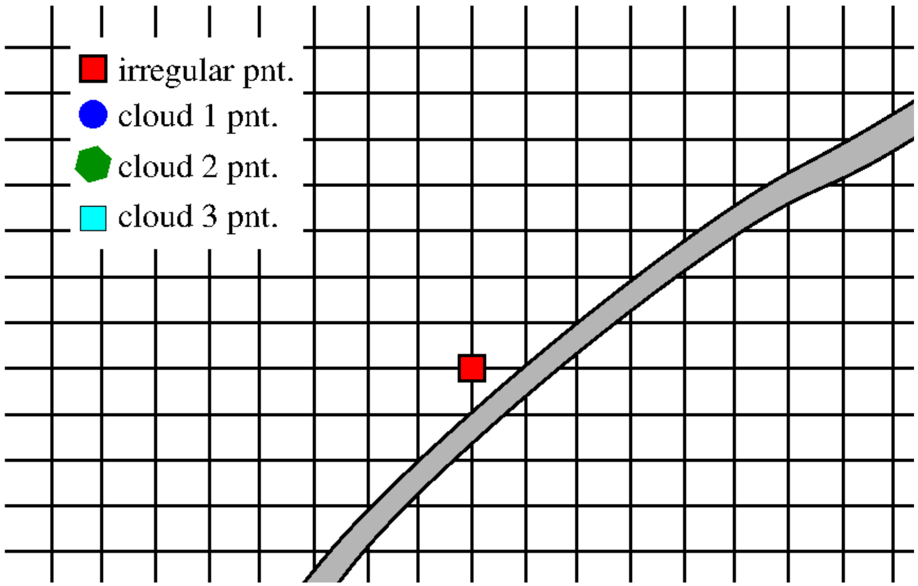
- Our approach is based on surface triangulations:
  - Exact queries, instead of (approximate) level-sets which are challenging for thin and/or moving geometry
  - Using highly optimized bounding volume hierarchy (BVH) based queries [thanks to Intel; and Tim Sandstrom]

Example ray-surface intersection queries:



IBM Accuracy Challenge: Point Cloud Selection

- Interior only IBM does not use ghosts
- Graph walking for stencil clouds: full clouds are built up from individual clouds at irregular points (reduces number of intersection tests)
- The clouds are used to maintain "leak proof" discretizations for thin geometry:
  - RHS operators
  - Surface interpolation for output
  - Etc



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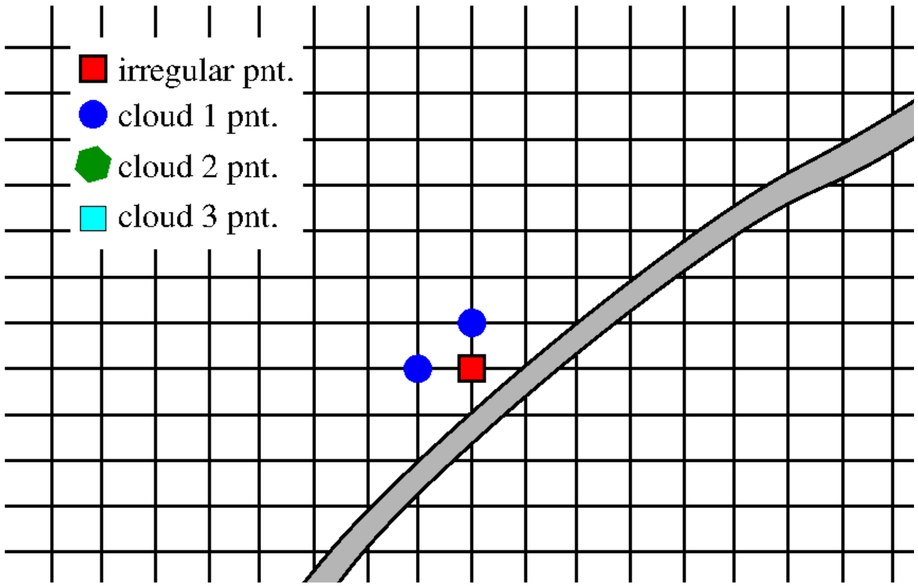

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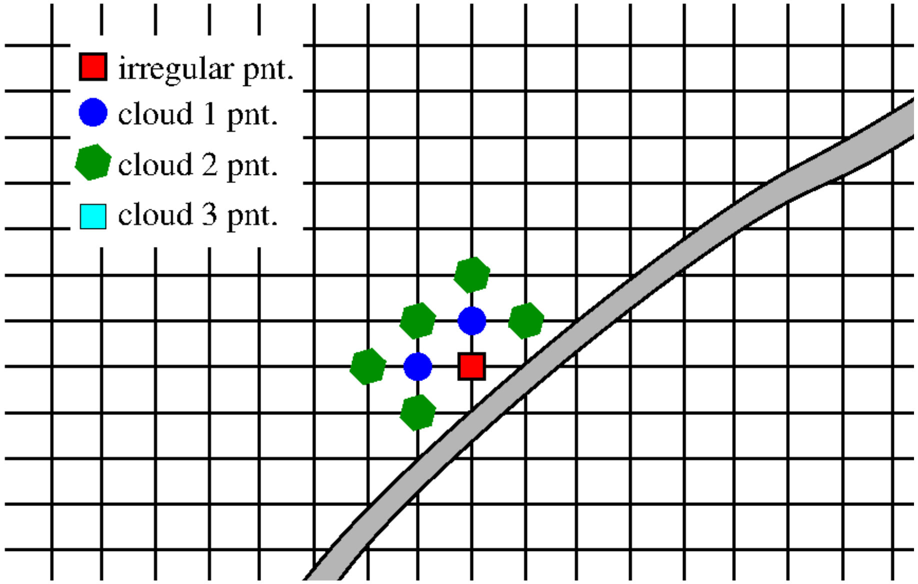

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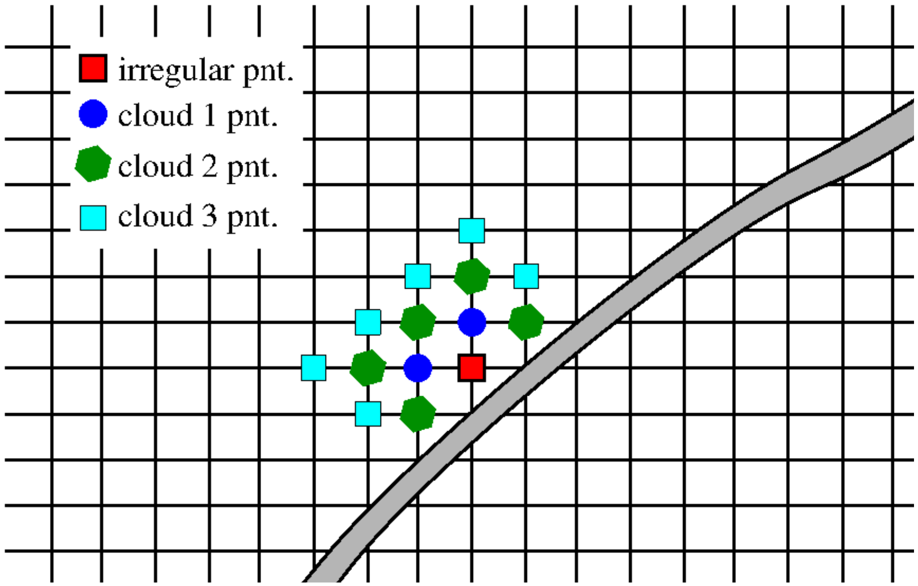
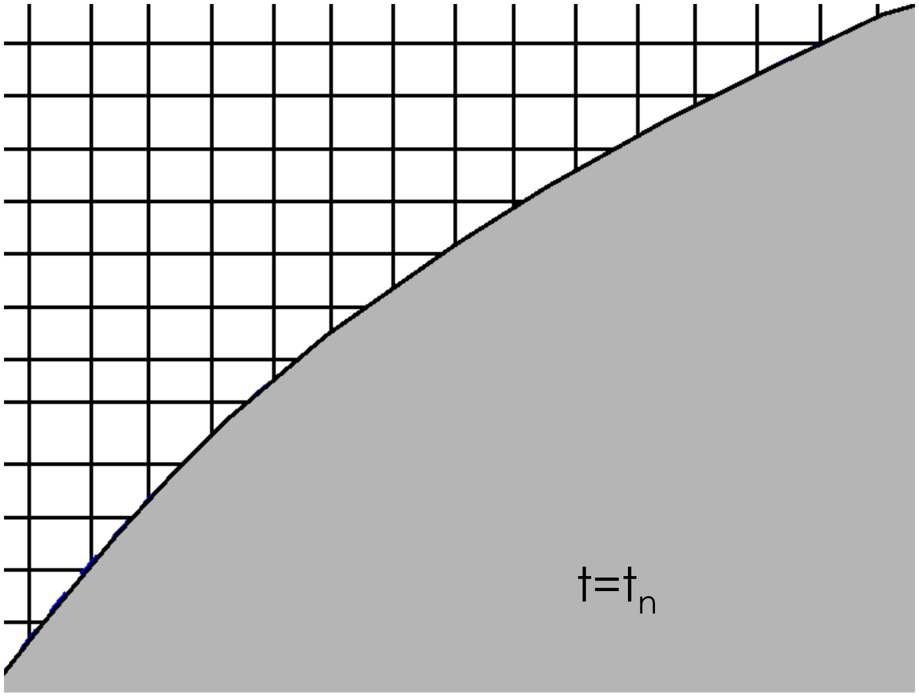


IBM Accuracy Challenge: Freshly Cleared Cells

- Invalid time history at Freshly Cleared Cells (FCC)
- Utilize neighboring information to update data in FCC (exclude other FCCs in point cloud), ie backfilling with least-squares + BC.
- More advanced approaches are being considered



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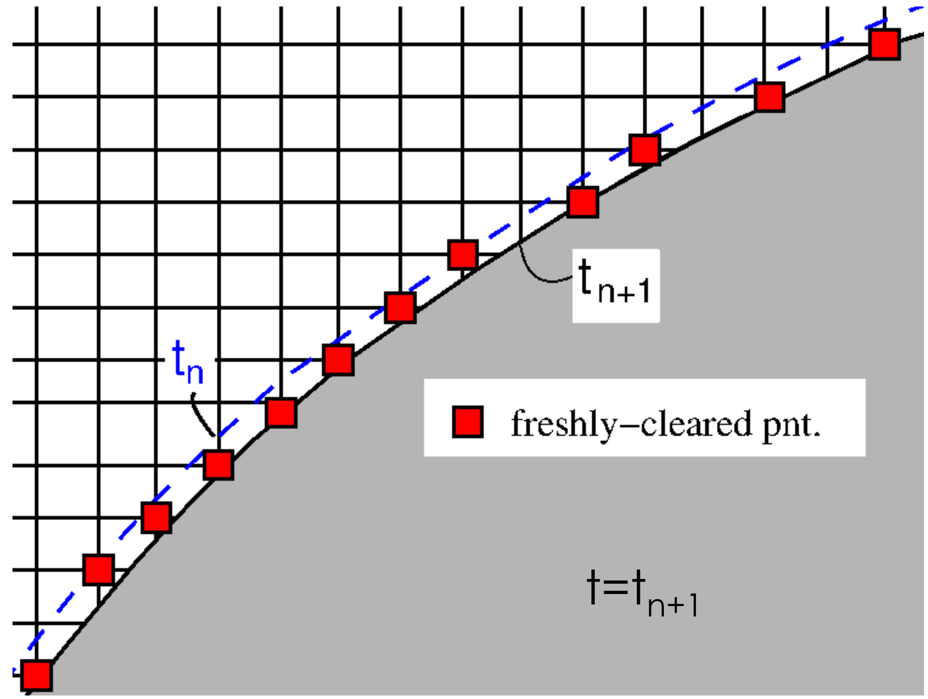
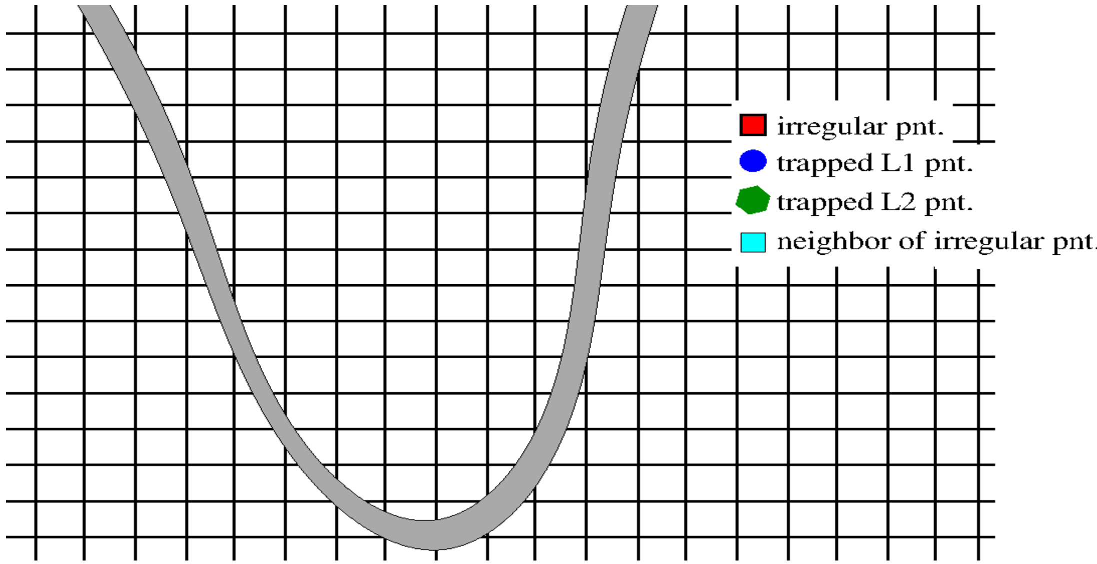


IBM Accuracy Challenge: Trapped Points

- 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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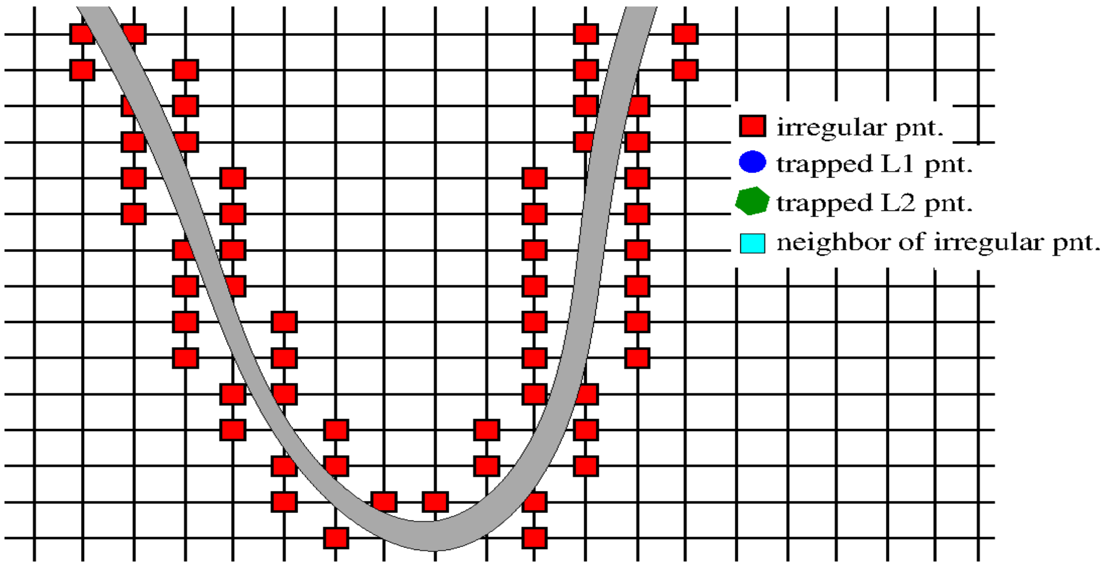

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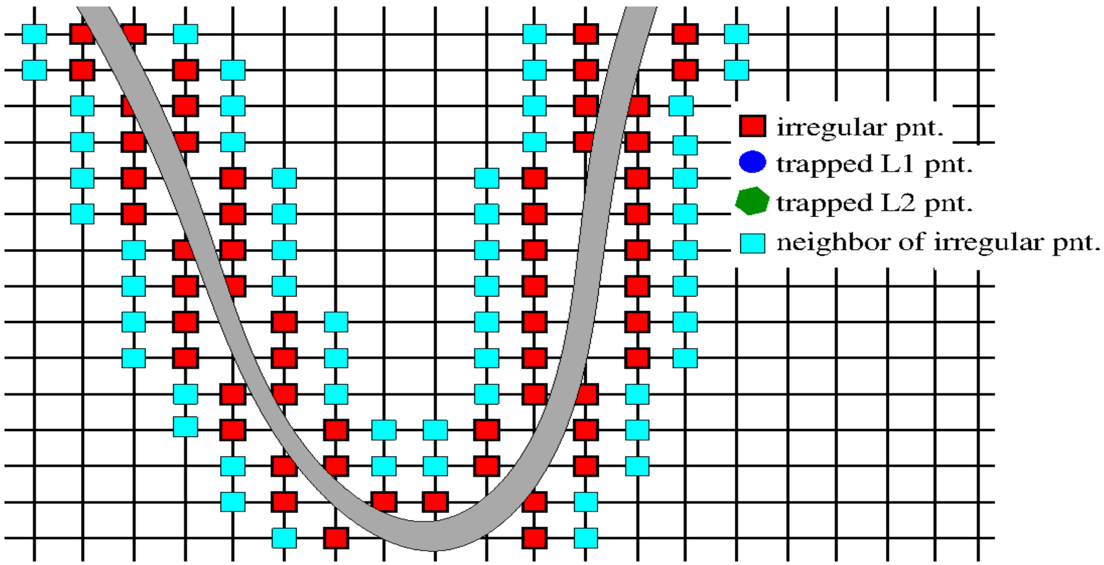

