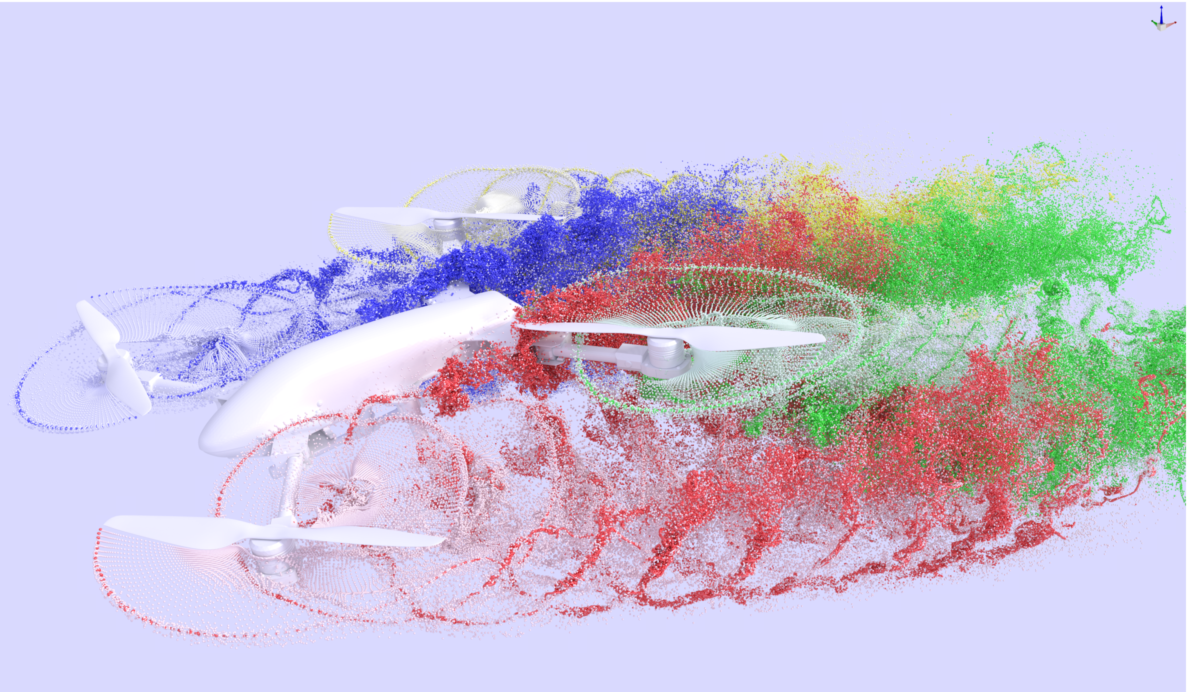

Predicting Quadcopter Drone Noise Using the Lattice Boltzmann Method

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Computational Aerosciences Branch