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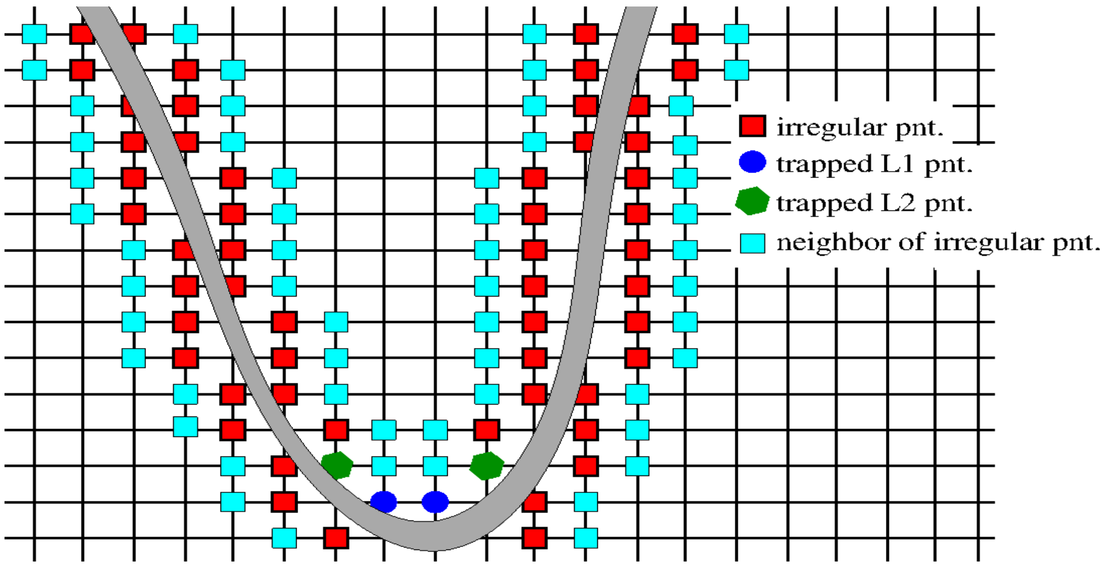
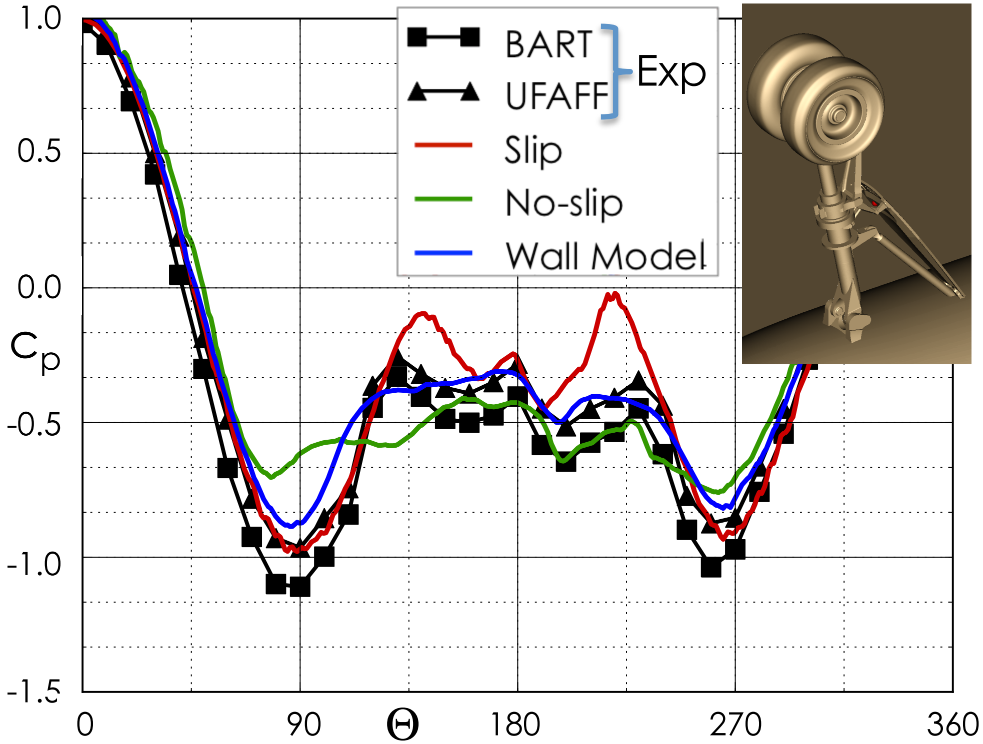
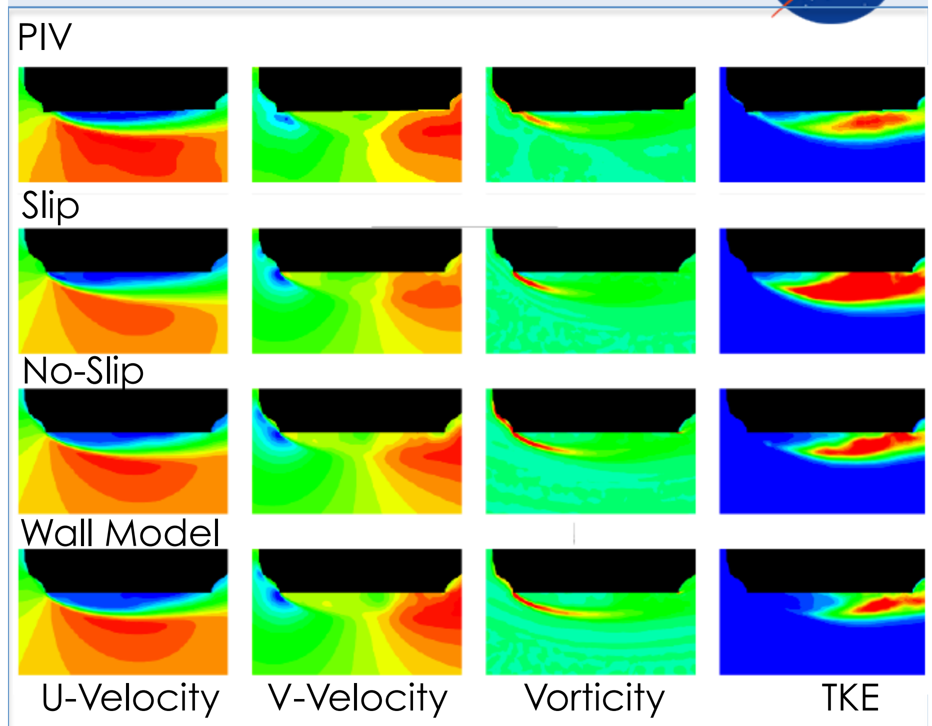
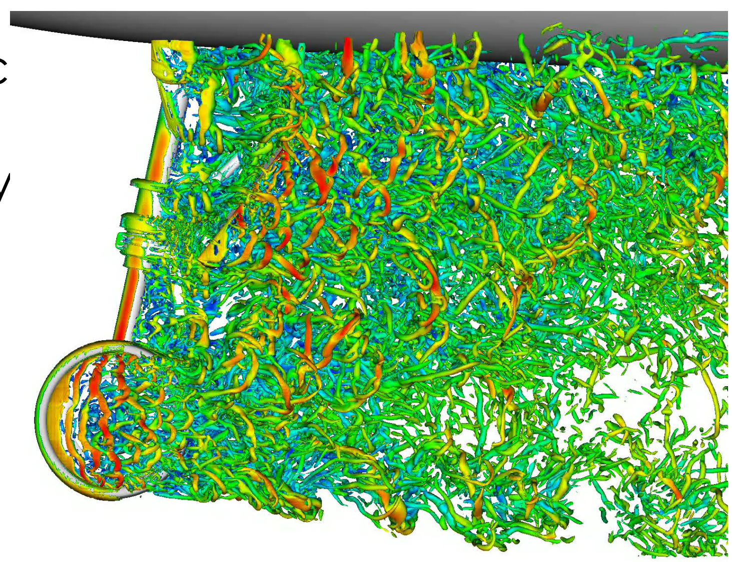


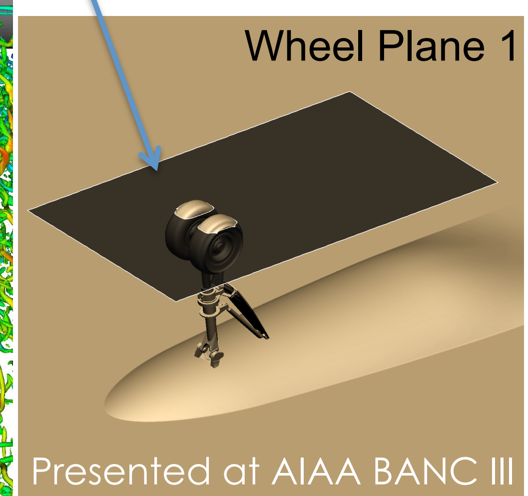
IBM Accuracy Challenge: Wall BCs at High Re





- ❑ 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





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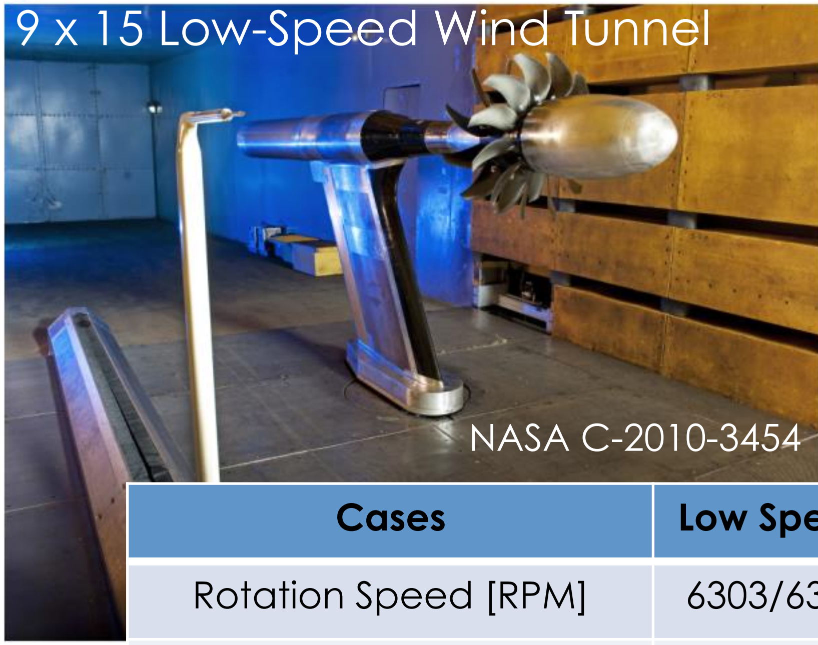
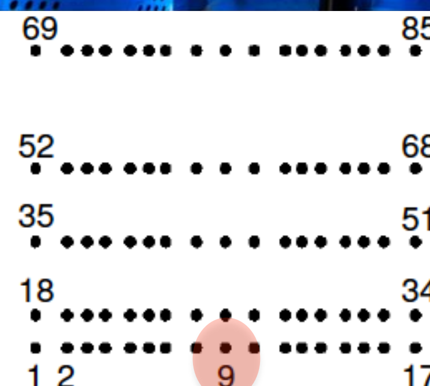
Flow Conditions



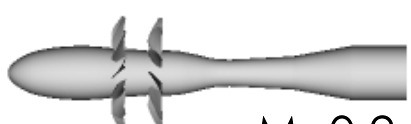
Cases	Low Speed	High Speed
Rotation Speed [RPM]	6303/6303	6848/6848
Blade Setting (fwd/aft) [°]	40.1/40.8	64.4/61.8
Mach	0.20	0.78

Pressure Sensors

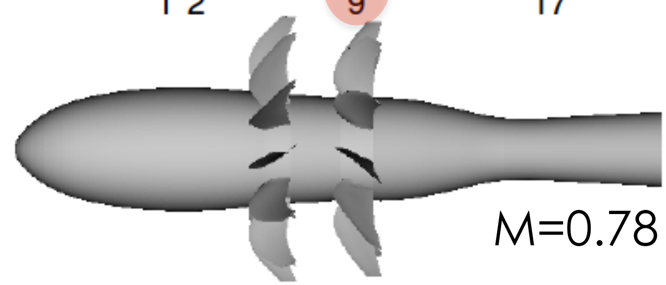


Note:

- 12 fwd blades
- 10 aft blades



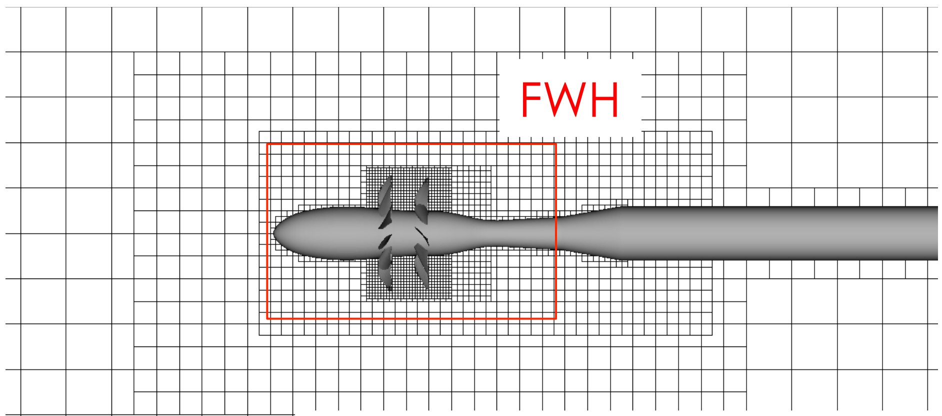
M=0.2



M=0.78

Computational Setup

Block Structured Cartesian Mesh



Each box contains 16^3 grid points

- Higher-order shock capturing scheme: modified ZWENO6
  (Brehm, Barad, Housman, and Kiris, CAF-2015)
- 4^{th}-order explicit RK time-integration with Δt defined through CFL≈1
- Implicit large eddy simulation based on previous experience with jet impingement problem

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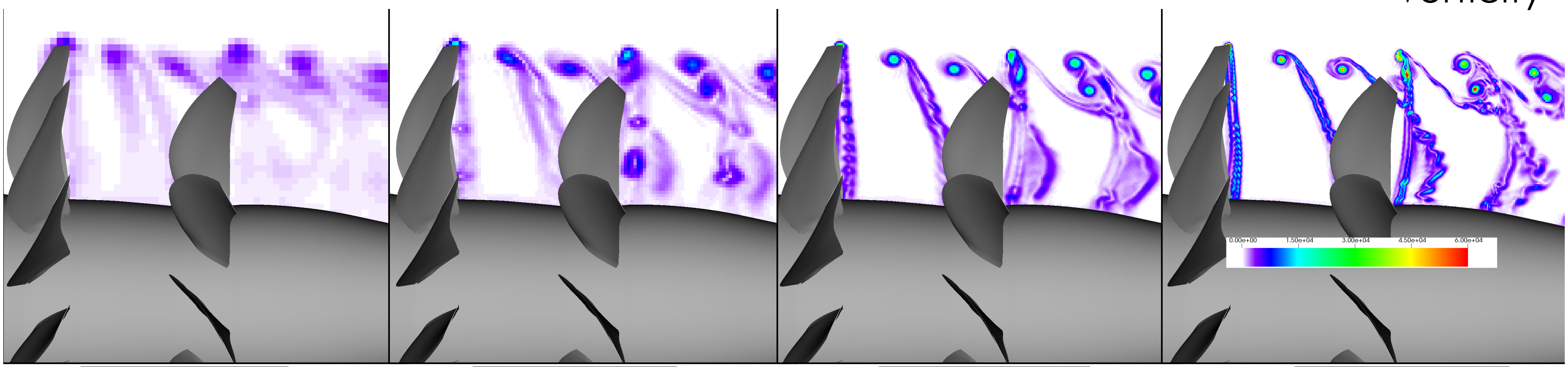
Grid Refinement Study for M=0.2:

Vorticity



8 Levels: Δx_{min}=8e-3 N_{tot}=65M	9 Levels: Δx_{min}=4e-3 N_{tot}=110M	10 Levels: Δx_{min}=2e-3 N_{tot}=160M	11 Levels: Δx_{min}=1e-3 N_{tot}=350M

Unsteady Flow Field – Passive Particle Viz

Low Speed

High Speed

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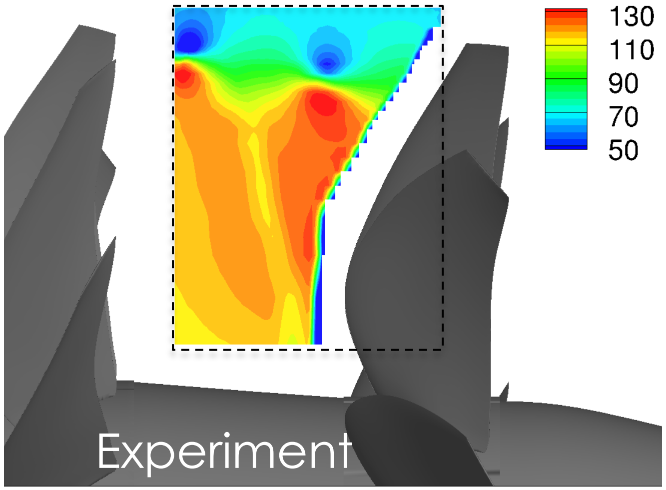
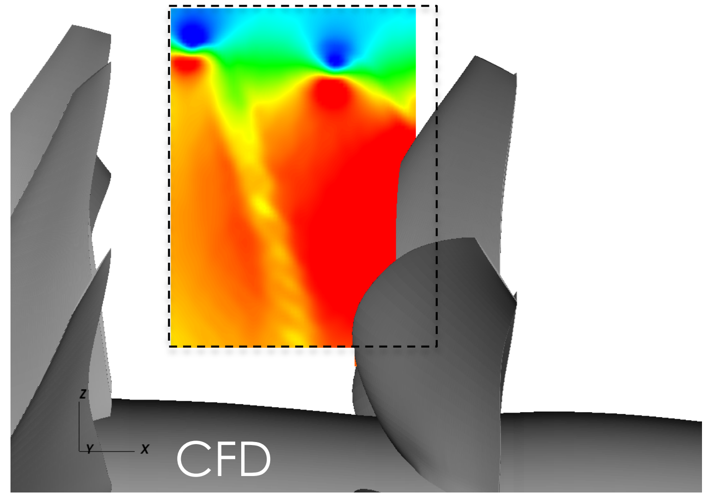
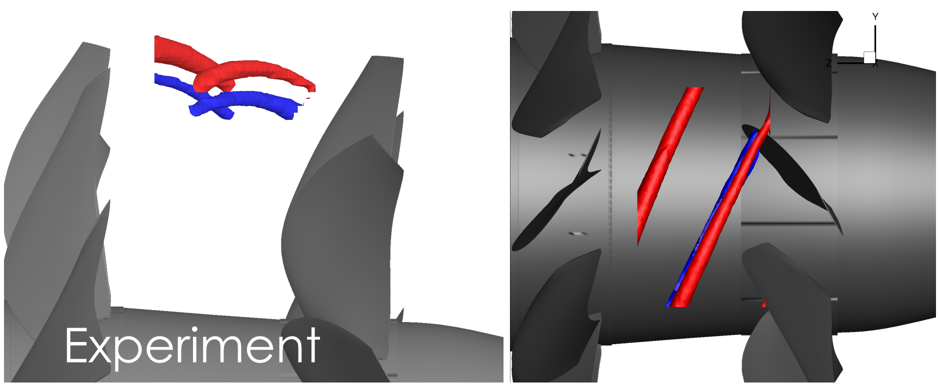
Comparison With Experiments (Low Speed)

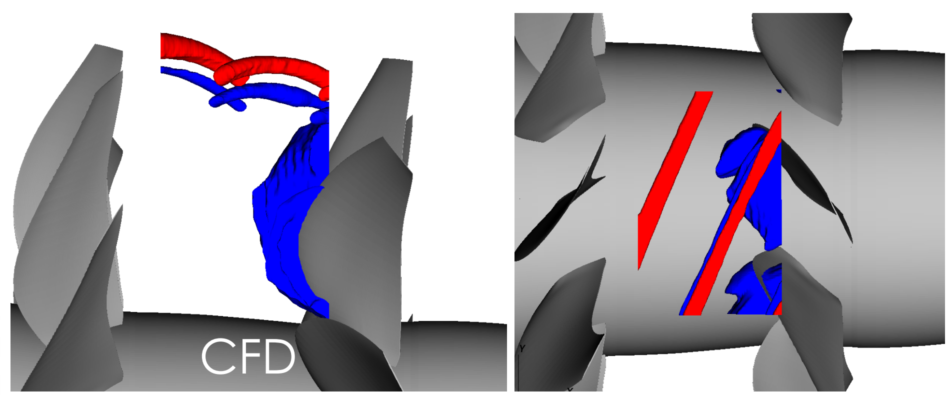
Velocity Magnitude Contours





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



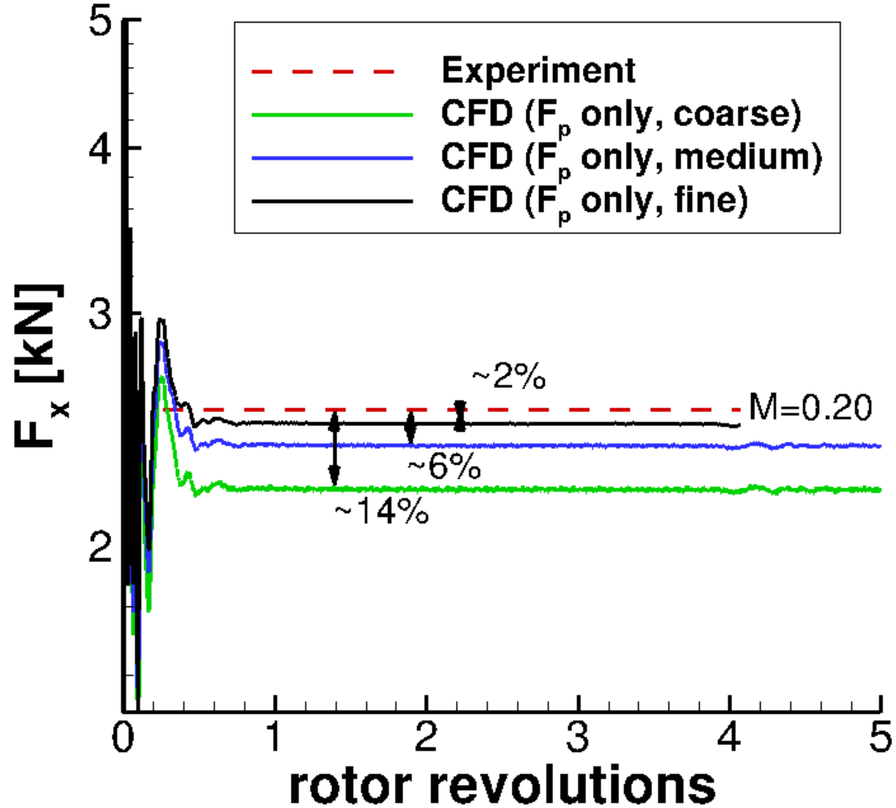


- Good agreement of velocity magnitude contours with experiment
- Evolution of tip vortices seems to be well captured

Thrust Comparison

Low Speed

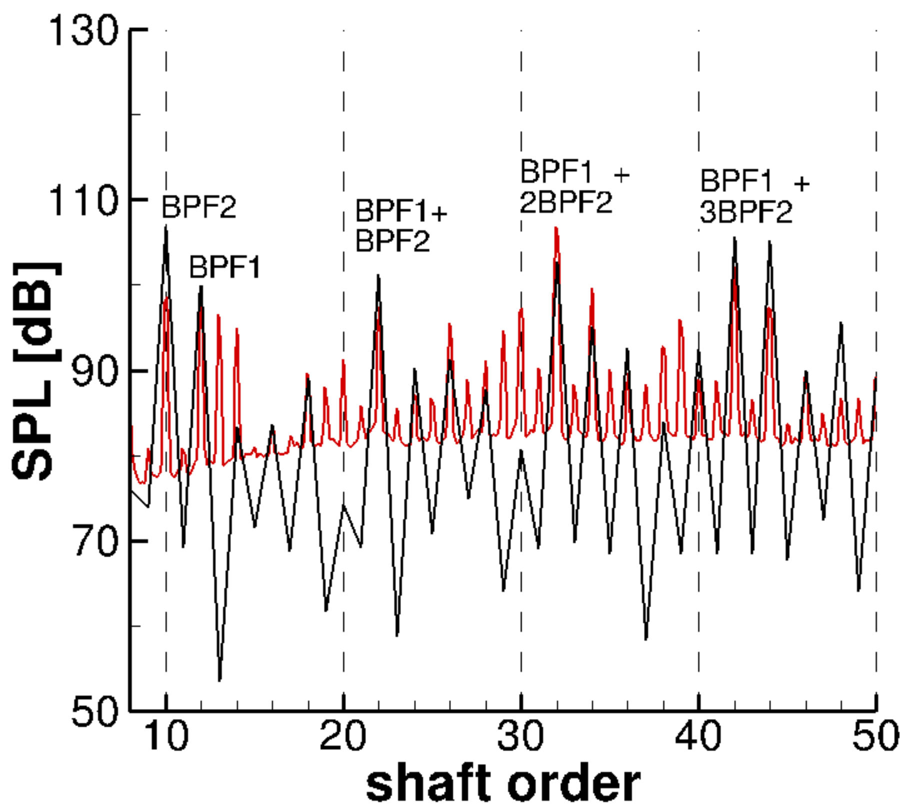
FIX



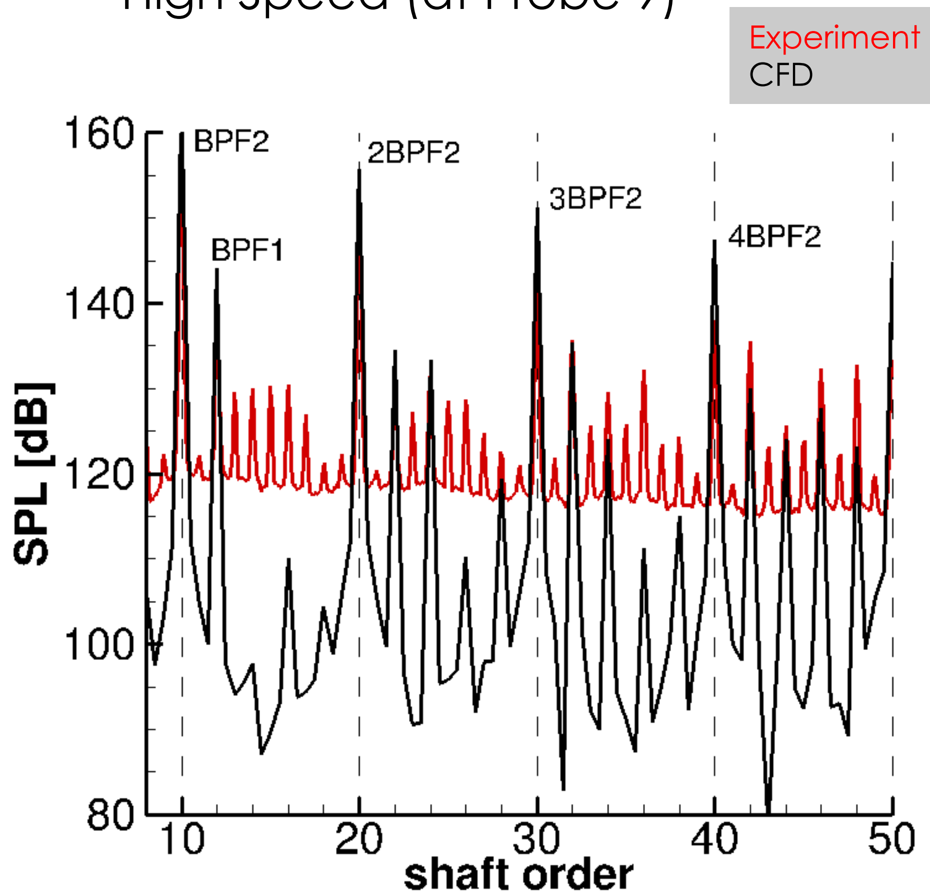
- ❑ Note that only pressure drag was considered (ratio 4:100 for M=0.78)
- ❑ Agreement with experiment is in the range of other computations (LAVA-Curvilinear, OVERFLOW, and *FINE*^{TM}*/Turbo*)

Far-Field Spectra

Low Speed (at Probe 9)

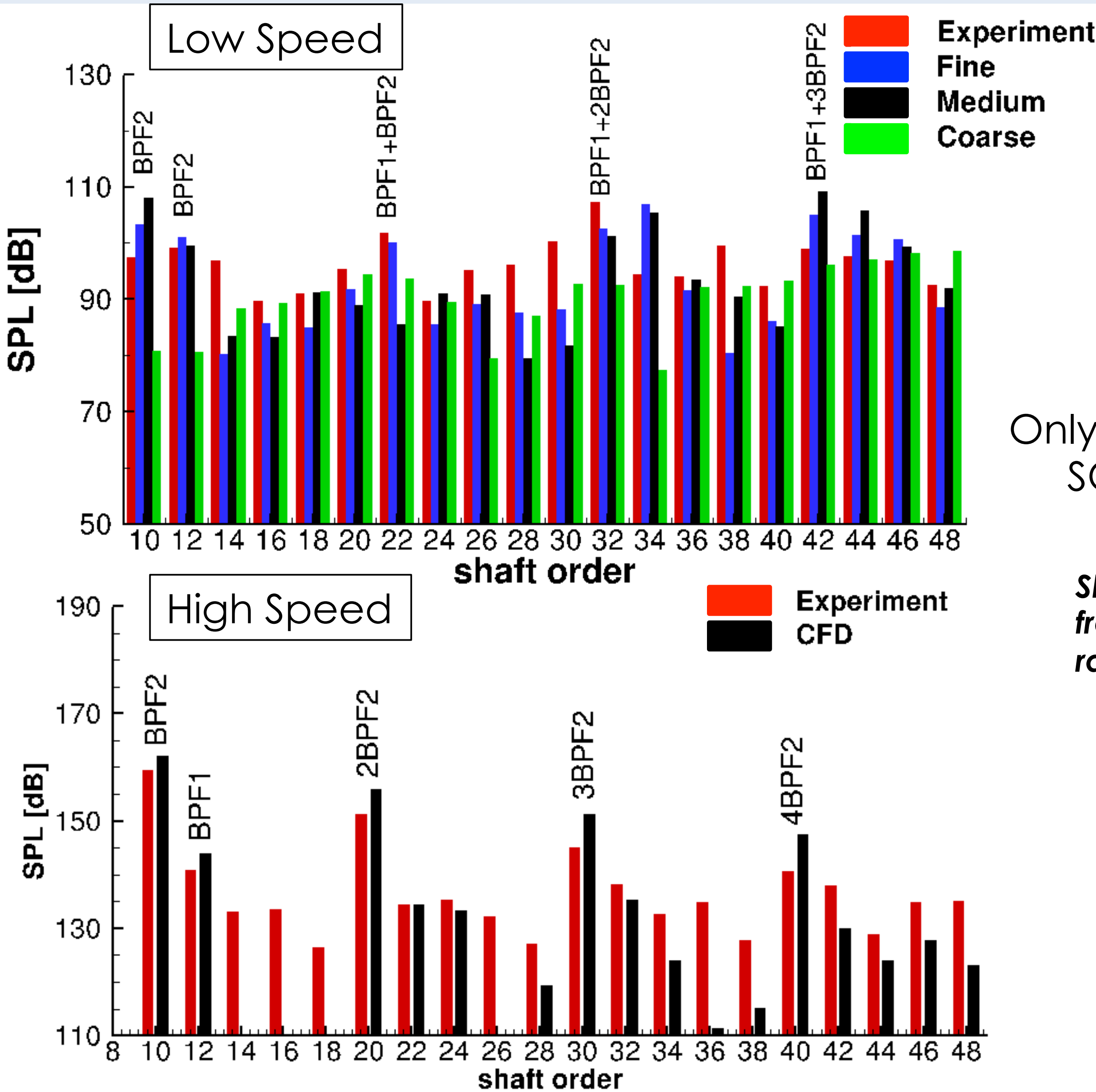


High Speed (at Probe 9)



- Shaft order (SO) = frequency/shaft rotation rate
- BPF = blade passing frequency
  - BPF1 corresponds to forward 12 blades -> SO=12,
  - BPF2 corresponds to aft 10 blades -> SO=10
- Experiment has inflowing broadband content that is not modeled -> focus on BPF tones

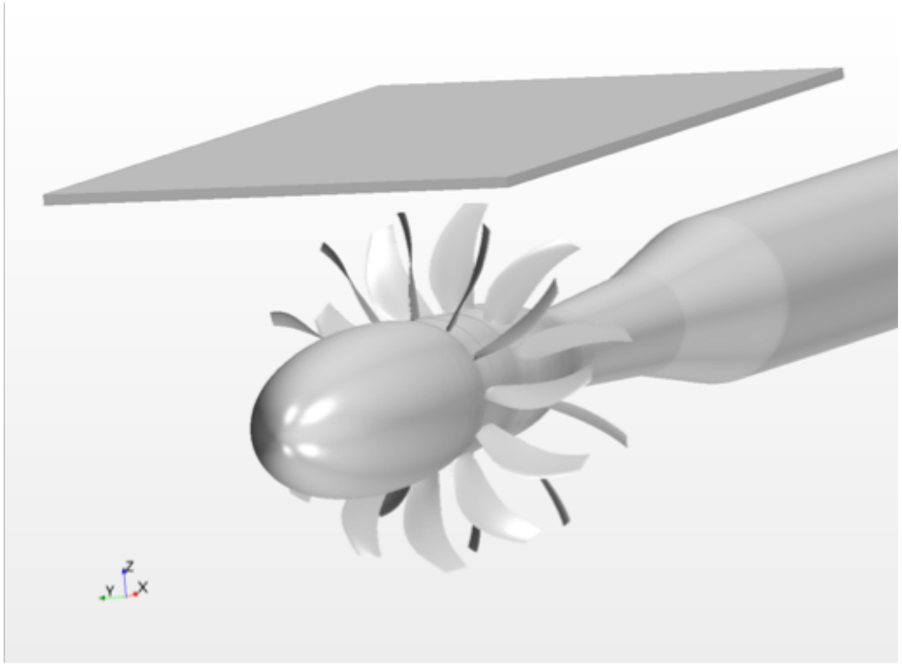
Far-Field Spectra



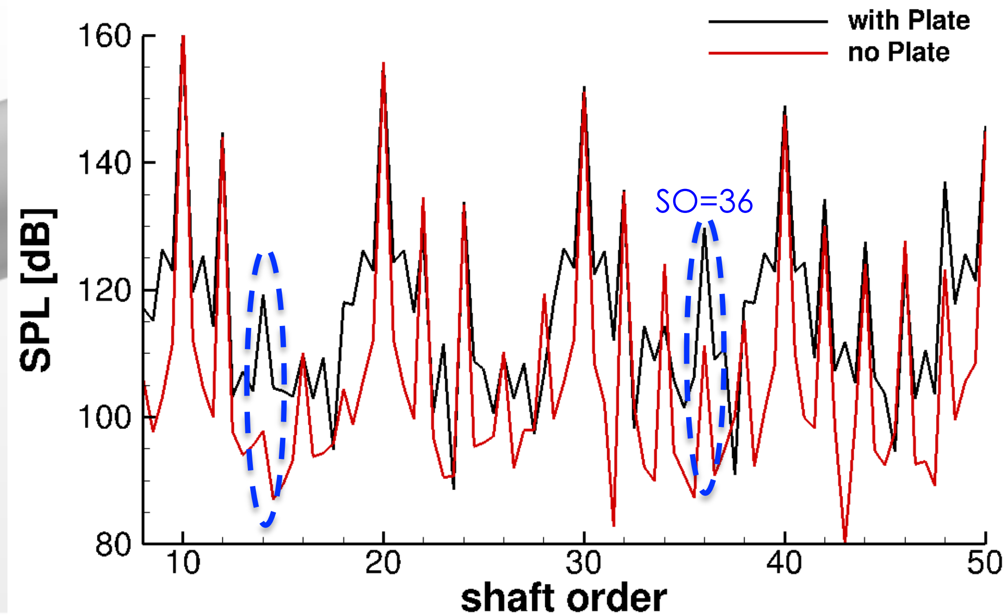
Only consider tones with SO(m,n)=12m+10n

Shaft order (SO) = frequency/shaft rotation rate

Plate Effect in High Speed Case



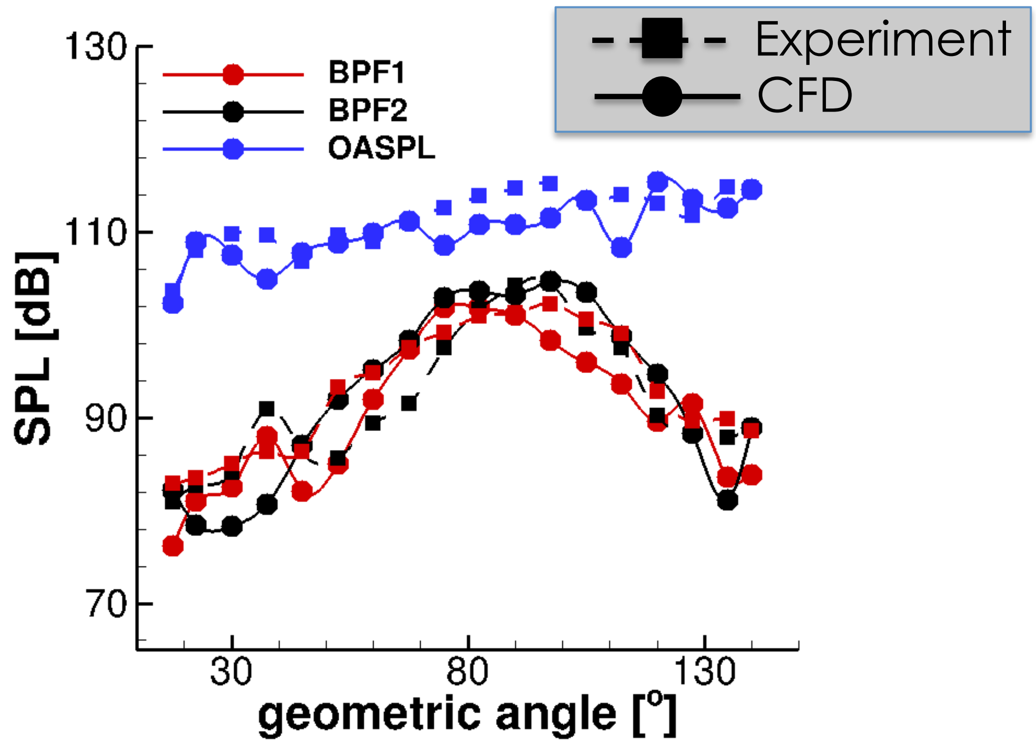
Probe #9



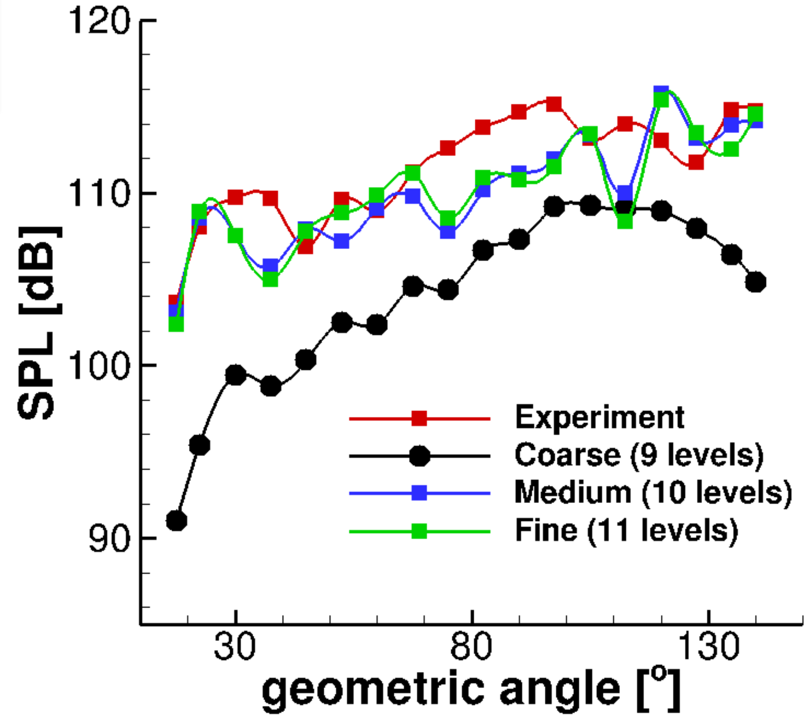
- Plate effect was accounted for in no-plate results by assuming perfect reflection ($6dB=10\log_{10}(2^2)$)
- Simulation with plate at first row of acoustic sensors
- Numerical simulation results with plate show odd tones
- Plate affects broadband noise level
- Plate does not affect the most dominant tones

Spatial Dependence Of Tones (Low Speed)

Fundamental Tones

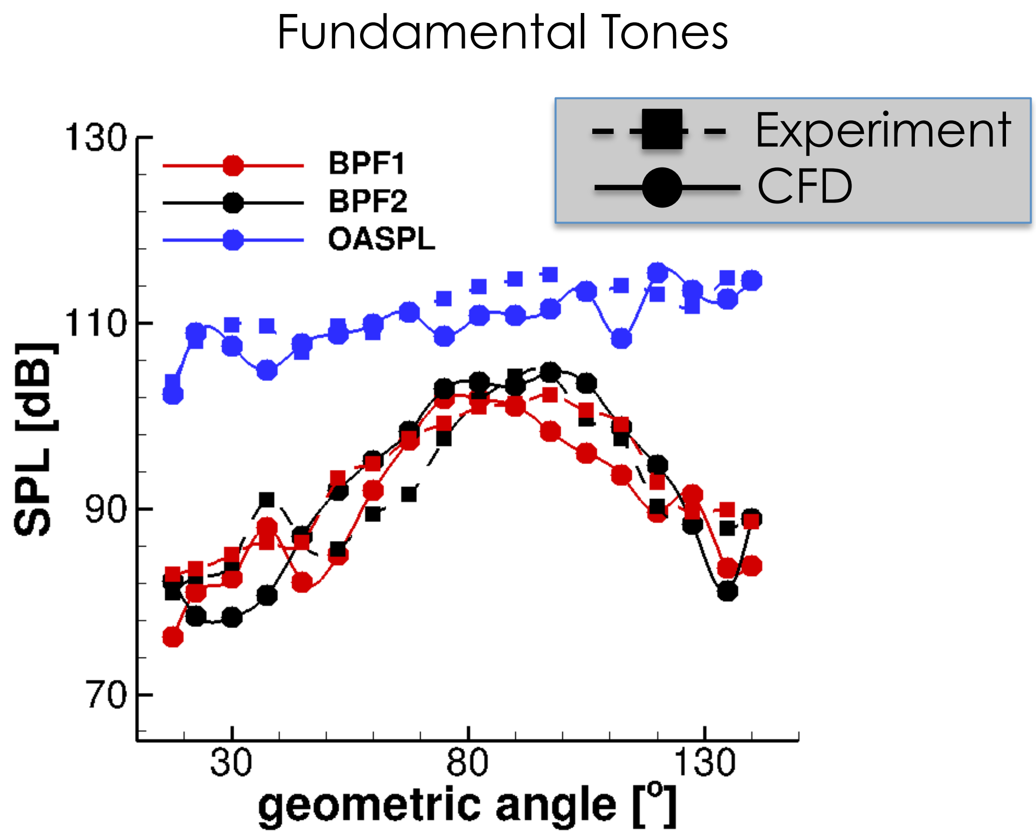


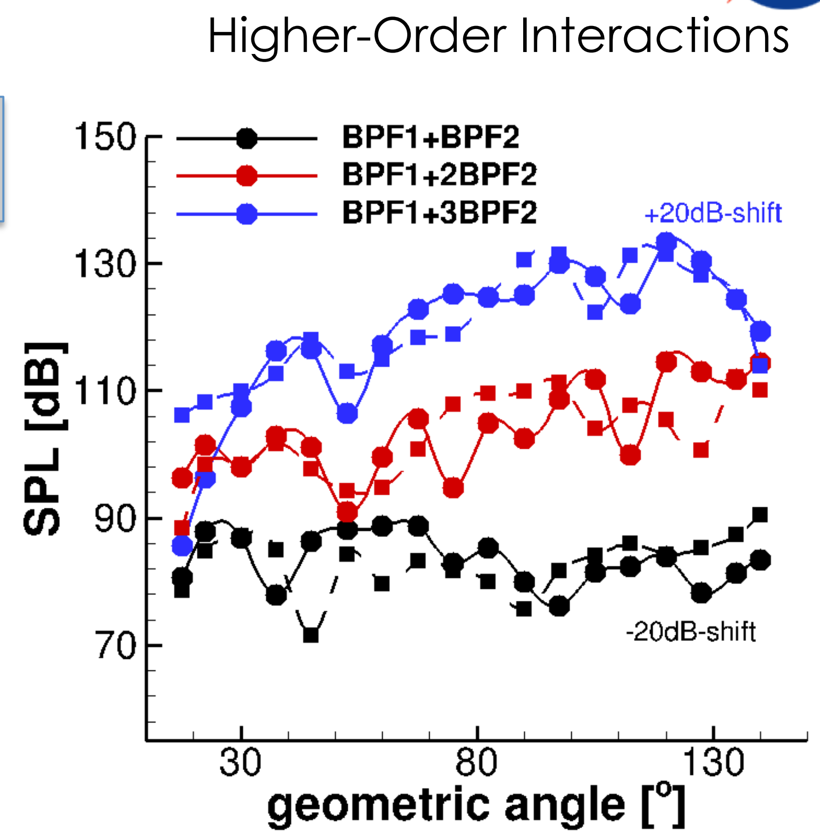
Grid Resolution Study



- Fundamental tones decay rapidly away from the blades
- OASPL is increasing with increasing geometric angle (i.e. downstream)
- Small difference in OASPL for fine and medium mesh