NASA Ames Research Center

Advanced Modeling and Simulation Seminar

12/18/2019

Motivation

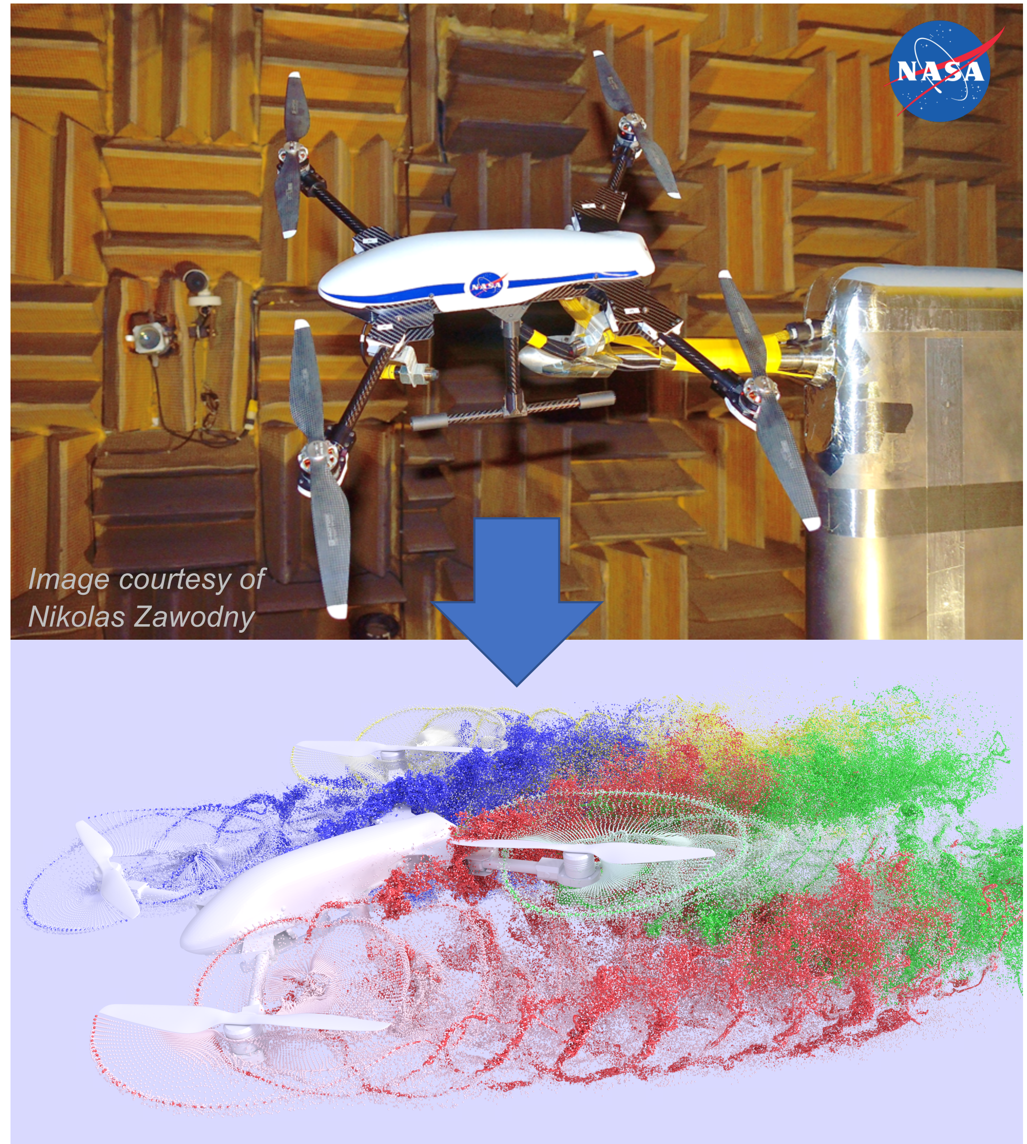
- Community noise is a major concern for drone delivery of packages and for urban air mobility vehicles (air taxis)
- Rotor tonal noise is fairly well-understood and can be predicted accurately with simple tools
- Multi-rotor wake interaction and rotor-fuselage interaction is harder, but still within the realm of possibility
- Reliable and accurate predictions of broadband noise of a full multi-rotor vehicle have yet to be demonstrated

Picture credit: *NASA / Lillian Gipson*

Research Objectives

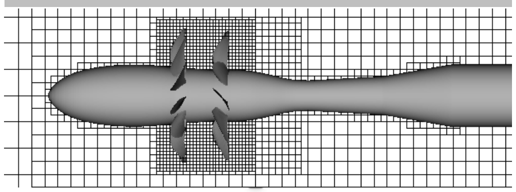
- Take first step toward predicting noise for future package delivery drones and urban air mobility vehicle
- Establish best practices to simulate a multi-rotor vehicle with complex fuselage
- Assess the computational cost and accuracy of the Lattice-Boltzmann Method (LBM) for acoustics
- Compare CFD predictions with experimental measurements:

  Zawodny, Nikolas, and Nicole Pettingill. "Acoustic wind tunnel measurements of a quadcopter in hover and forward flight conditions." *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*. Vol. 258. No. 7. Institute of Noise Control Engineering, 2018.