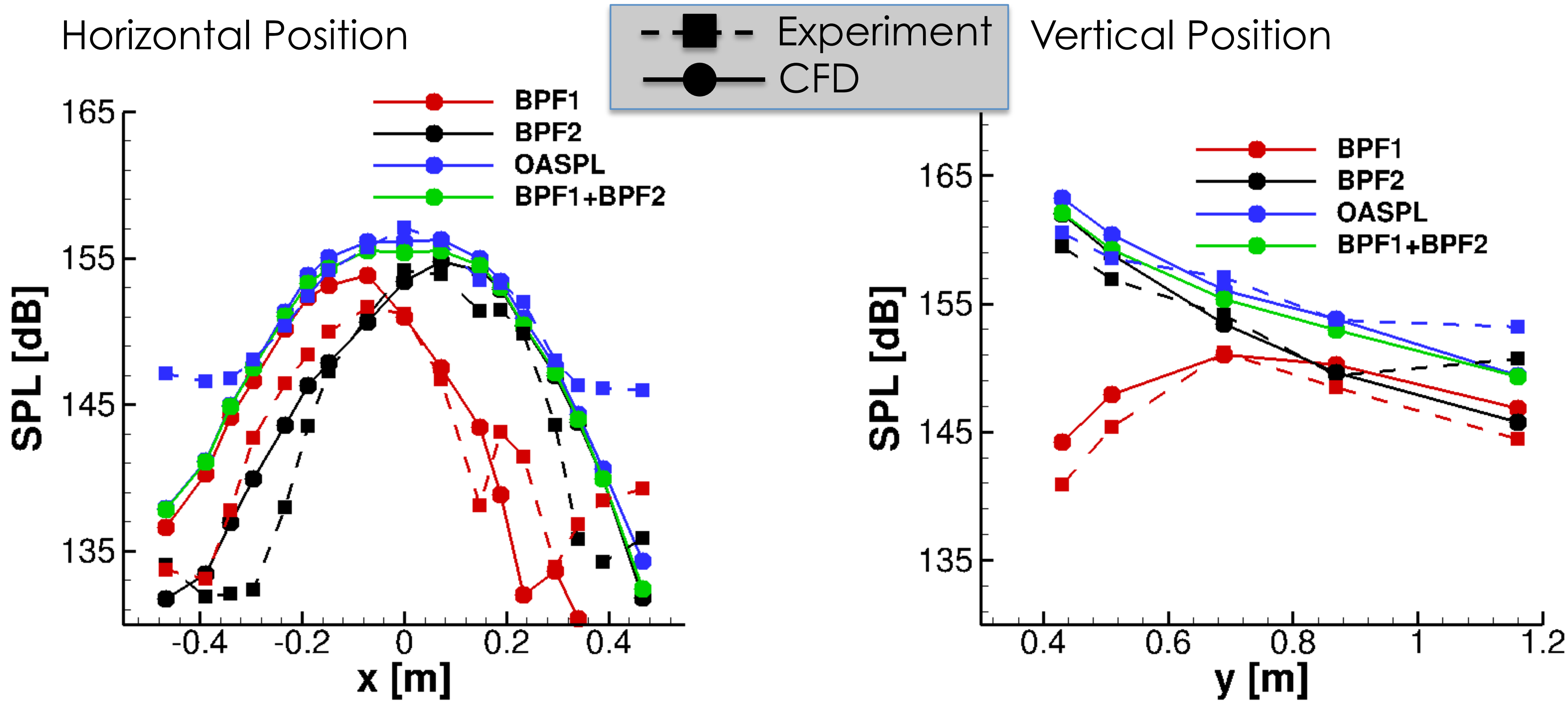
Spatial Dependence Of Tones (Low Speed)





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

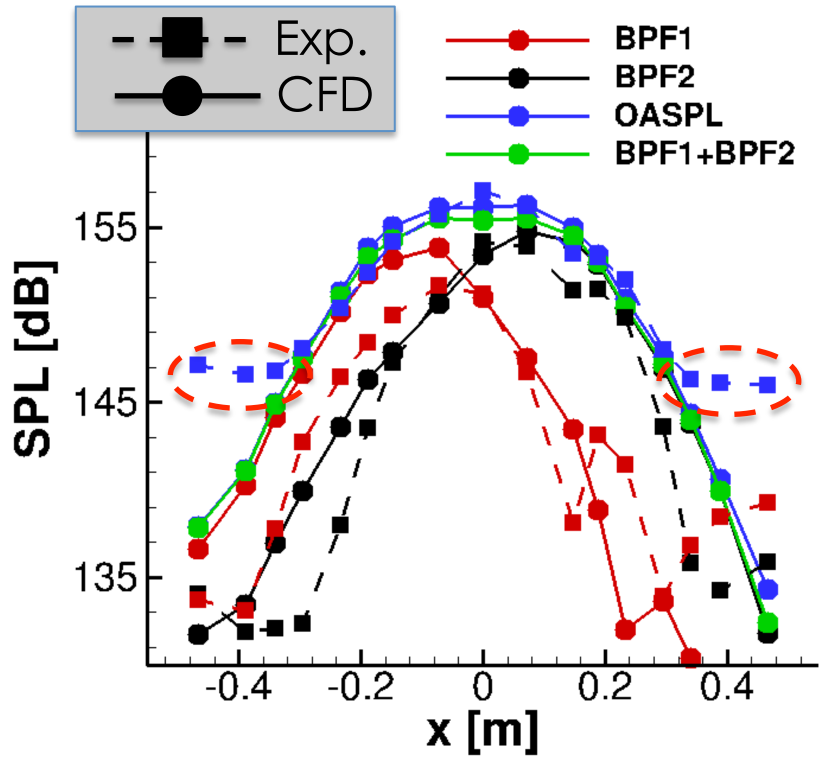
Spatial Dependence Of Tones (high Speed)



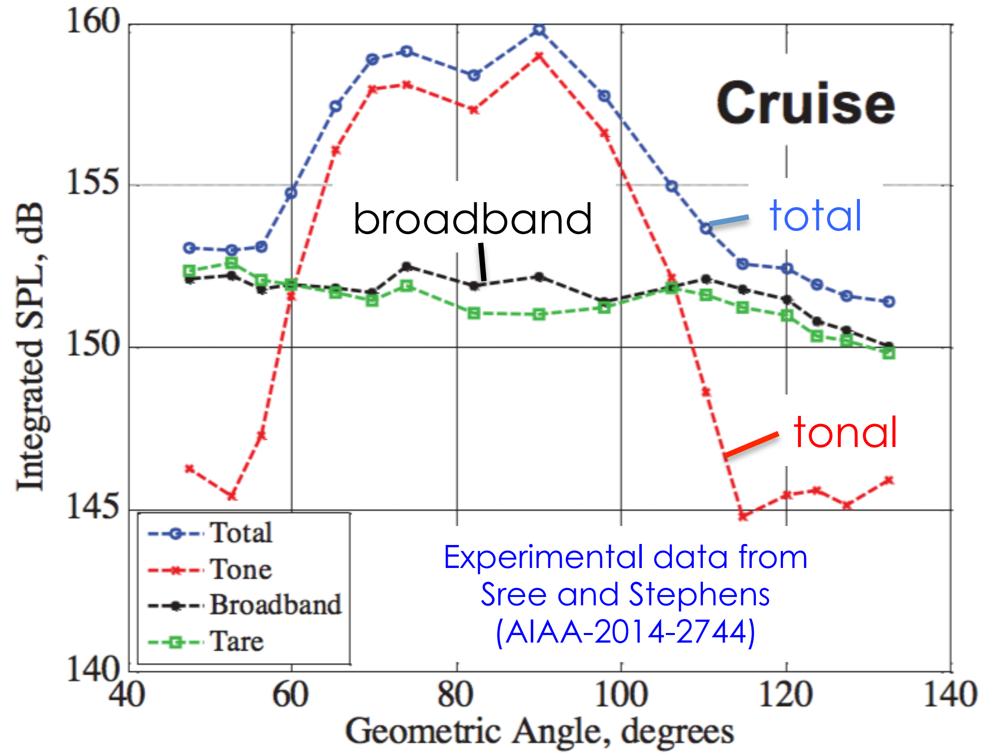
- ❑ Fundamental tones dominate OASPL
- ❑ Added tonal SPL with BPF1+BPF2 only for comparison
- ❑ General trends are well captured for low and high speed cases
- ❑ Broadband noise important at small x (<-0.4) and large x (>0.4)

Spatial Dependence Of Tones (high Speed)

Horizontal Position



Broadband + Tonal Noise



- ❑ 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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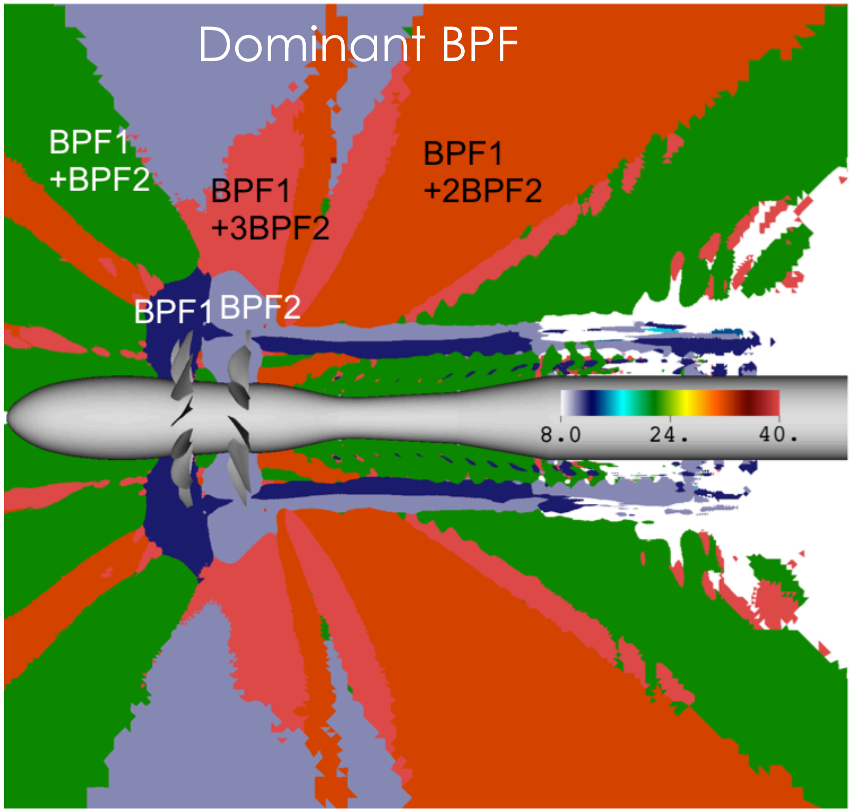
7. Summary

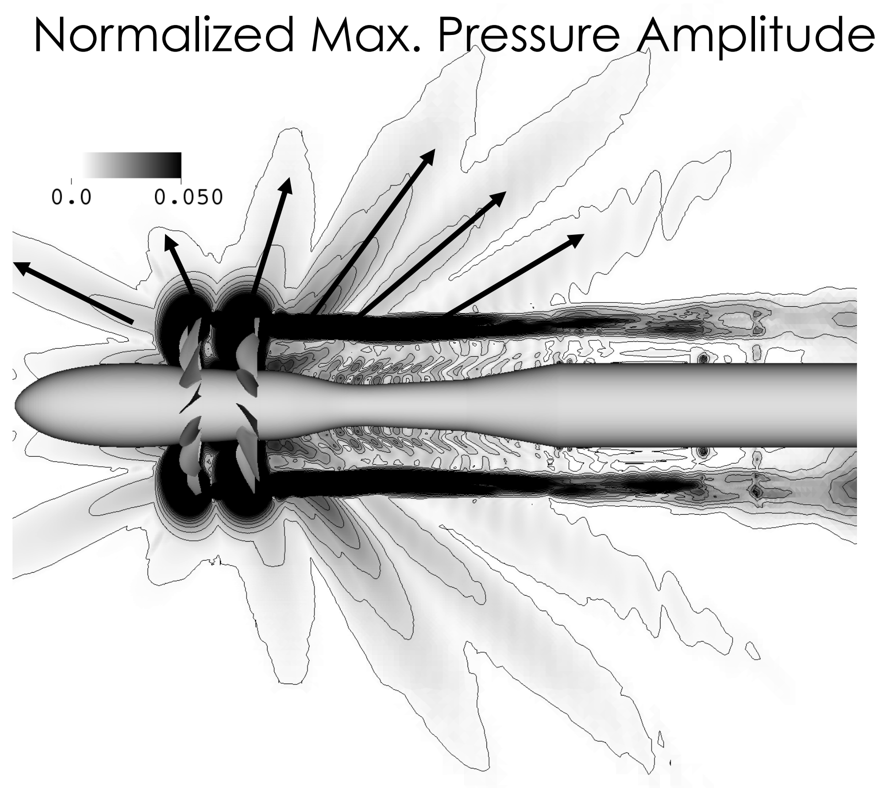
Unsteady Flow Field – Numerical Schlieren

Low Speed

High Speed

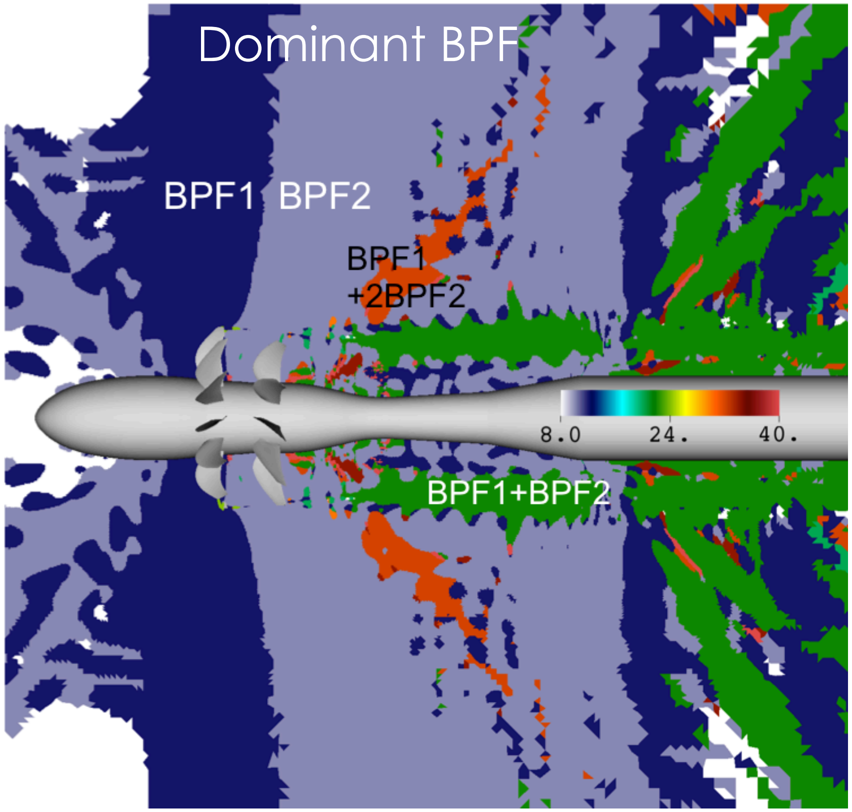
Near Field Acoustic Analysis (Low Speed)

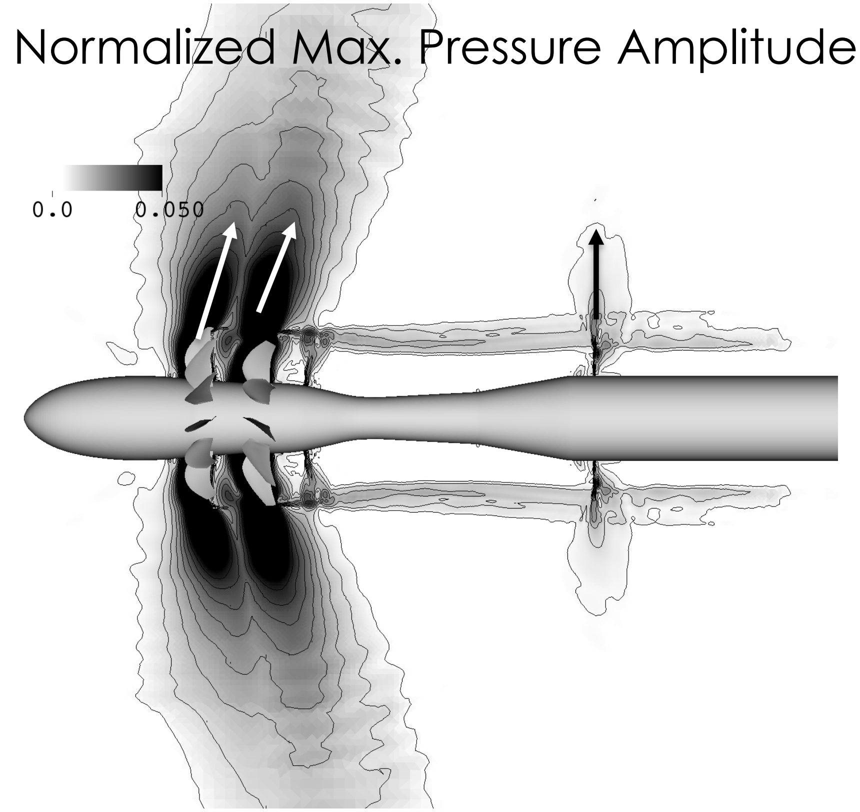




- Analysis captures acoustic waves but also hydrodynamic instability waves
- BPF1 and BPF2 are dominant in a very small region around the rotors and along the tip vortices
- Various higher-order interactions play an important role

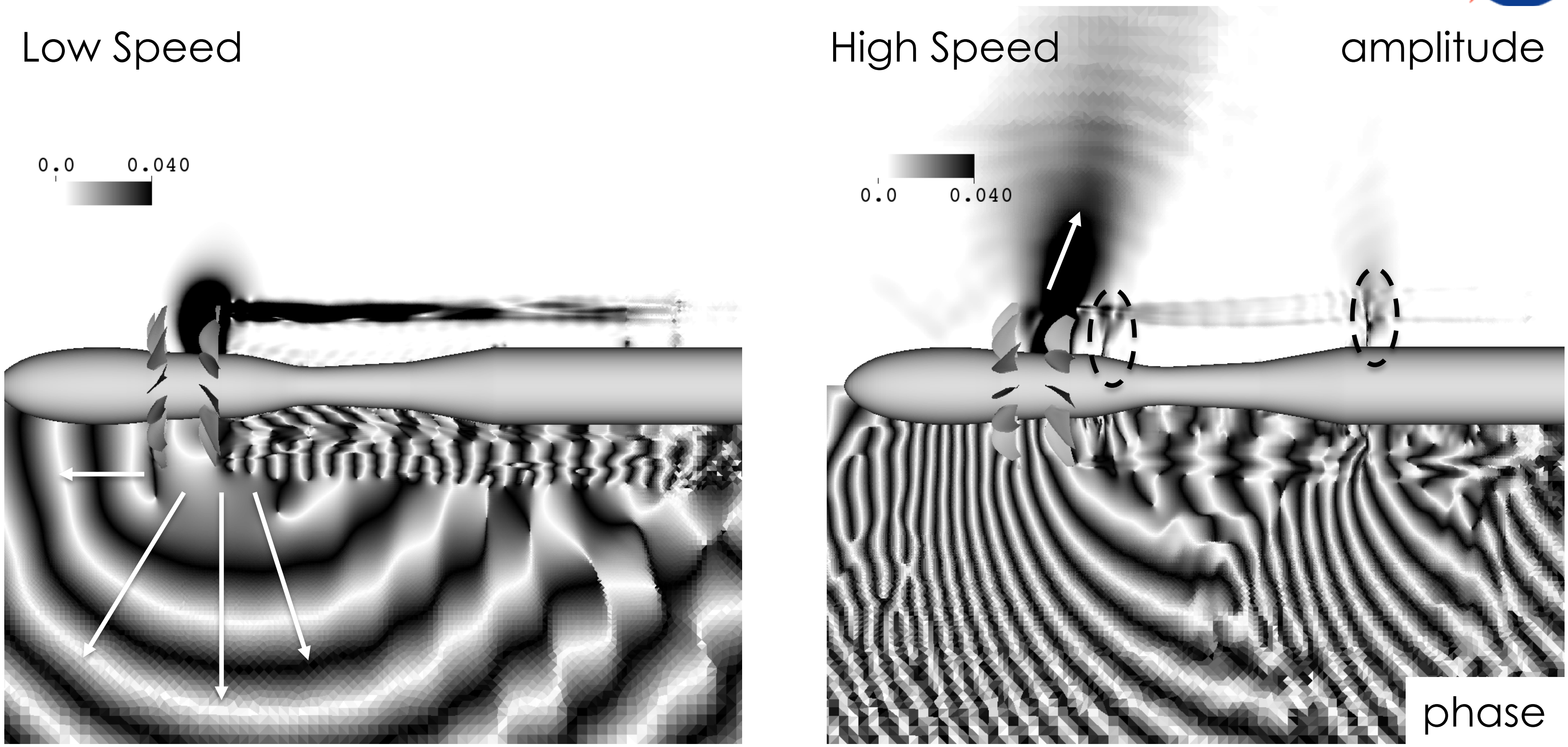
Near Field Acoustic Analysis (High Speed)





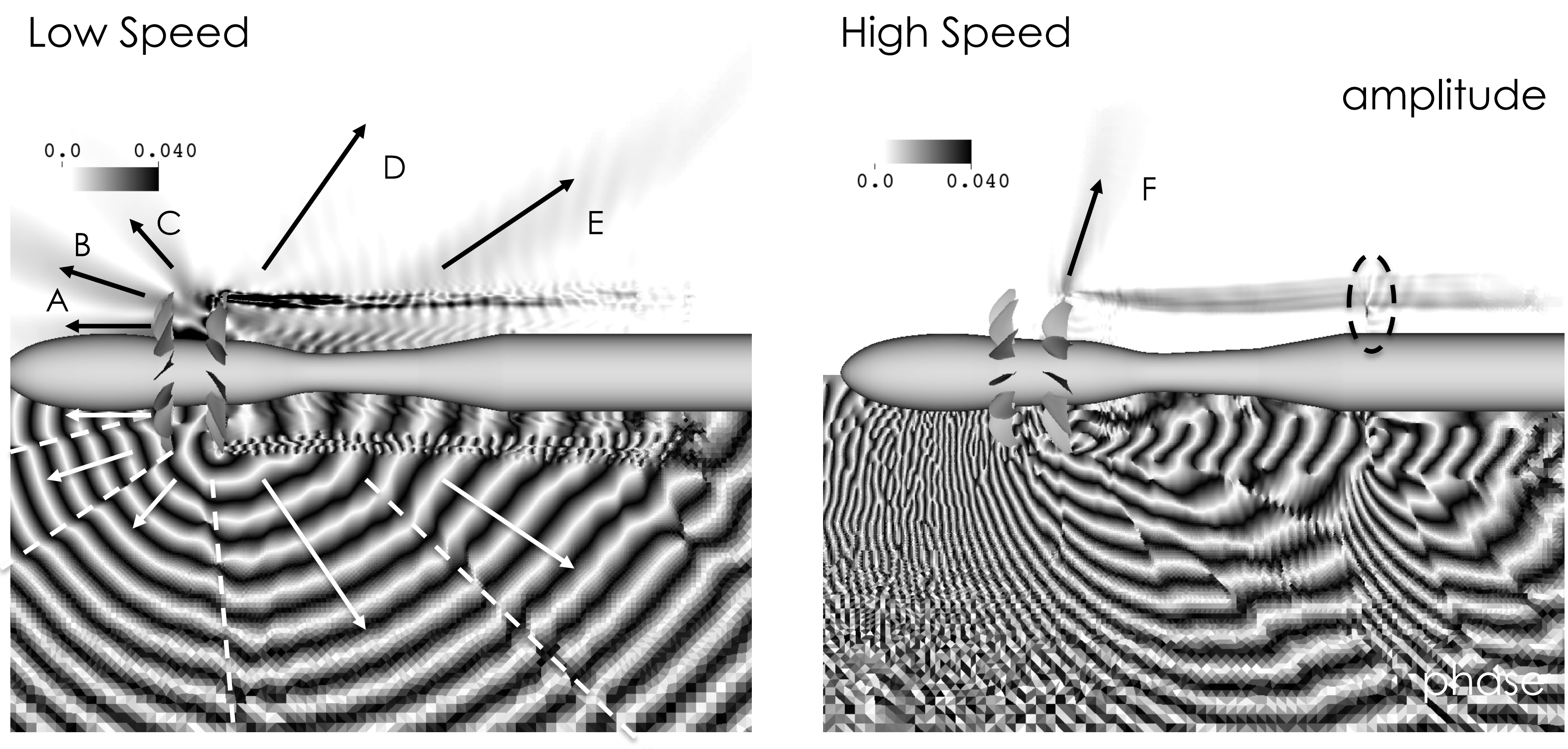
- ❑ BPF1 and BPF2 are the dominant frequencies
- ❑ BPF1+BPF2 is dominant along the tip vortices and induces unsteady shock motion that generates acoustic waves in the back

Near Field Acoustic Analysis (BPF2)



- BPF2 amplitude is dominant in small region around rotor for M=0.2 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

Near Field Acoustic Analysis (BPF1+BPF2)



- ❑ 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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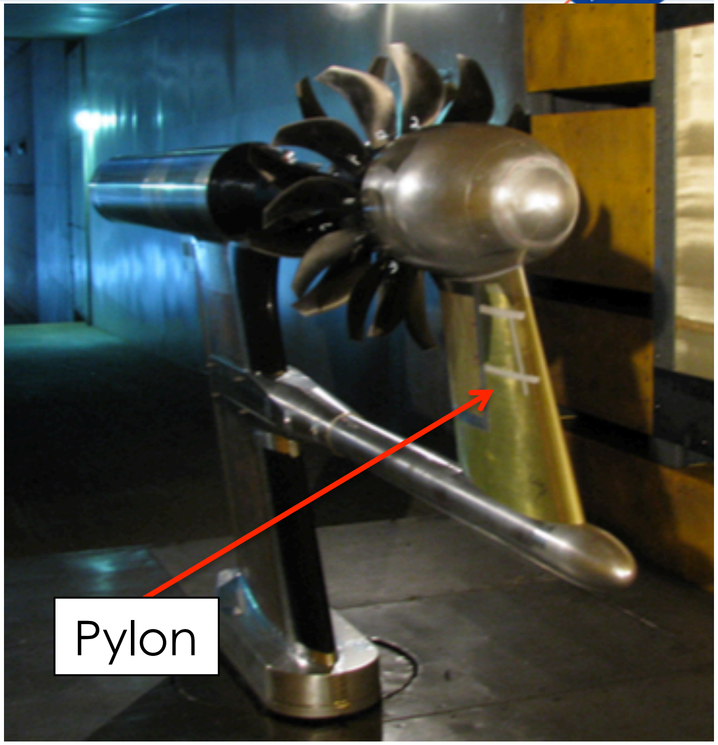
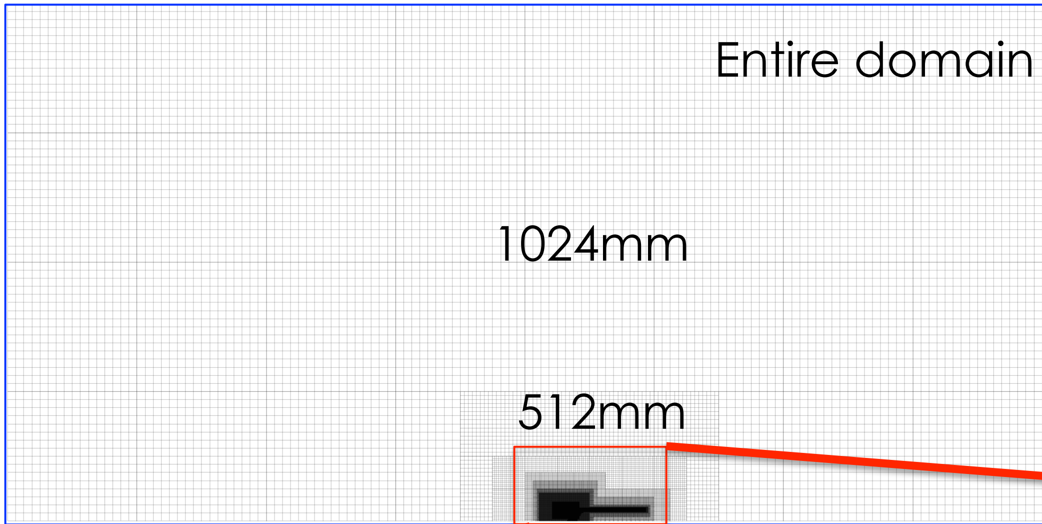
Conditions:

Case	Low Speed
Rotation Speed [RPM]	6303/6303
Blade Setting (fwd/aft) [°]	40.1/40.8
Mach	0.20

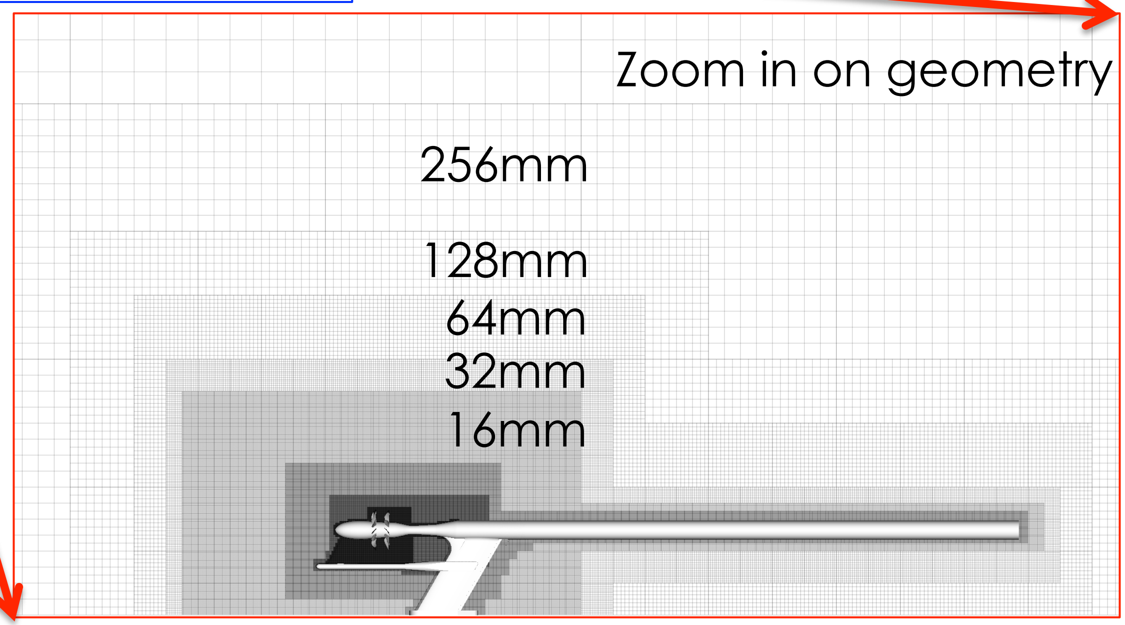


- Sound field measured at 1.524 [m] or 60 inches (same as previous no pylon low speed case)
- Wall model used to generate a pylon wake. Previously, we used slip wall BC (for no-pylon cases).