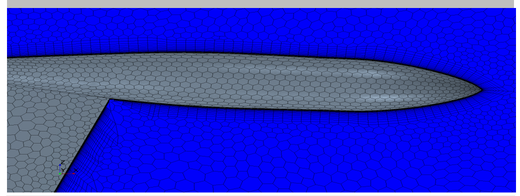
CFD Grid Paradigms

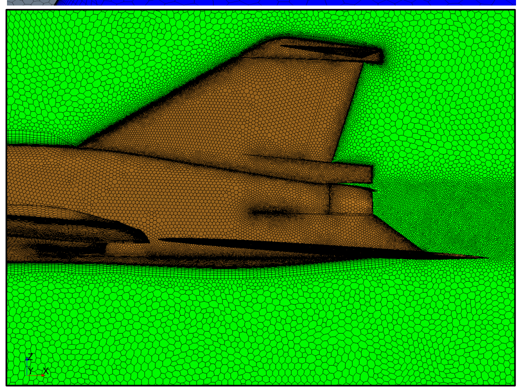
Structured Cartesian AMR



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

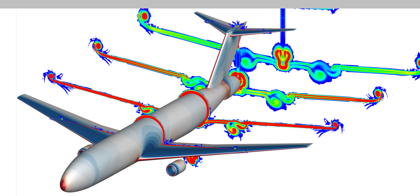
Unstructured Arbitrary Polyhedral

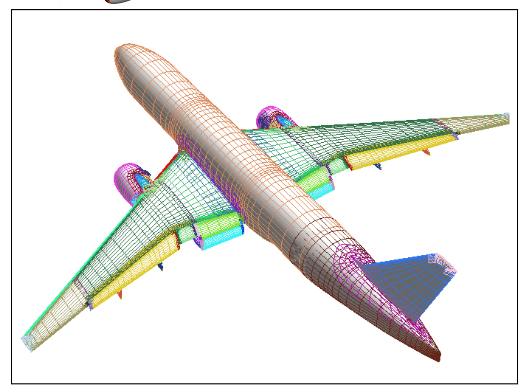




- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

Structured Curvilinear

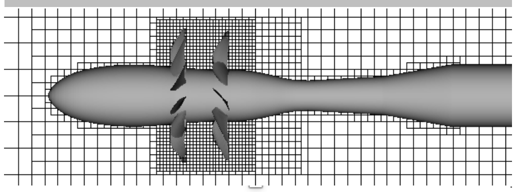




- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

CFD Grid Paradigms

Structured Cartesian AMR

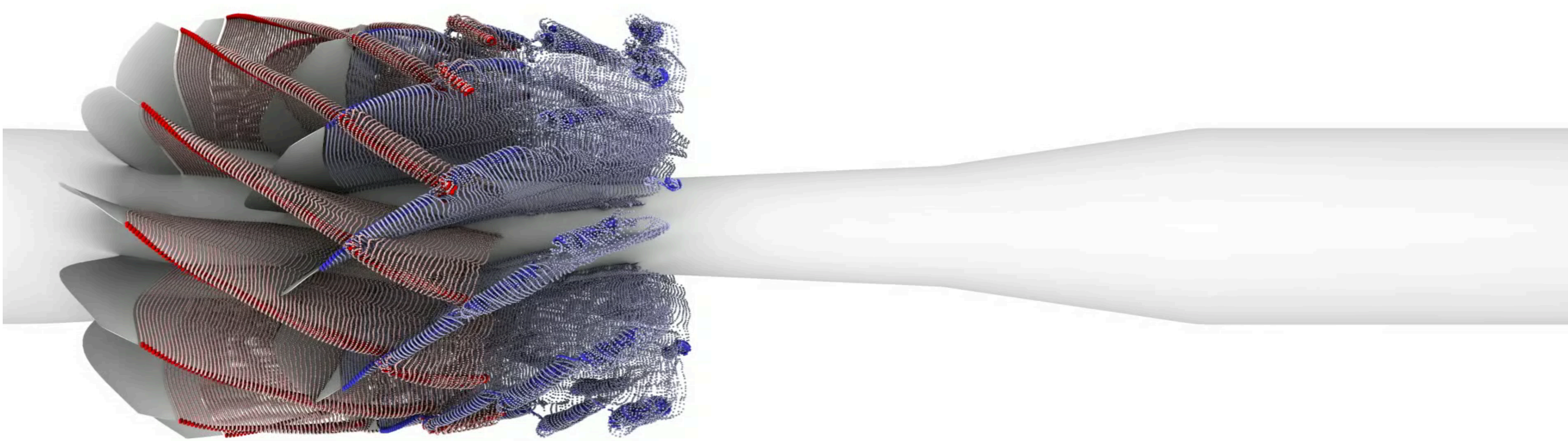


- Essentially no manual grid generation
- Highly efficient structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient

Predict multi-rotor and rotor-fuselage interaction noise, including broadband noise for a quadcopter:

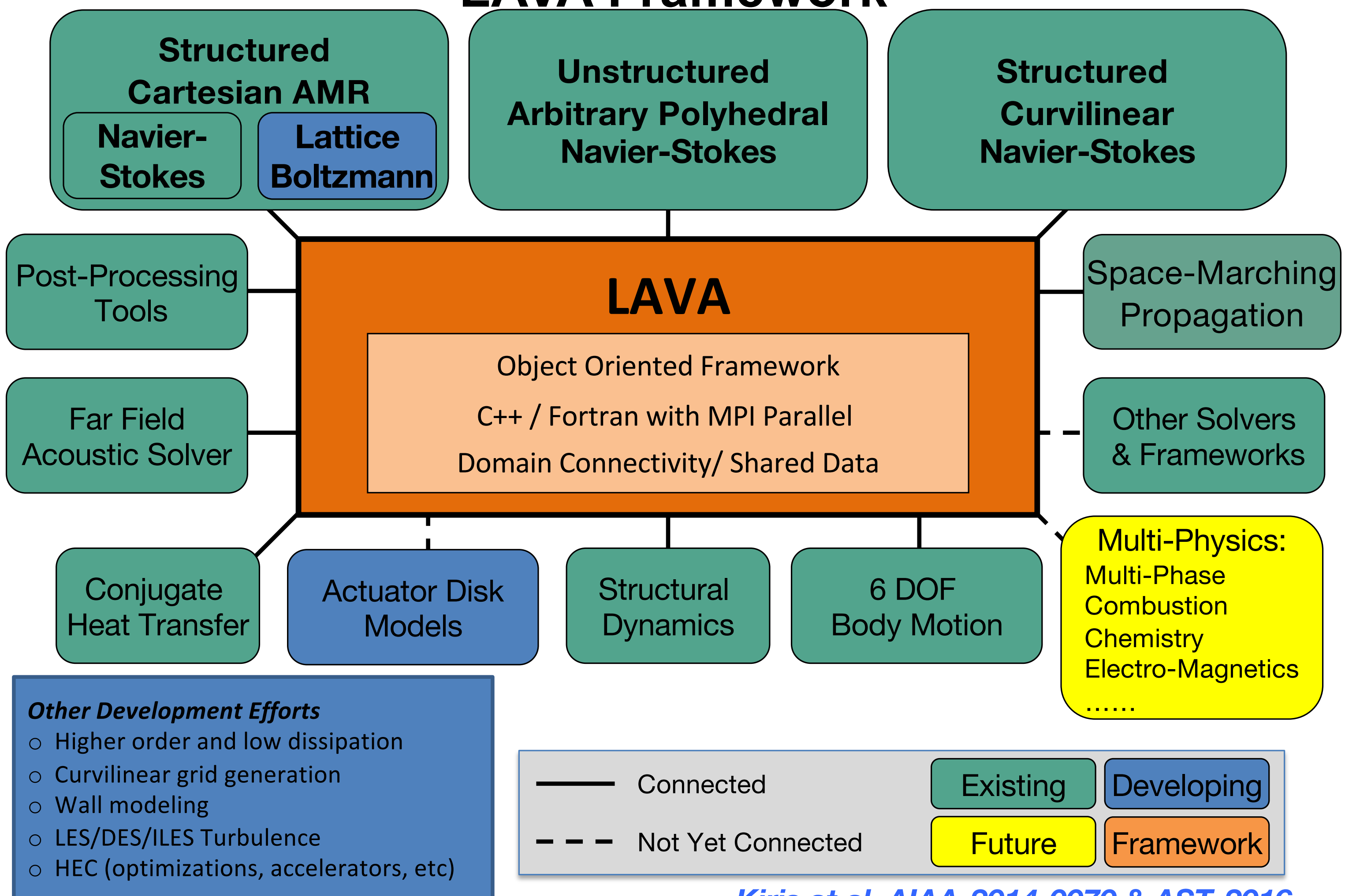
- Simulate complex vehicle without simplification
  - ✓ Automatic mesh generation and immersed boundary representation
- Track all sources of noise as they propagate
  - ✓ Adaptive mesh refinement (AMR) using on-the-fly statistics
- Capture acoustic waves from 135 Hz to 18 kHz
  - ✓ Low-dissipation high-resolution scheme (EMRT) can capture waves accurately with only 5 cells per wavelength
  - ✓ Near-isotropic cells are best for predicting acoustics
  - ✓ Boundary layers do not play critical role in the quantities of interest for this project
- Short turnaround time for decision making
  - ✓ Automatic grid generation means we can get started immediately
  - ✓ Sub-cycling algorithm increases computational efficiency

Cartesian Navier-Stokes Simulation of Open Counter-Rotating Rotors Successfully Used to Predict Tonal And Rotor-Rotor Interaction Noise



Animation Credit: Timothy Sandstrom

Launch, Ascent, and Vehicle Aerodynamics
LAVA Framework



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

Why Lattice-Boltzmann?