Pylon Installed Case: Mesh

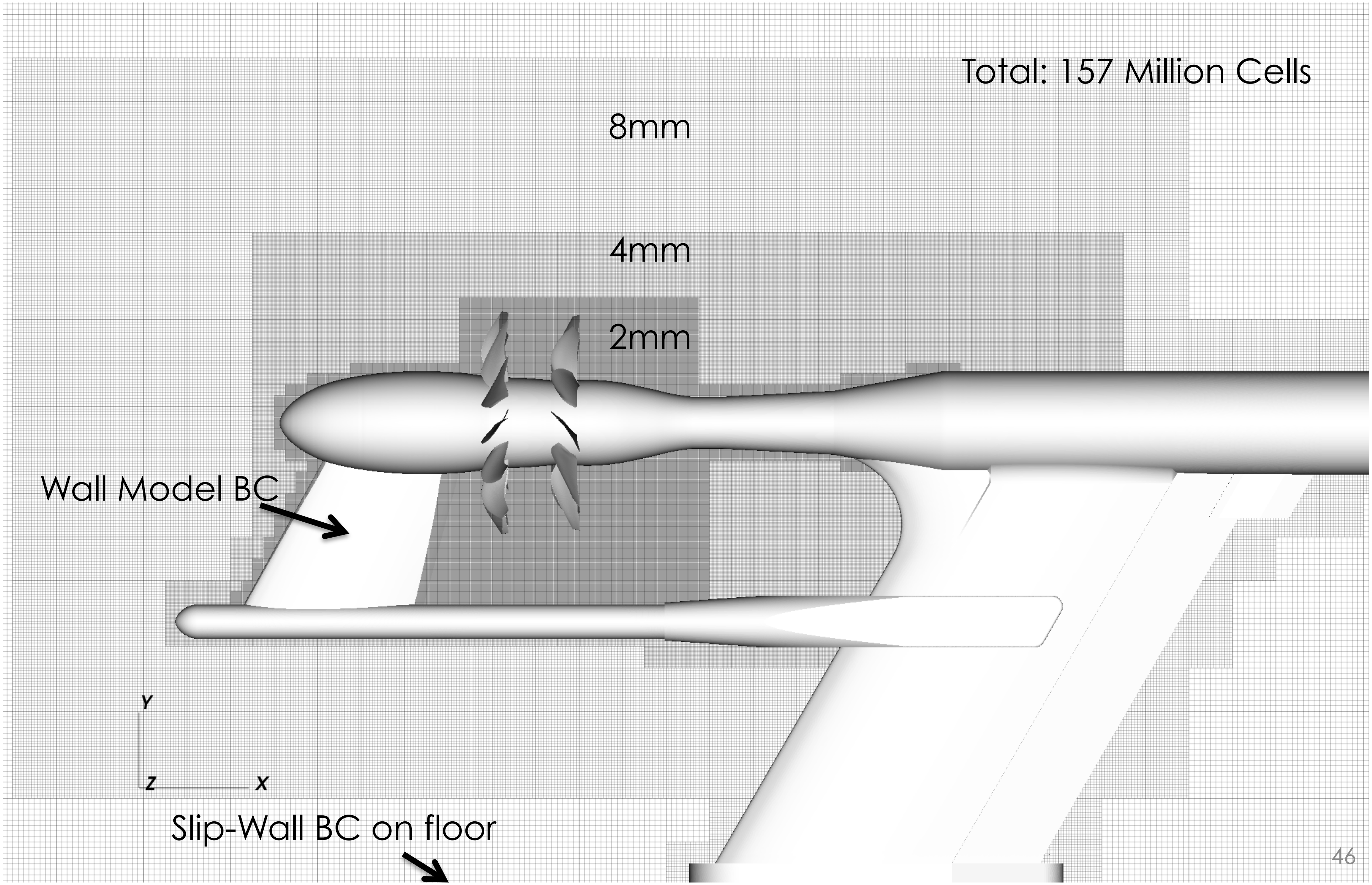


Total: 157 Million Cells

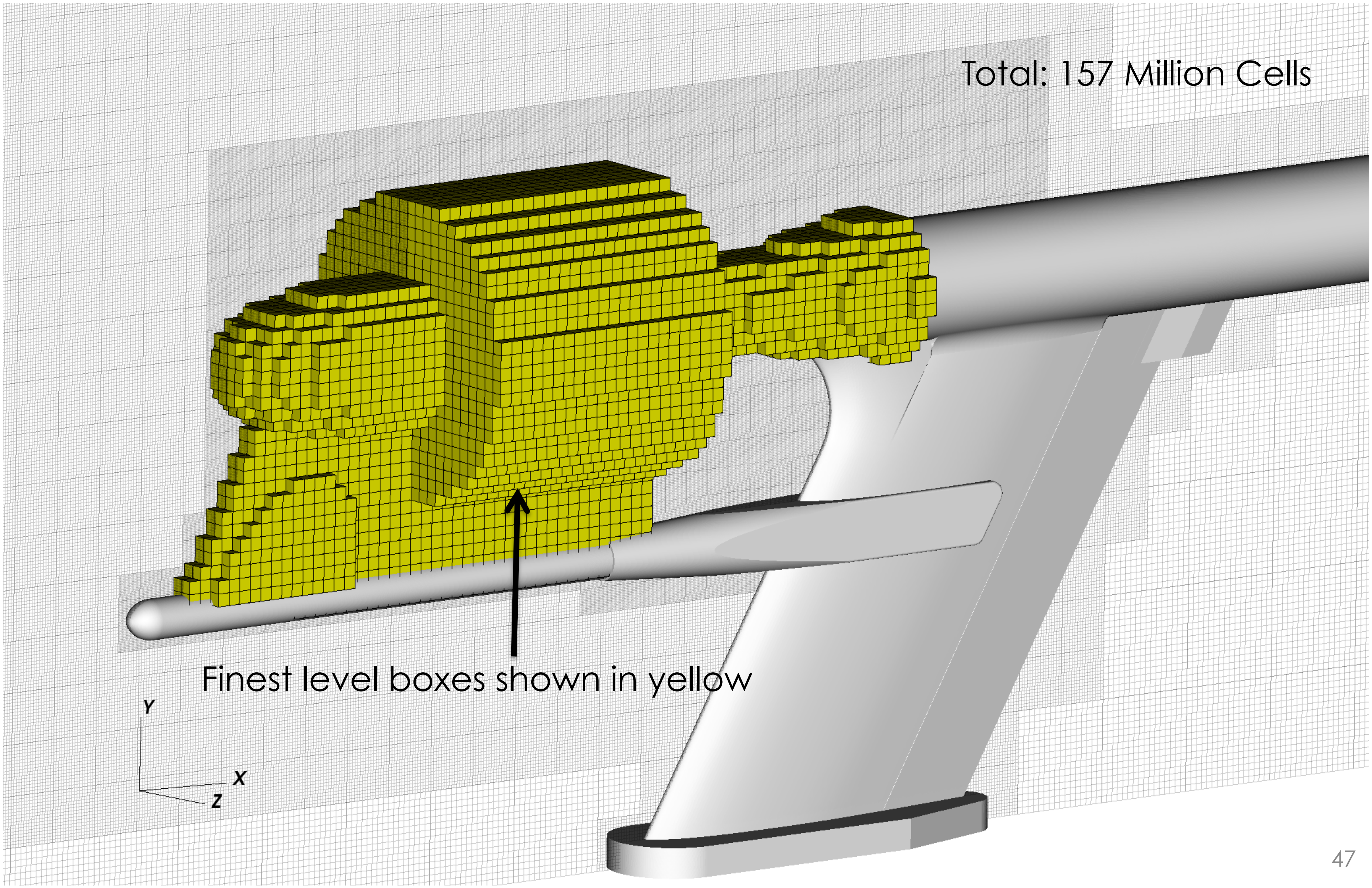


Entire domain size:
- Length = 131.072 m
- Height = 65.536 m
- Width = 131.072 m

Pylon Installed Case: Mesh

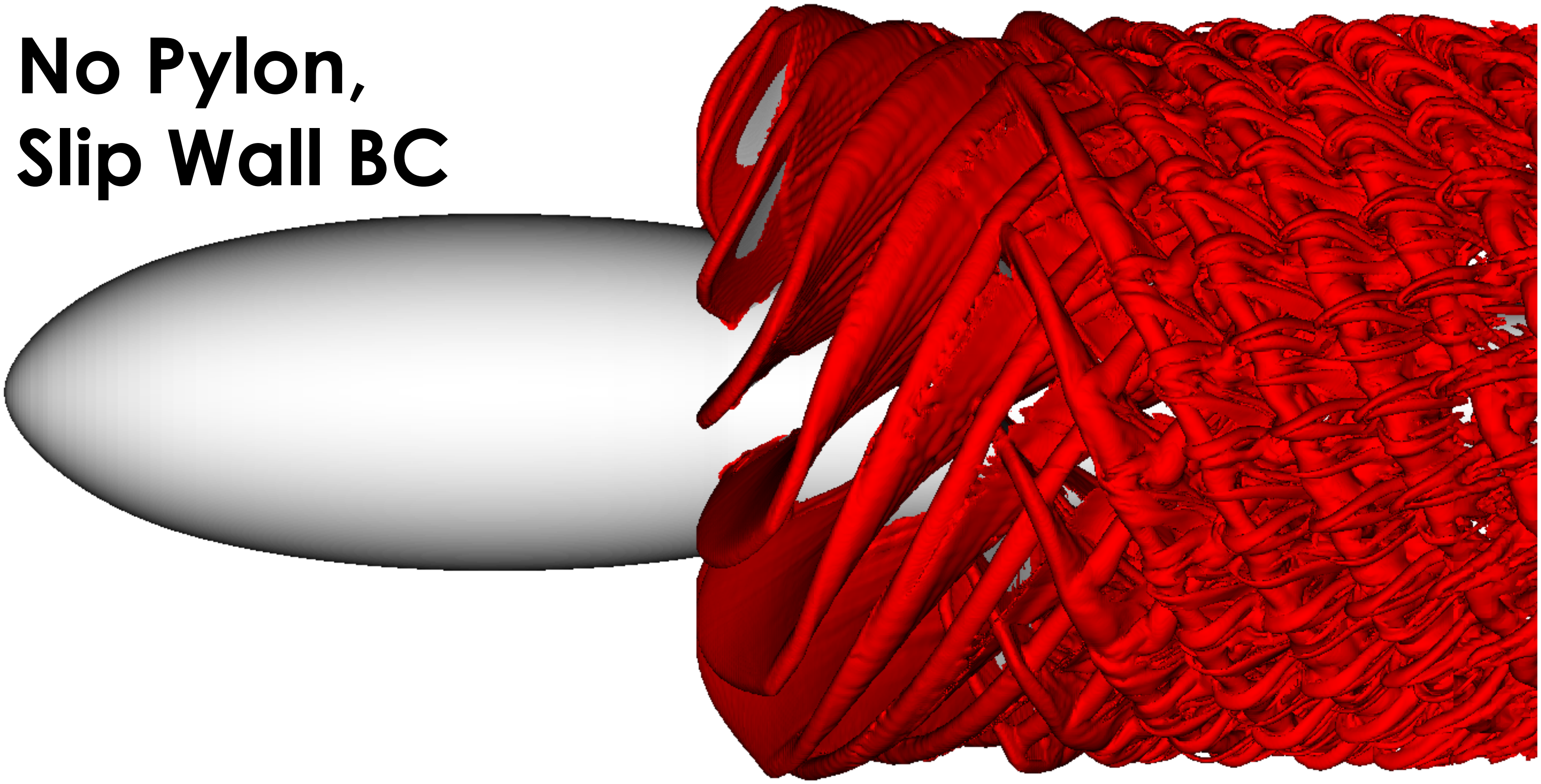


Pylon Installed Case: Mesh

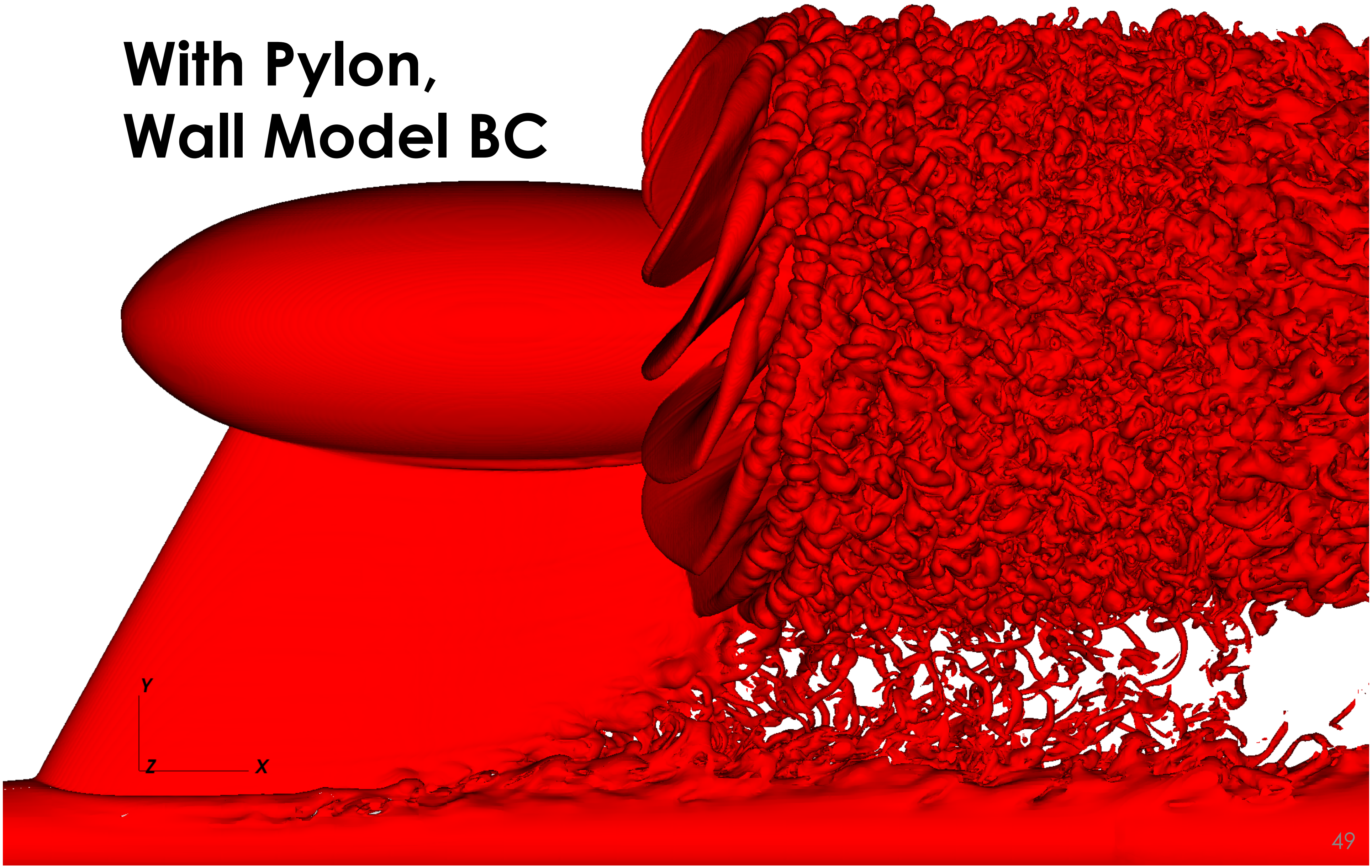


Pylon Installed Case: Vorticity @ 2000 [1/s]

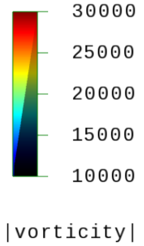
No Pylon,
Slip Wall BC



Pylon Installed Case: Vorticity @ 2000 [1/s]



Volume Rendering of Vorticity Magnitude: Pylon Case

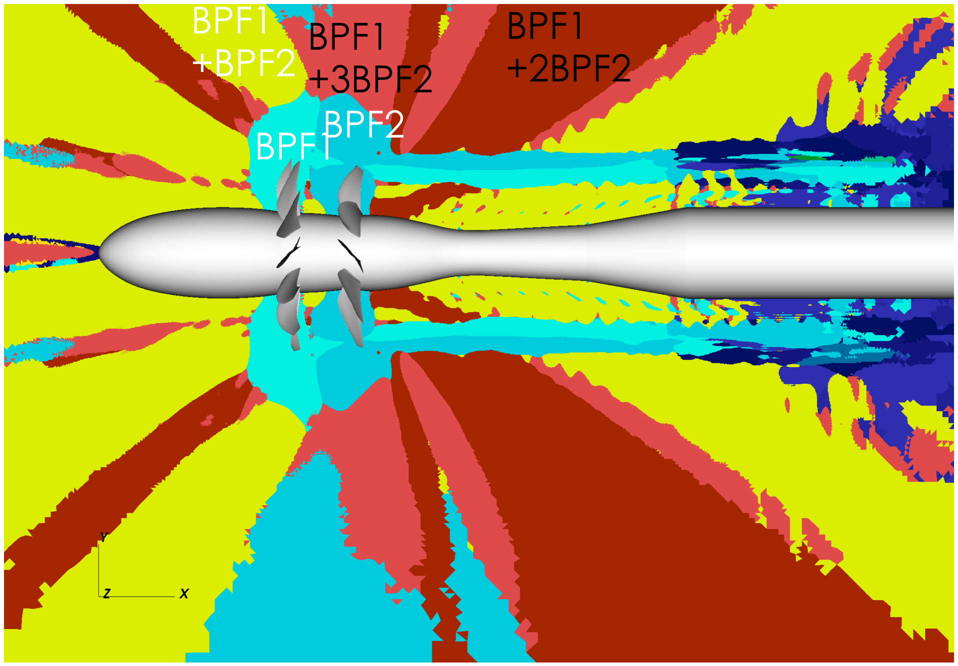


Notes: 1) Higher turbulence levels vs no-pylon case partially due to wall model
2) Pylon wake chopping enhances blade wake breakup

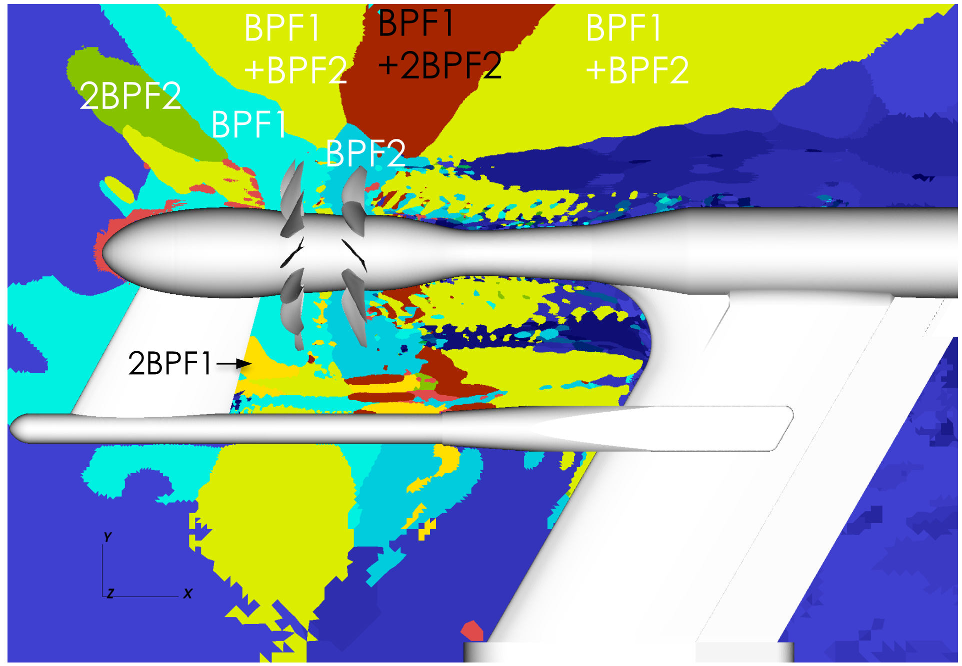
Pylon Installed Case: FFT

Shaft Order (Frequency) at Peak Amplitude:

No Pylon



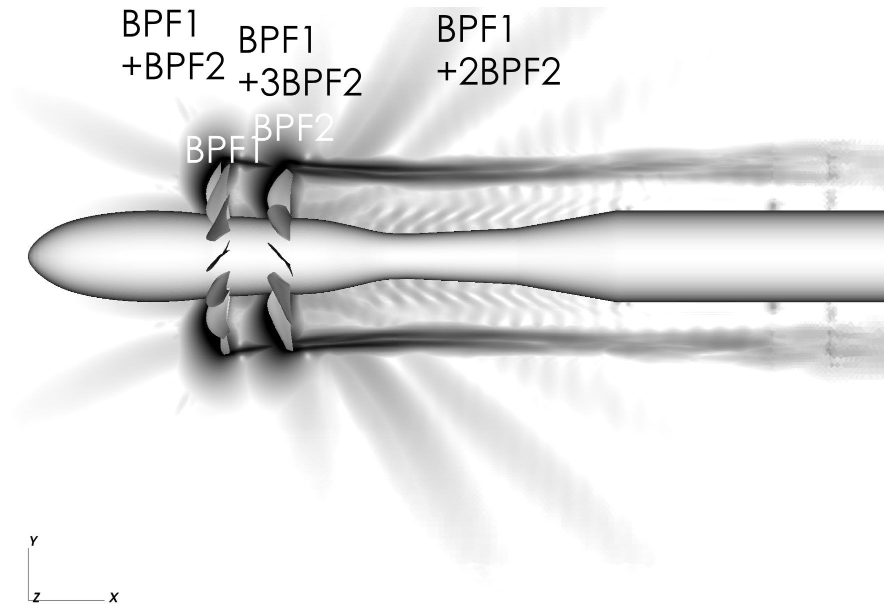
With Pylon



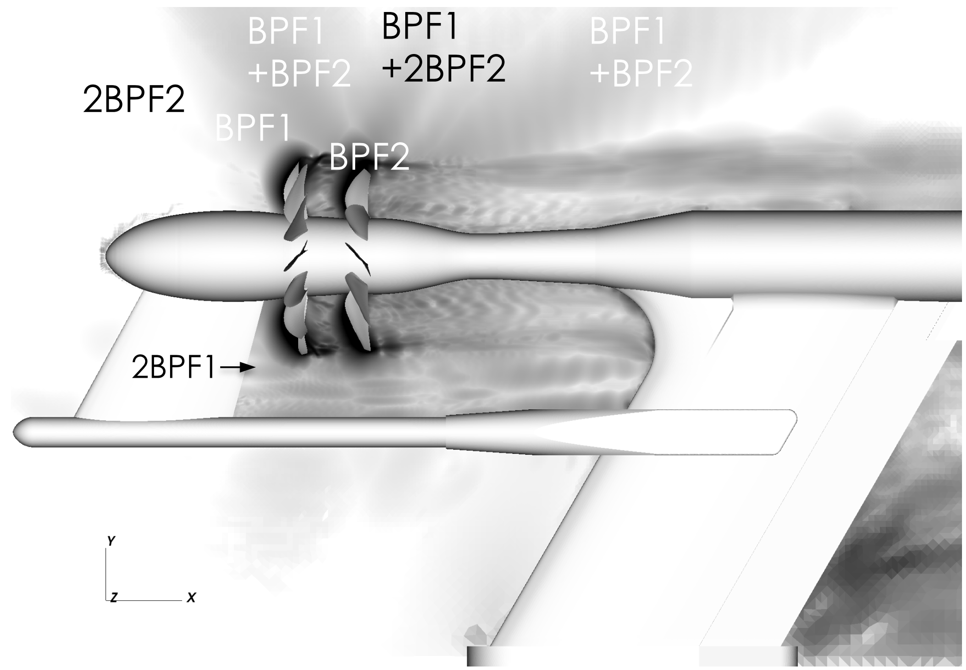
Pylon Installed Case: FFT

Normalized Peak Amplitude:

No Pylon



With Pylon

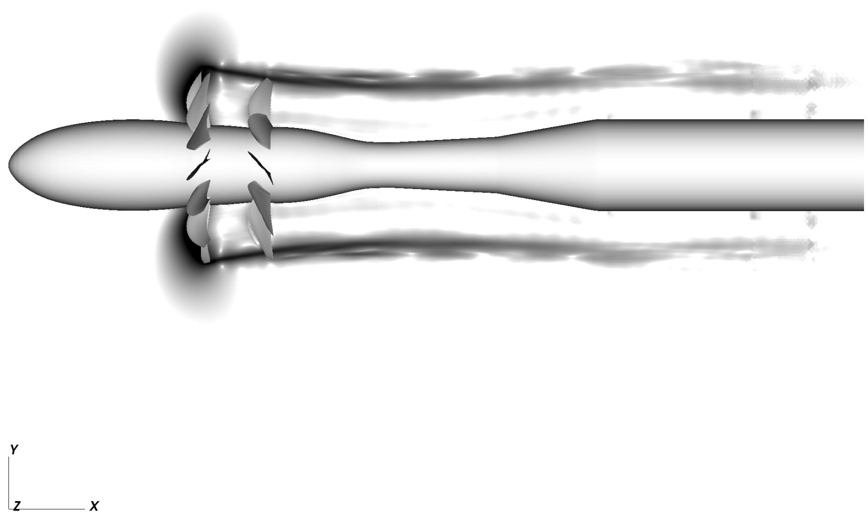


Pressure normalized with dynamic pressure

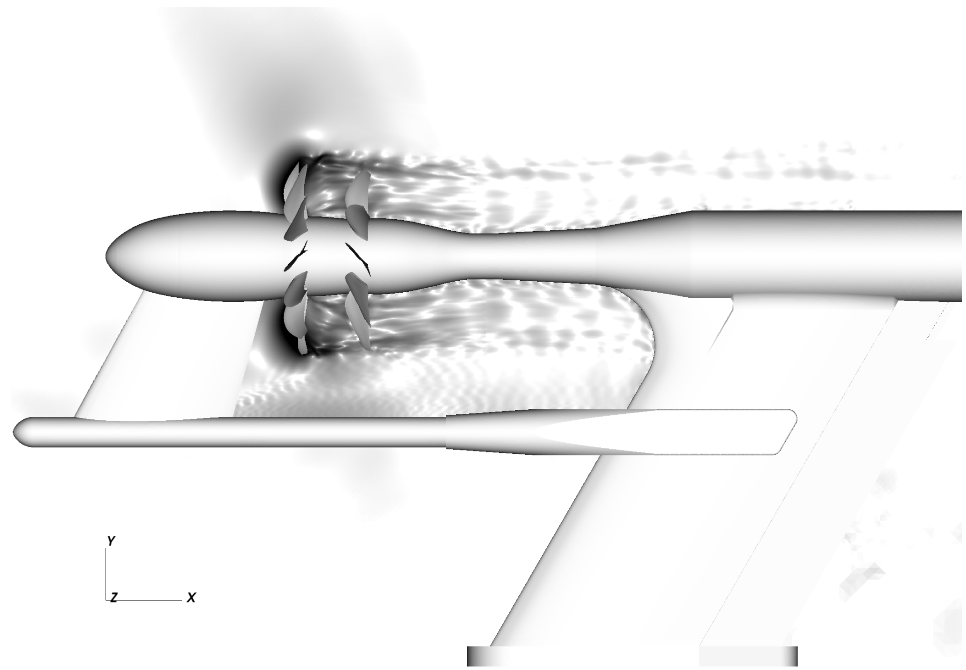
Pylon Installed Case: FFT

Amplitude at BPF1

No Pylon



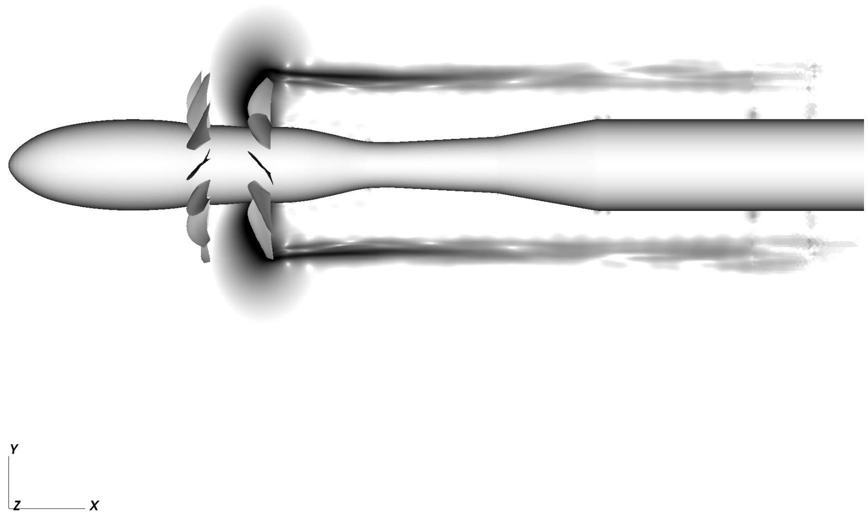
With Pylon



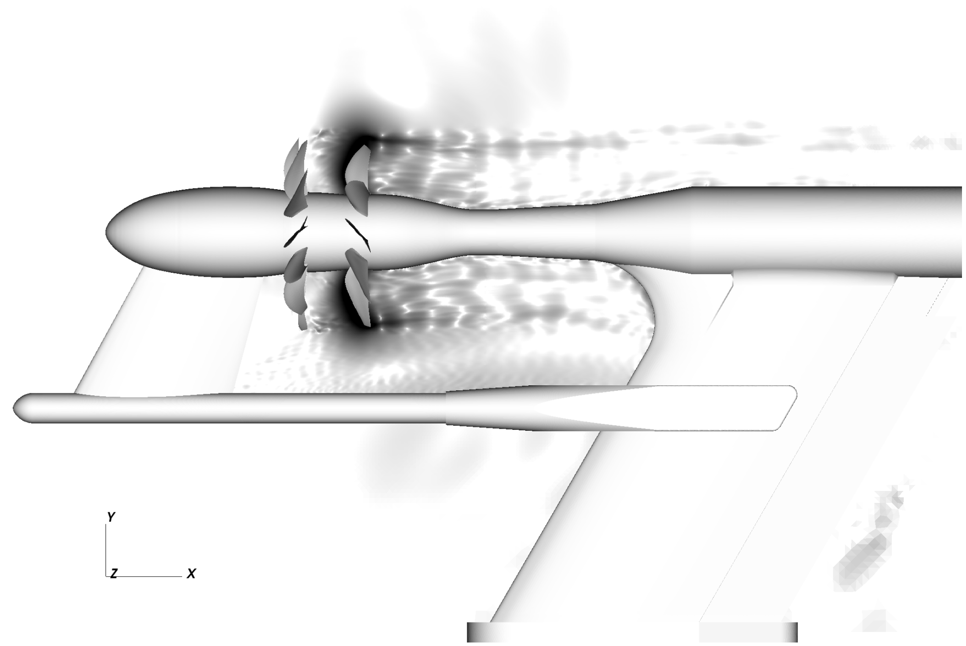
Pylon Installed Case: FFT

Amplitude at BPF2

No Pylon



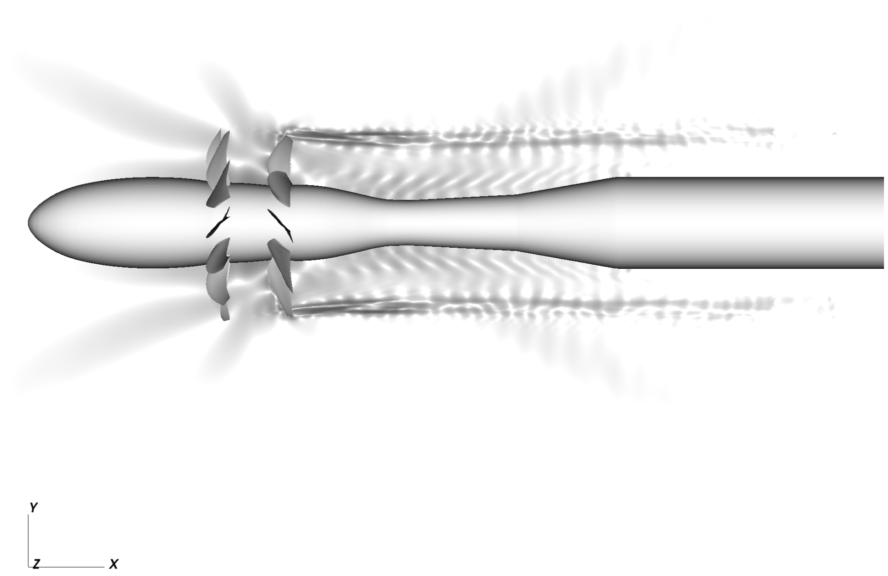
With Pylon



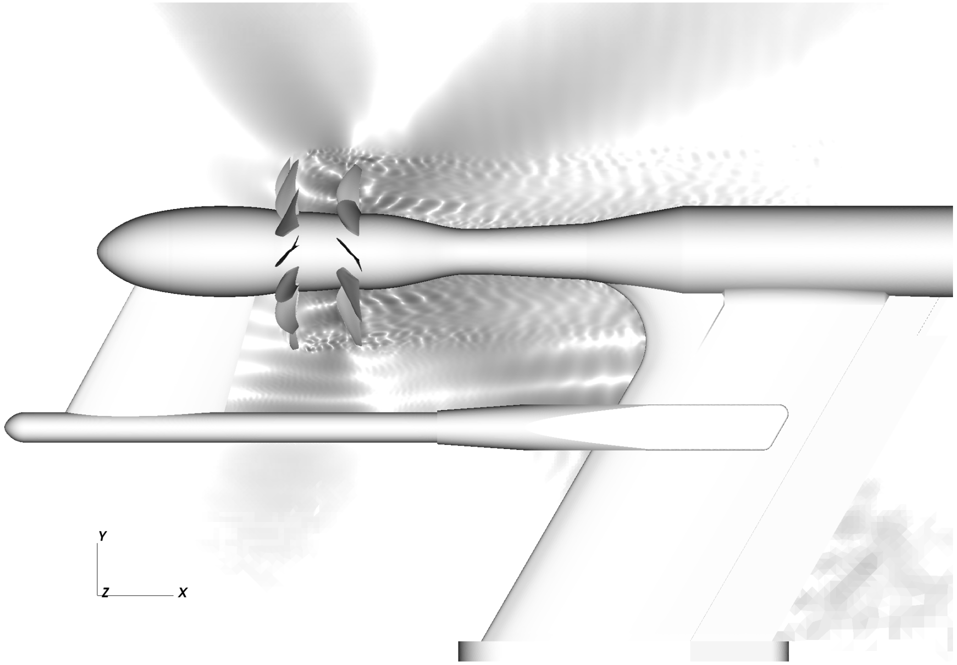
Pylon Installed Case: FFT

Amplitude at BPF1 + BPF2

No Pylon



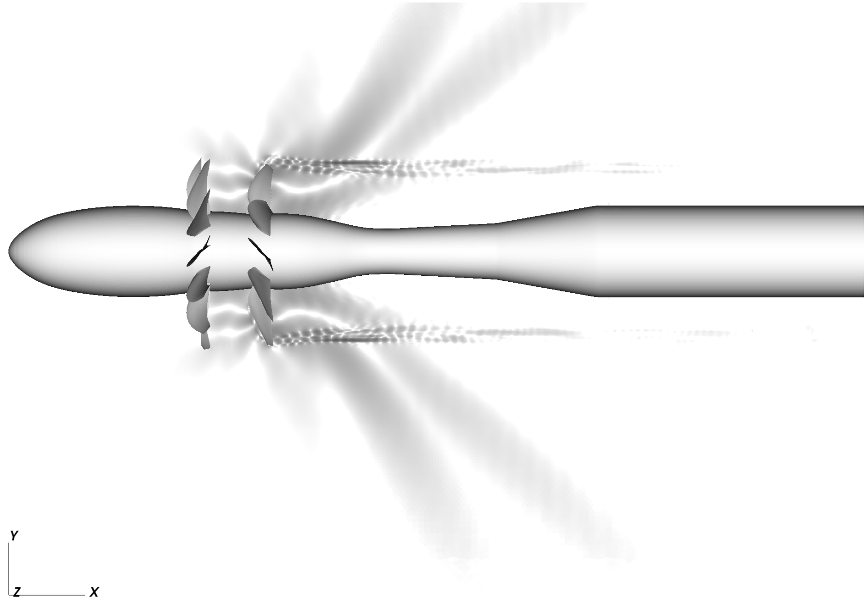
With Pylon



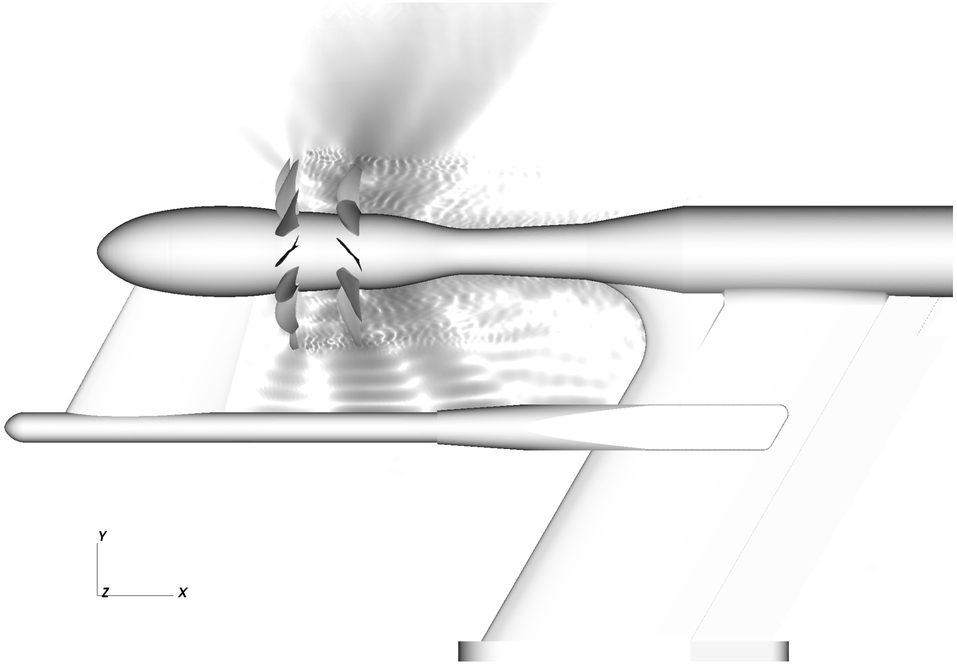
Pylon Installed Case: FFT

Amplitude at BPF1 +2BPF2

No Pylon



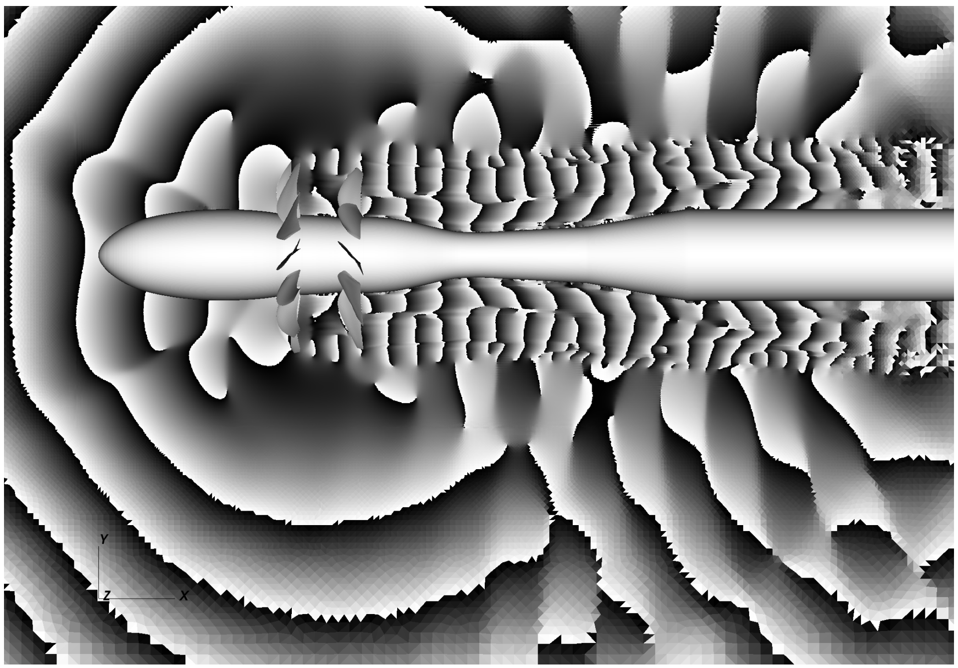
With Pylon



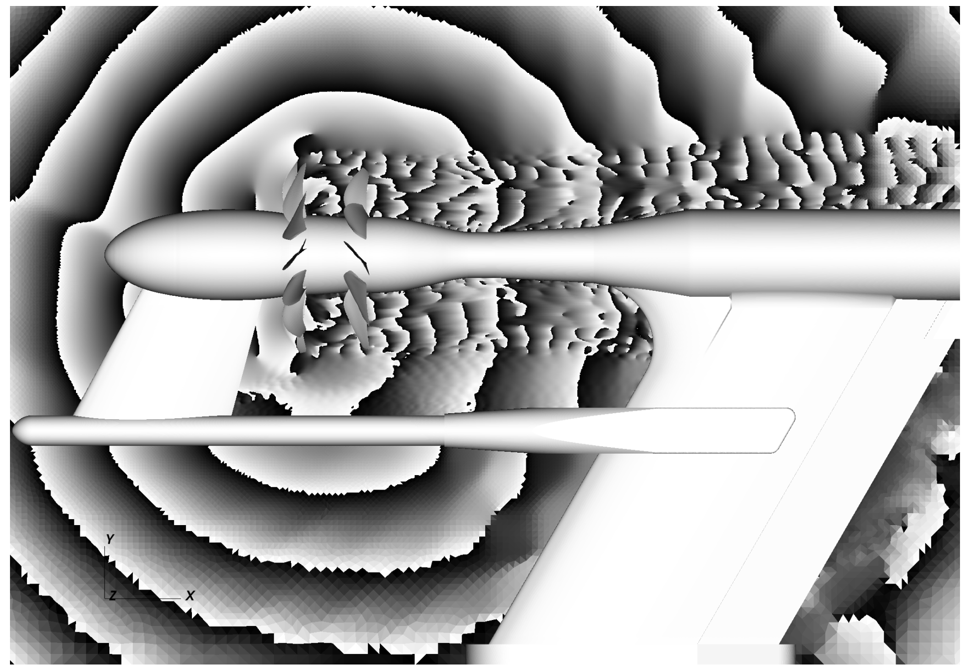
PYLON INSTALLED CASE: FFT

Phase at BPF1

No Pylon



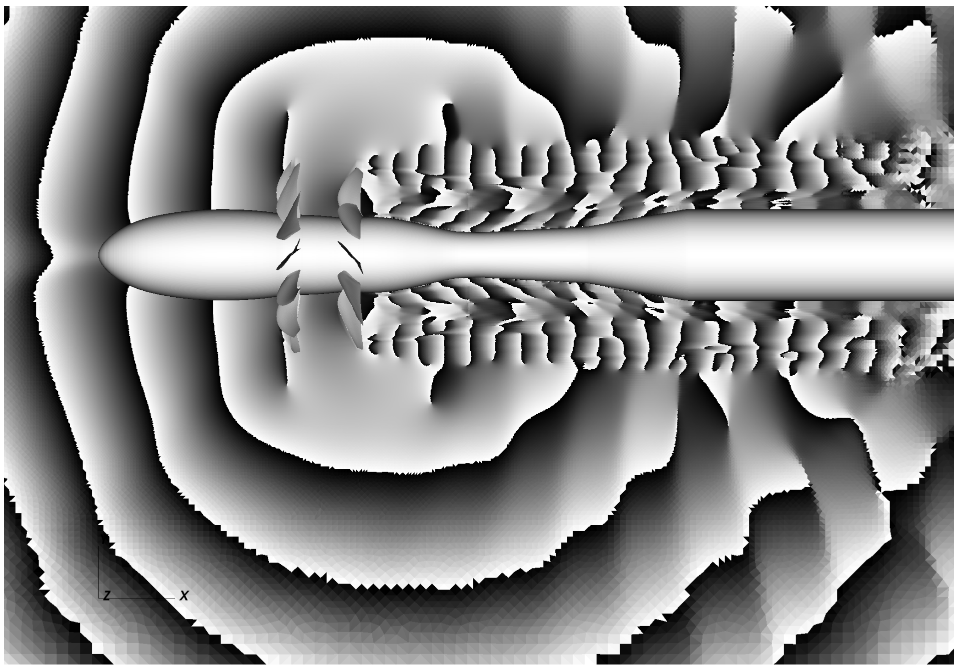
With Pylon



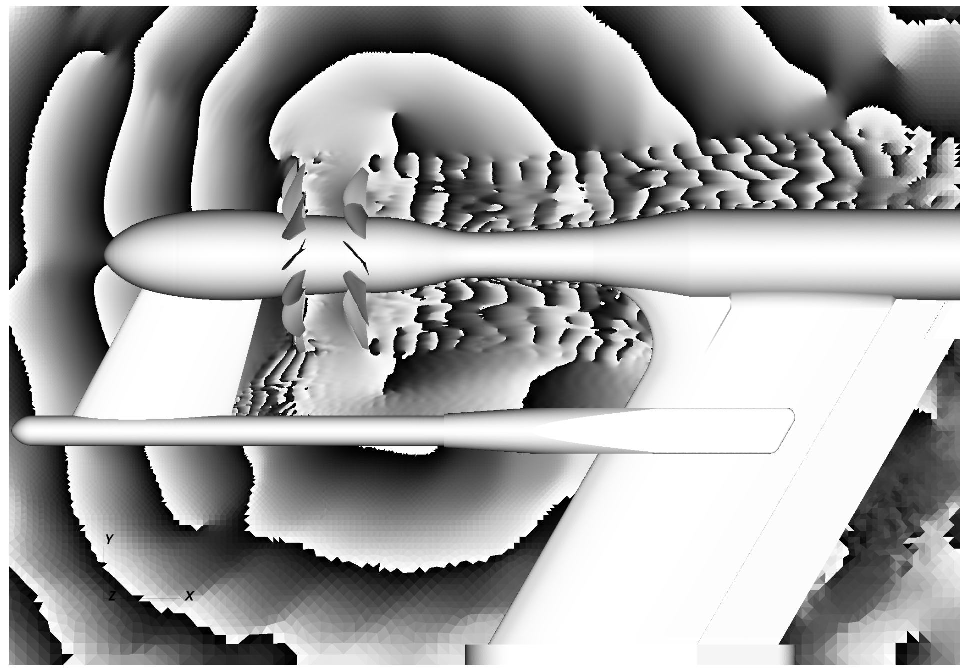
Pylon Installed Case: FFT

Phase at BPF2

No Pylon



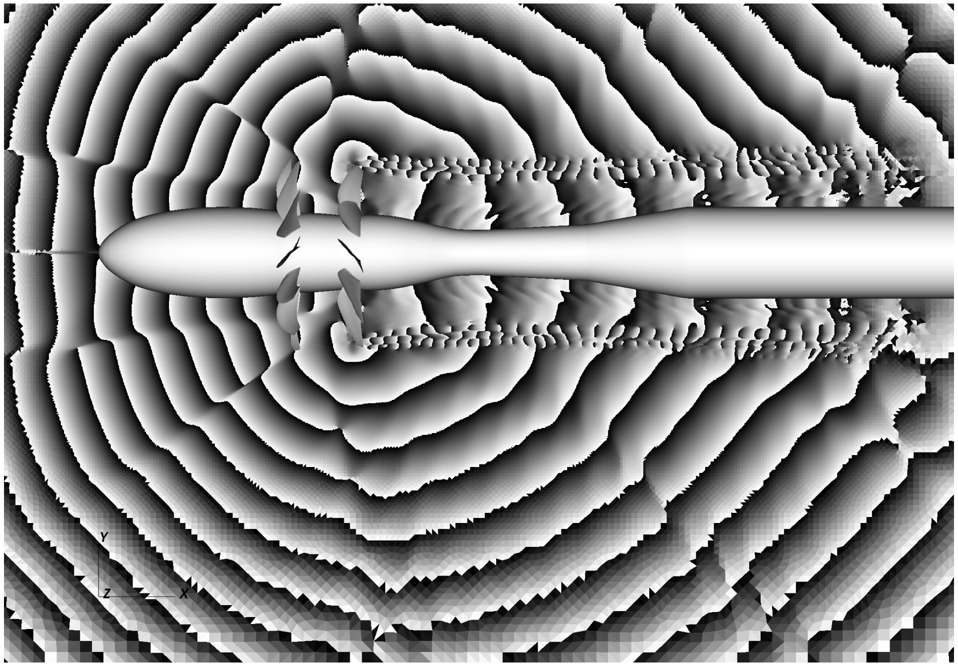
With Pylon



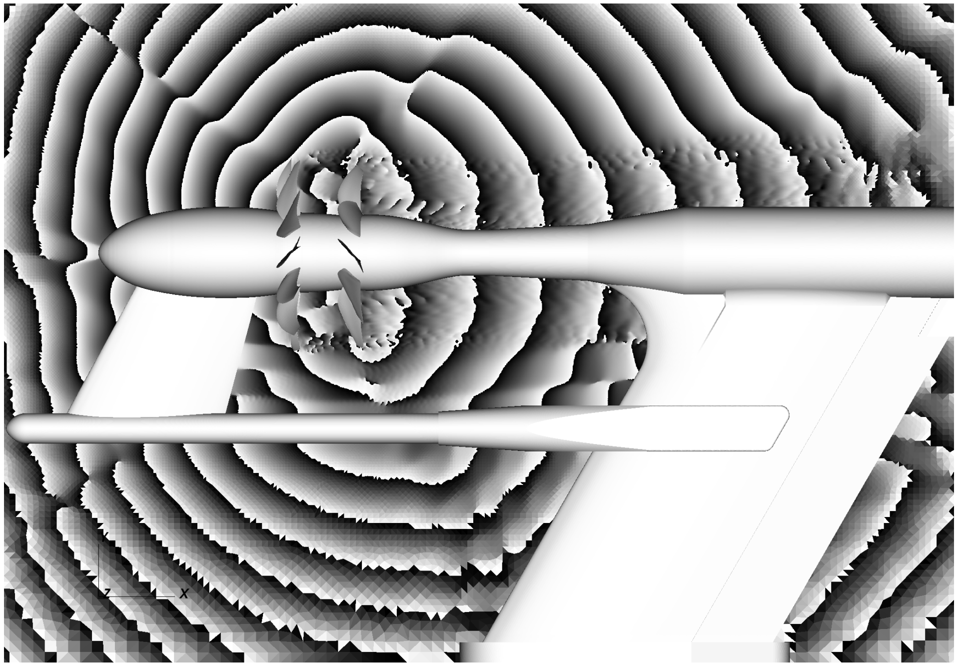
Pylon Installed Case: FFT

Phase at BPF1+BPF2

No Pylon



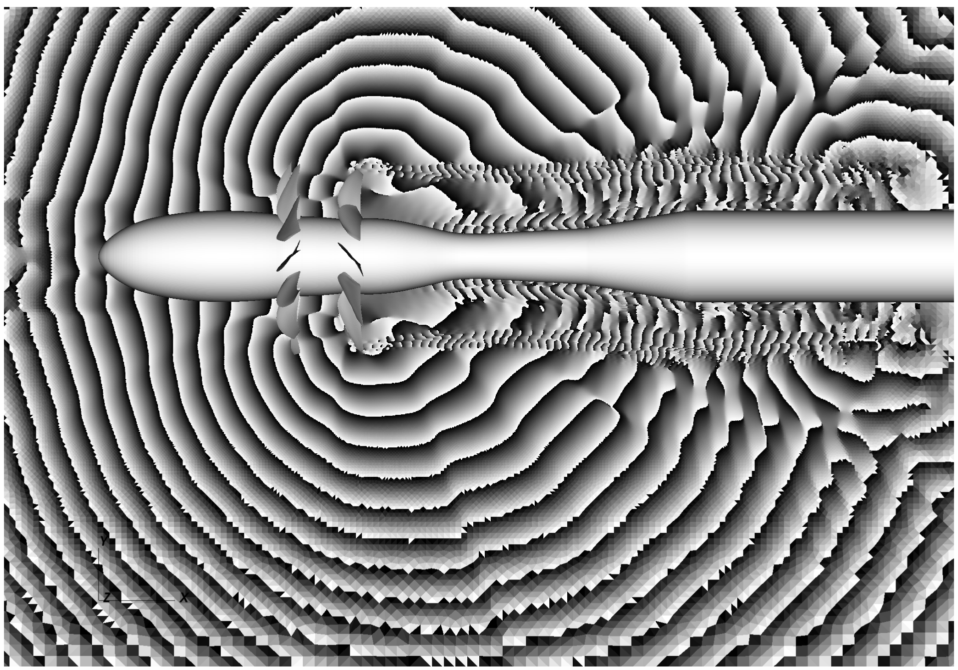
With Pylon



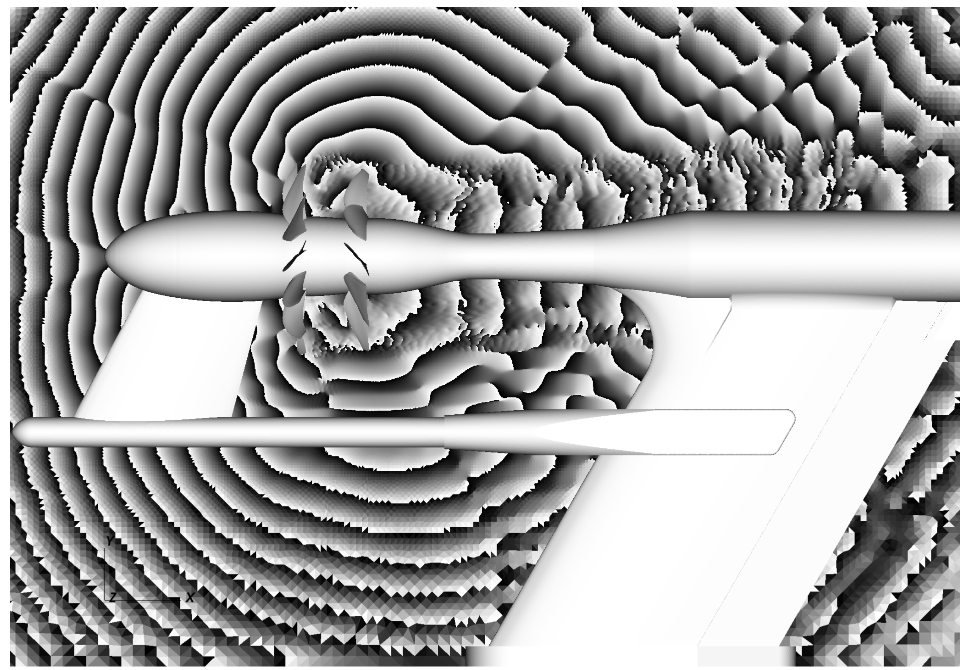
Pylon Installed Case: FFT

Phase at BPF1+2BPF2

No Pylon

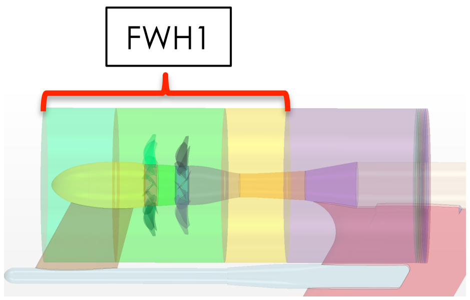


With Pylon

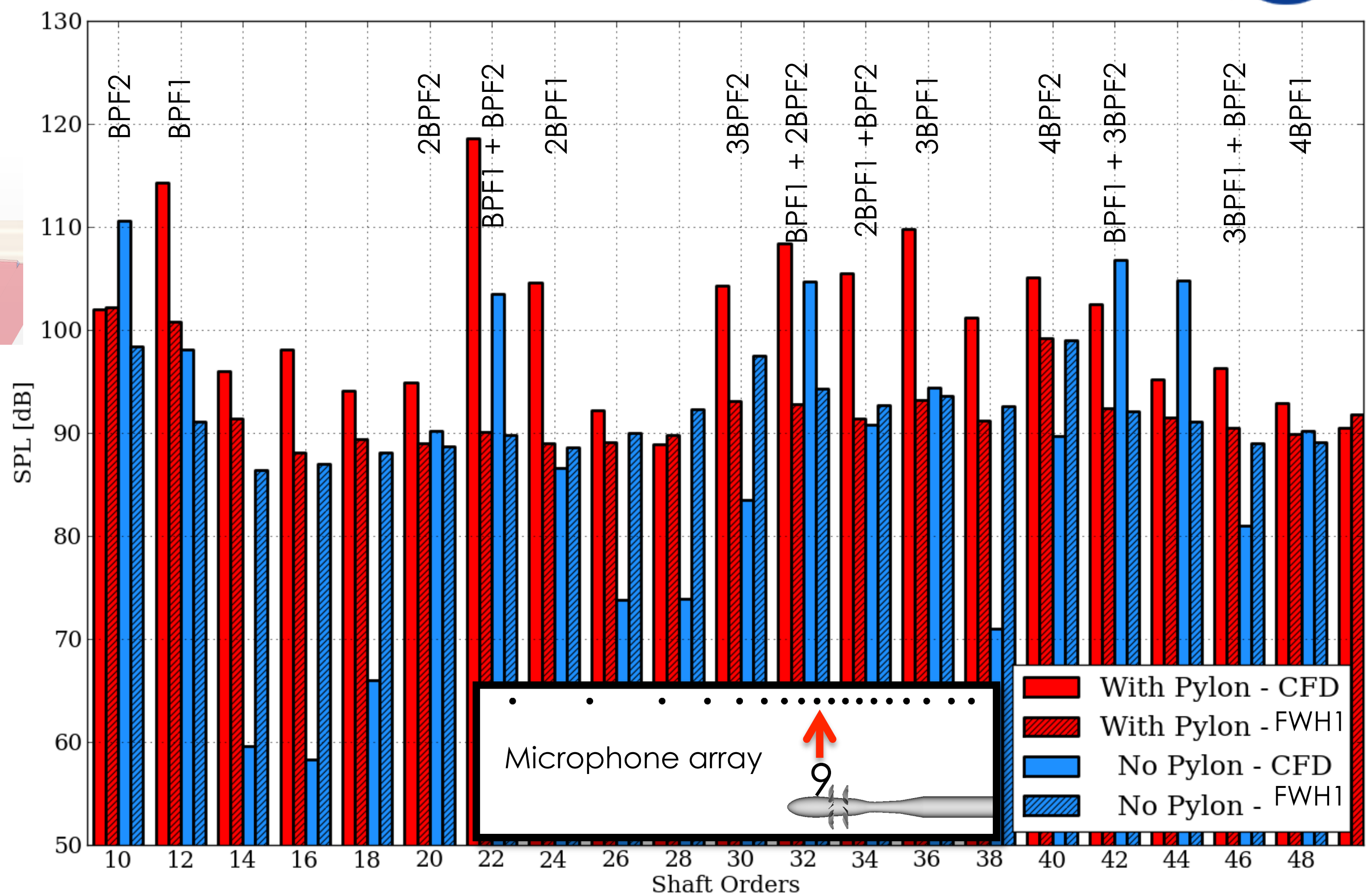


Microphone Comparison: Pylon vs no Pylon

FWH Surface:



"The primary acoustic influence of the pylon is to increase the individual rotor harmonics amplitude."
Source: NASA TM-2015-218853



Pylon vs no pylon results:

- Pylon runs had higher SPL at most shaft orders (Exp and CFD)
- Wall model improves results
- Blades chopping through pylon wake increase harmonic interactions, and reduces SPL for BPF1 and BPF2
- Inflowing broadband content in wind tunnel, but not in CFD. Will impact energy cascade to higher frequencies.

Passive Particles: Pylon Trailing Edge Seeds

Seed colors:
- Green = Pylon Edge

Notes: 1) Particles are pulled towards, and chopped by blades
2) Particles are swept around hub

Passive Particles: Blade Trailing Edge Seeds

Seed colors:

- Red = FWD Blade Edges
- Blue= AFT Blade Edges