10X faster and extremely accurate*

No manual CFD mesh generation

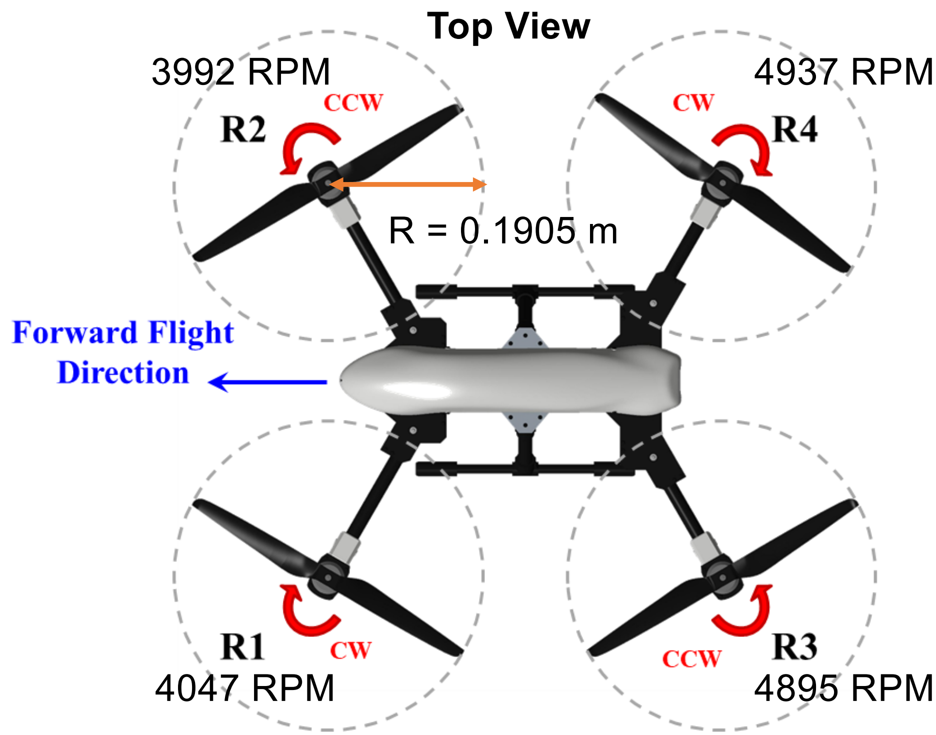
Fast turnaround time

*to perform scale-resolving simulations of low Mach number flows

Problem Setup

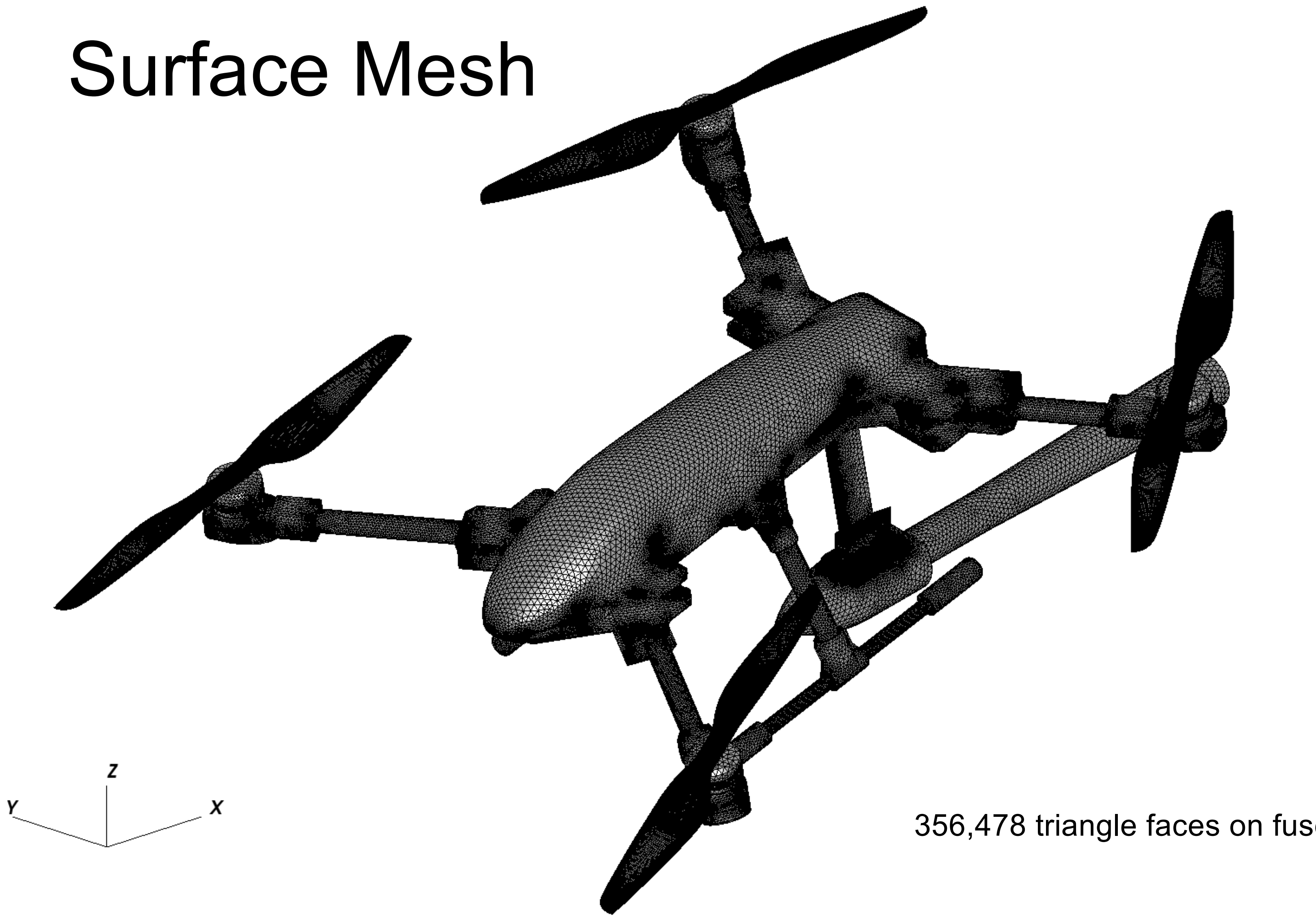
- SUI Endurance quadcopter in forward flight as tested in Low Speed Aeroacoustic Wind Tunnel (LSAWT) at the NASA Langley Research Center by Zawodny & Pettingill (2018)