Notes: 1) Higher turbulence levels vs no-pylon case partially due to wall model
2) Pylon wake chopping enhances blade wake breakup

Passive Particles: Pylon and Blade Trailing Edge Seeds

Seed colors:
- Green = Pylon Edge
- Red = FWD Blade Edges
- Blue= AFT Blade Edges

Notes: 1) Higher turbulence levels vs no-pylon case partially due to wall model
2) Pylon wake chopping enhances blade wake breakup

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SUMMARY

- LAVA's sharp immersed boundary (IBM) method was used to simulate flow around a contra-rotating open rotor for nominally takeoff and cruise conditions, both free and pylon installed
- Key issues for simulating moving boundaries with IBM were addressed:
  - Treatment of freshly cleared cells
  - Treatment of thin geometry:
    - Interior only scheme
    - Stencil cloud selection
    - Interpolation to thin surfaces
  - Efficiency improvements required (moving every time-step!):
    - Geometry queries
    - Re-computation of irregular clouds and stencils
- Acoustic data obtained from combination of CFD near-field + FWH method compare well with experiments
- Distinct differences in low and high speed acoustic fields
  - OASPL for M=0.78 peaks around 90° while OASPL keeps increasing with increasing geometric angle for M=0.2
  - High speed case is dominated by BPF1 and BPF2
  - Low speed case showed complicated higher-order interactions that are relevant for the OASPL
- Pylon installed and no-Pylon cases were compared

Acknowledgments

- 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

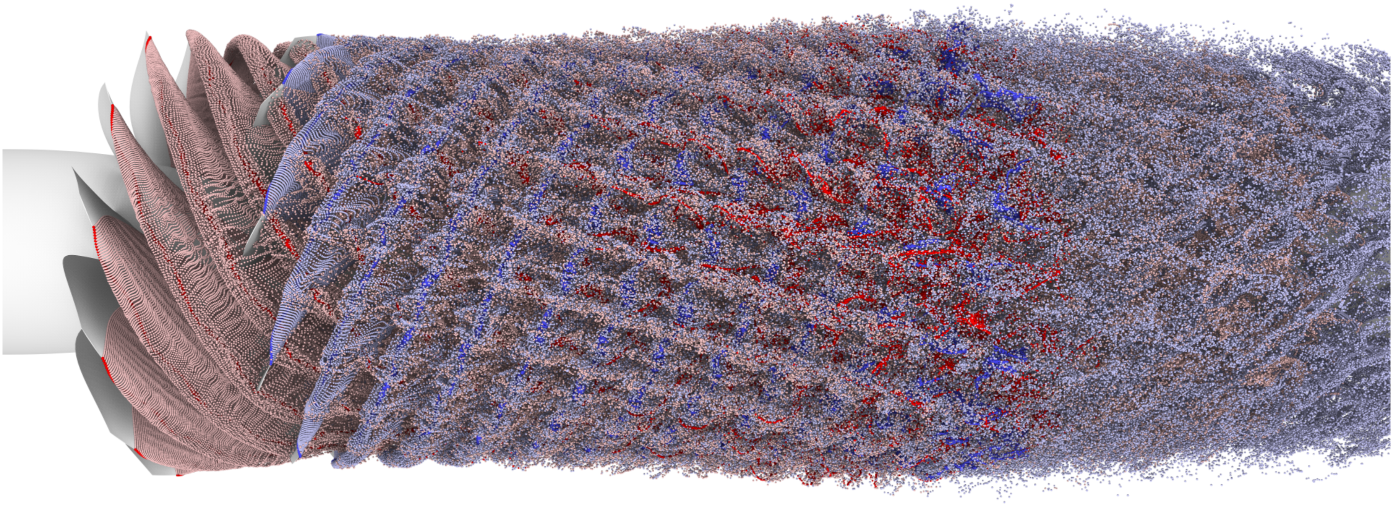
- Team members of the acoustic working group

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

Questions?

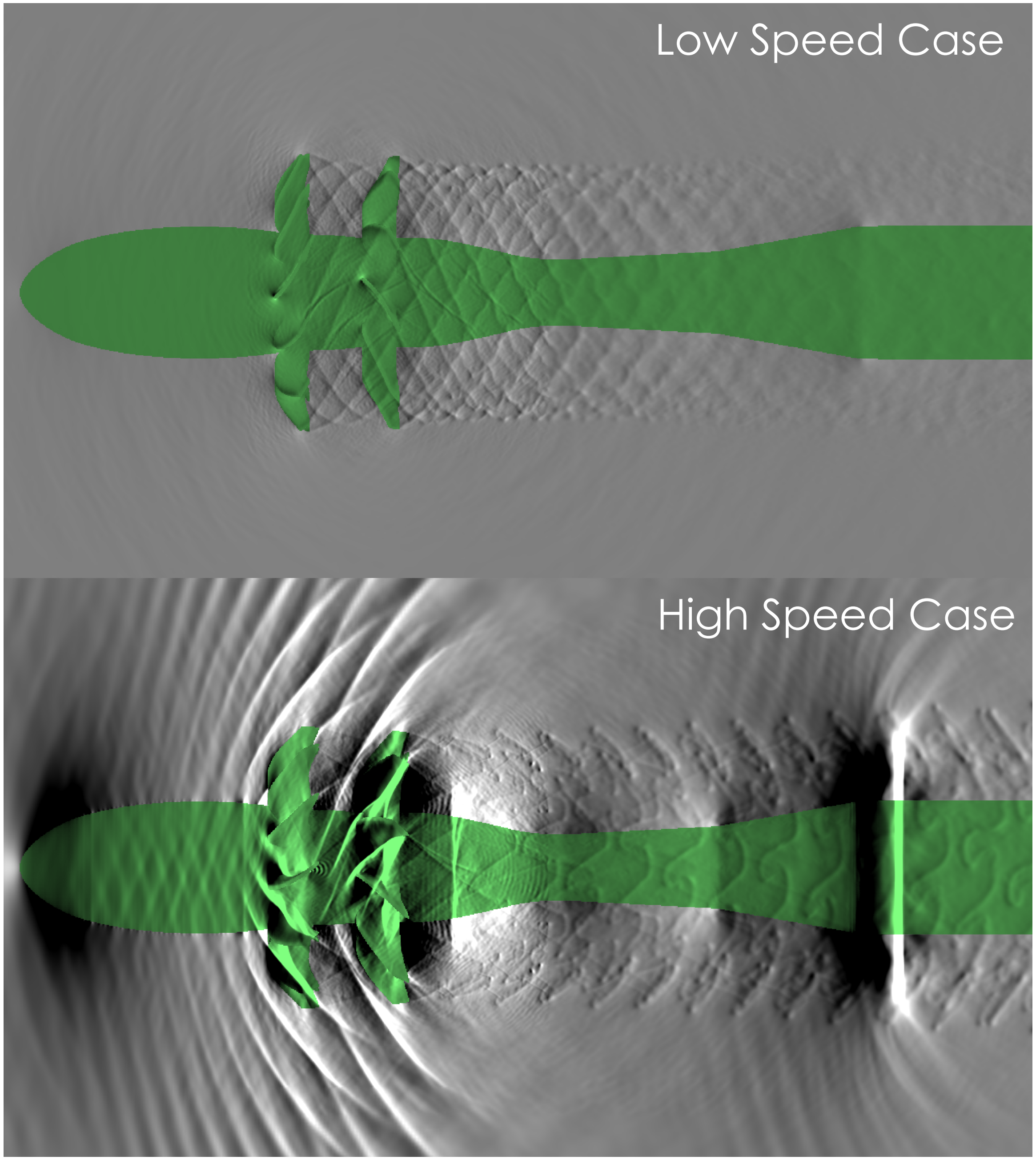
Unsteady Flow Field – Passive Particle Viz

M=0.2



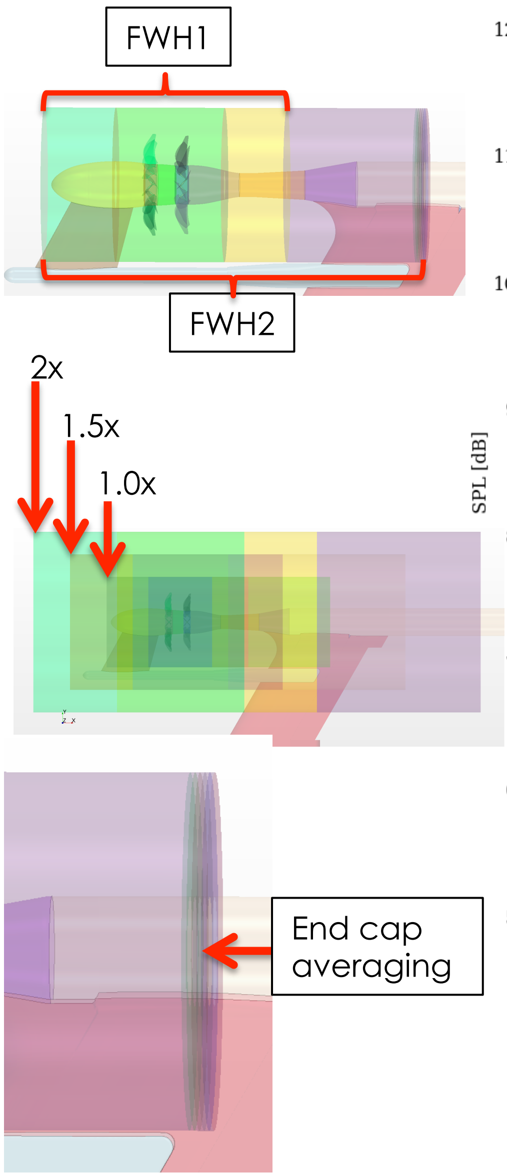
M=0.78

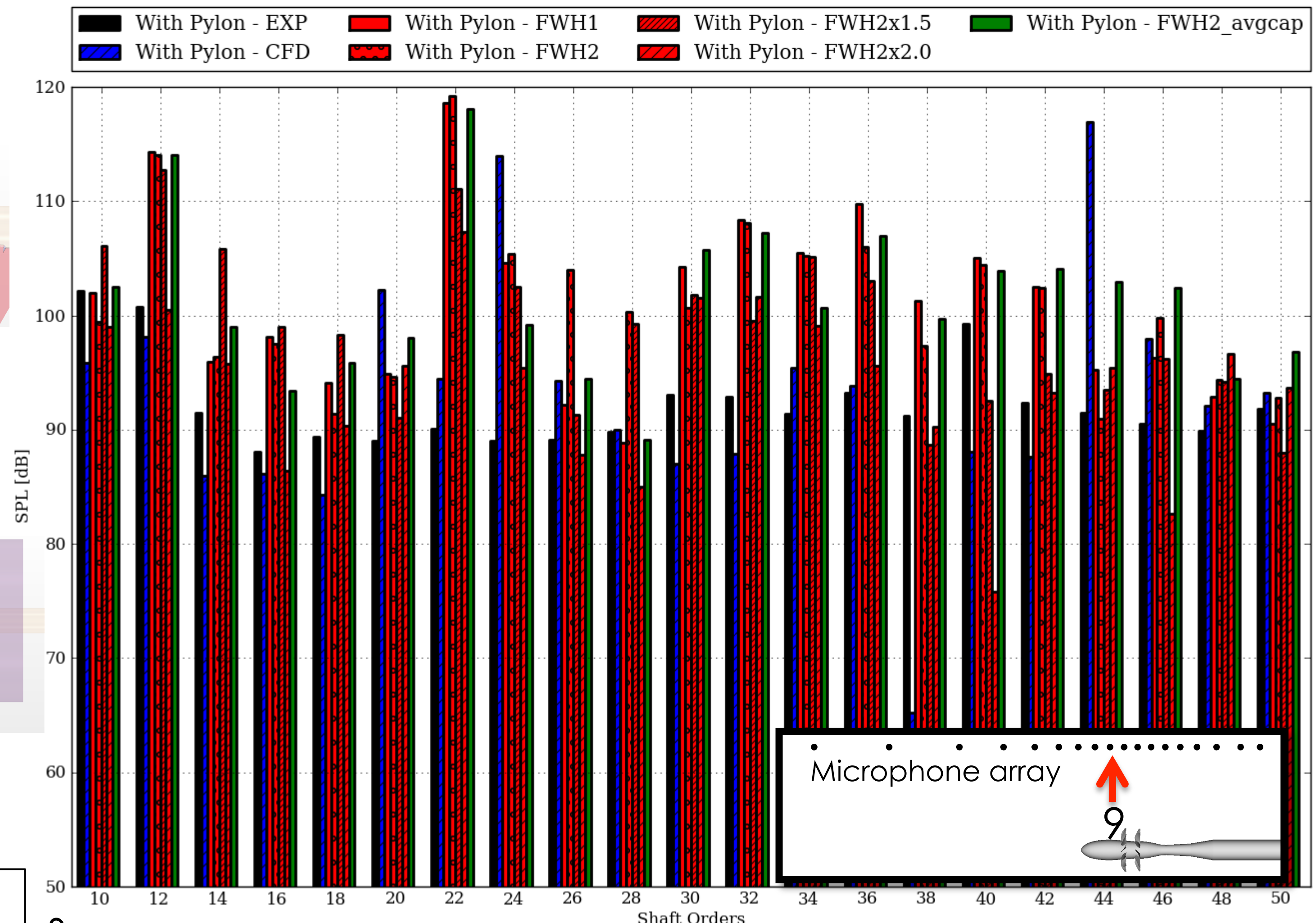
Unsteady Flow Field – Numerical Schlieren



Microphone Comparison: Propagation Methods

FWH Surfaces:





Summary:

- High-order CFD does surprisingly well for propagation to this distance, but FWH is required for far-field.
- Larger FWH surfaces not significantly improving comparisons
- End cap averaging not significantly improving comparisons