Mach = 0.045, AoA = -10°



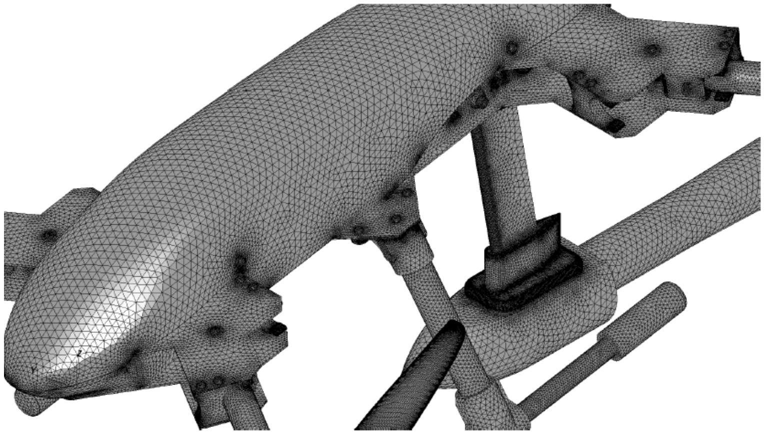
Images courtesy of Nikolas Zawodny

Surface Mesh

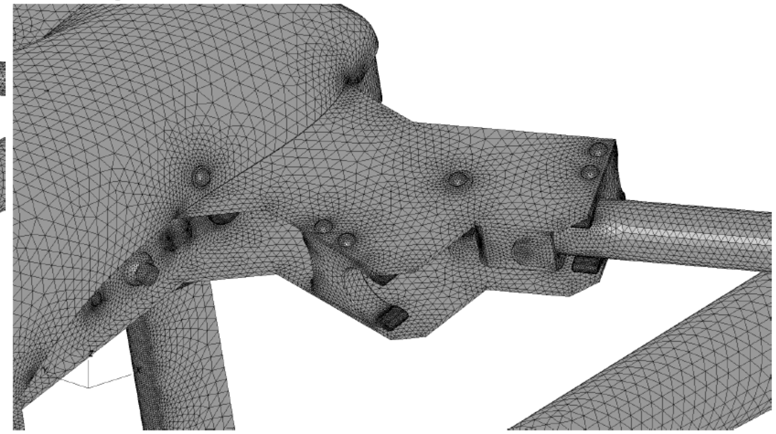


356,478 triangle faces on fuselage

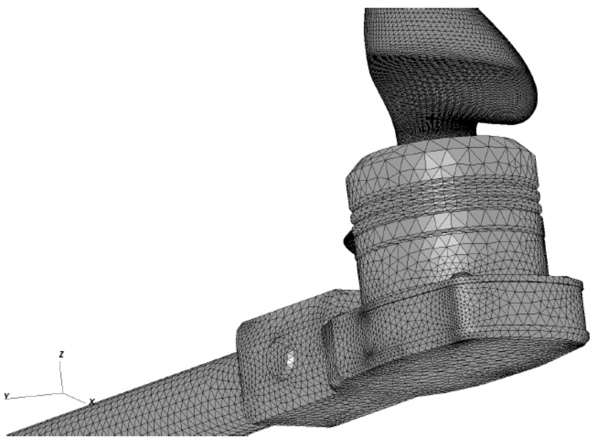
Surface Mesh: Fuselage Details



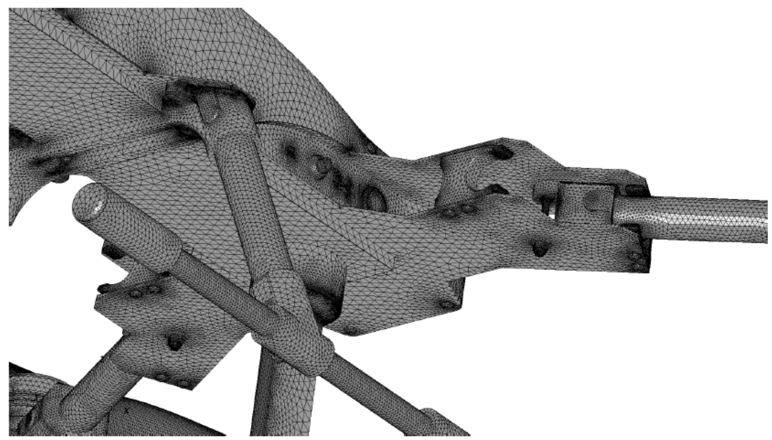
(b) Arm Attachments



(c) Rear Arm Attachment



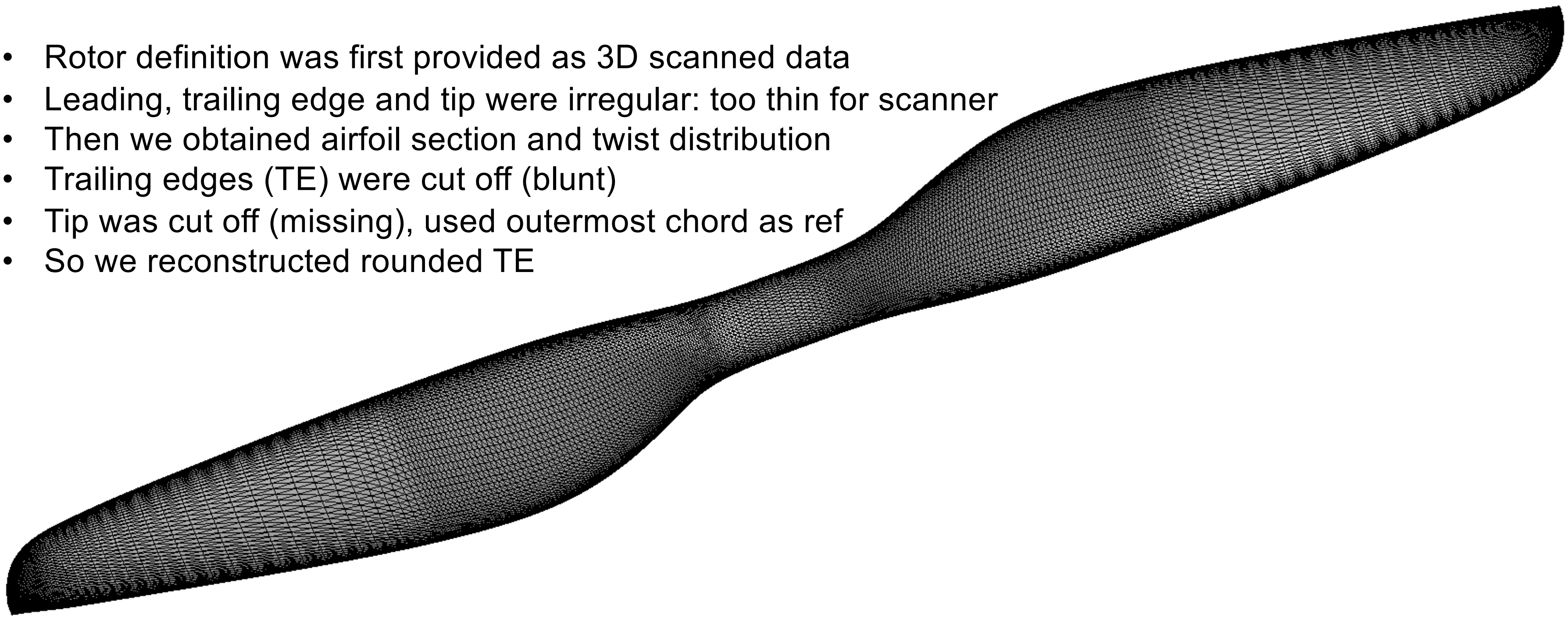
(d) Propeller Hub



(e) Undercarriage and Rear Arm Attachment

Surface Mesh: Rotor

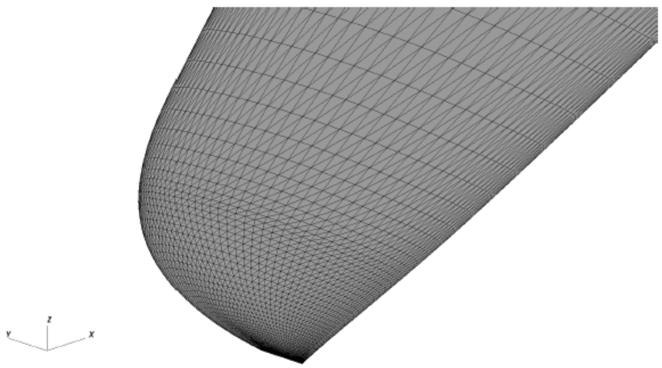
- Rotor definition was first provided as 3D scanned data
- Leading, trailing edge and tip were irregular: too thin for scanner
- Then we obtained airfoil section and twist distribution
- Trailing edges (TE) were cut off (blunt)
- Tip was cut off (missing), used outermost chord as ref
- So we reconstructed rounded TE



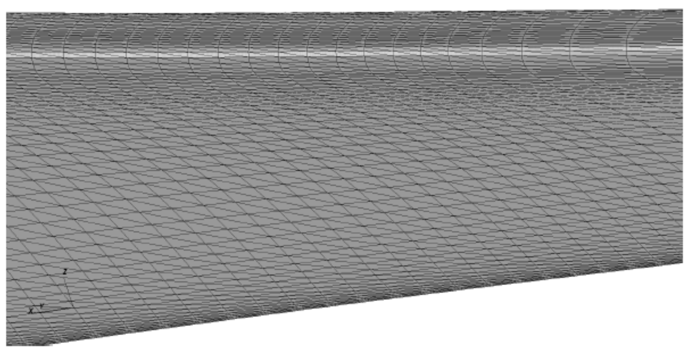
60,972 triangle faces on each blade

Surface Mesh: Rotor

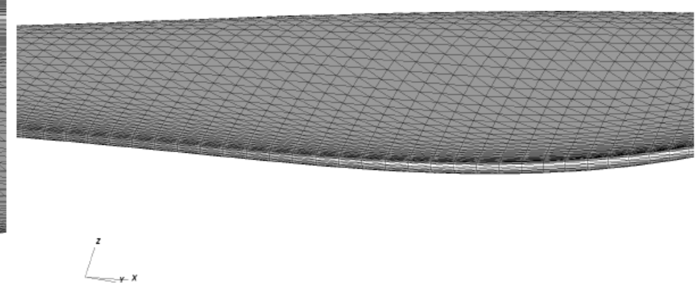
- Initial simulations showed vortices generated along span due to discrete representation (C0/C1 continuous at best)
- So we purchased the actual rotor to confirm shape
- And reconstructed sharper TE, added tip definition, and smoothed the spanwise curves



(c) Tip



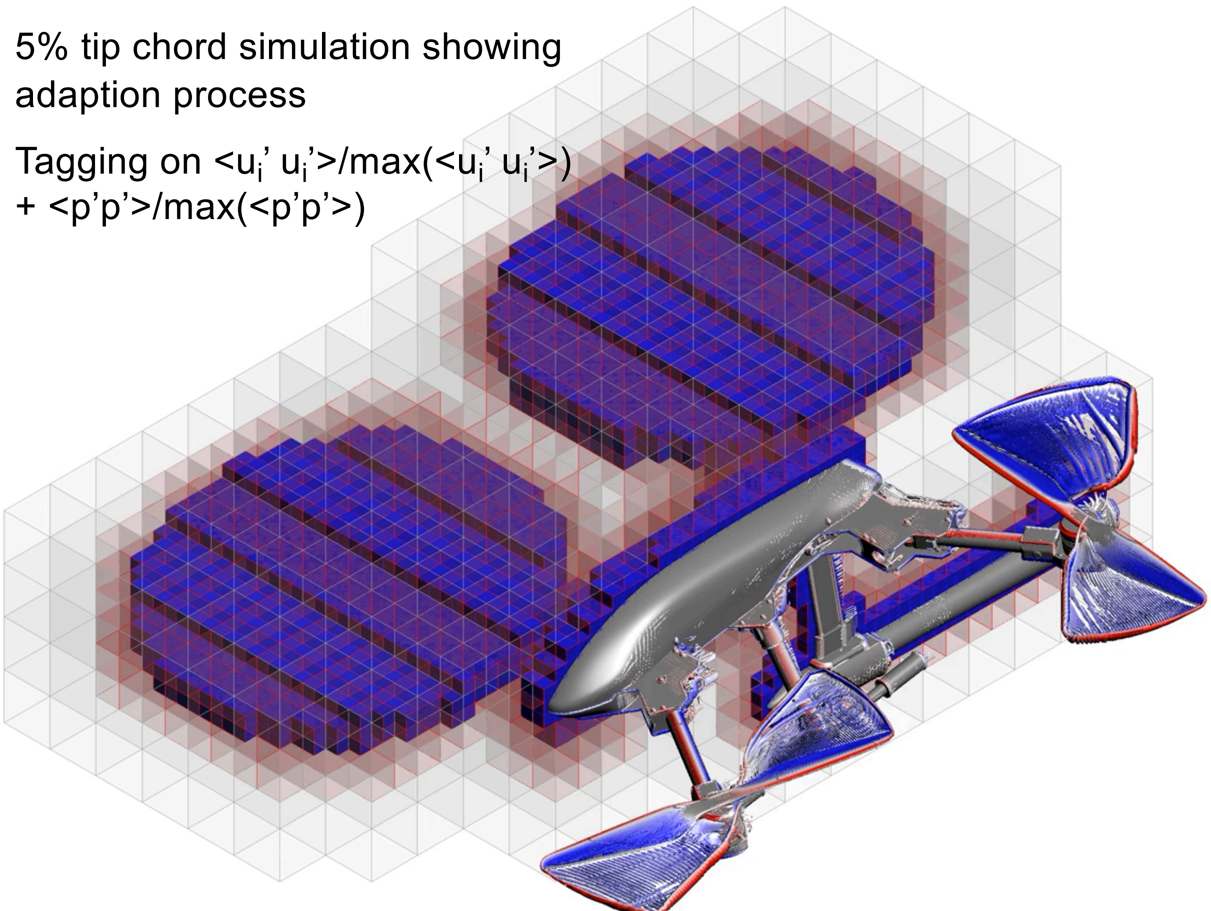
(d) Leading Edge



(e) Trailing Edge

Adaptive Mesh Refinement

- 5% tip chord simulation showing adaption process
- Tagging on <u_i' u_i'>/max(<u_i' u_i'>) + <p'p'>/max(<p'p'>)



- Left: 3 finest mesh levels box distribution
- Boxes each contain 32^3 cells

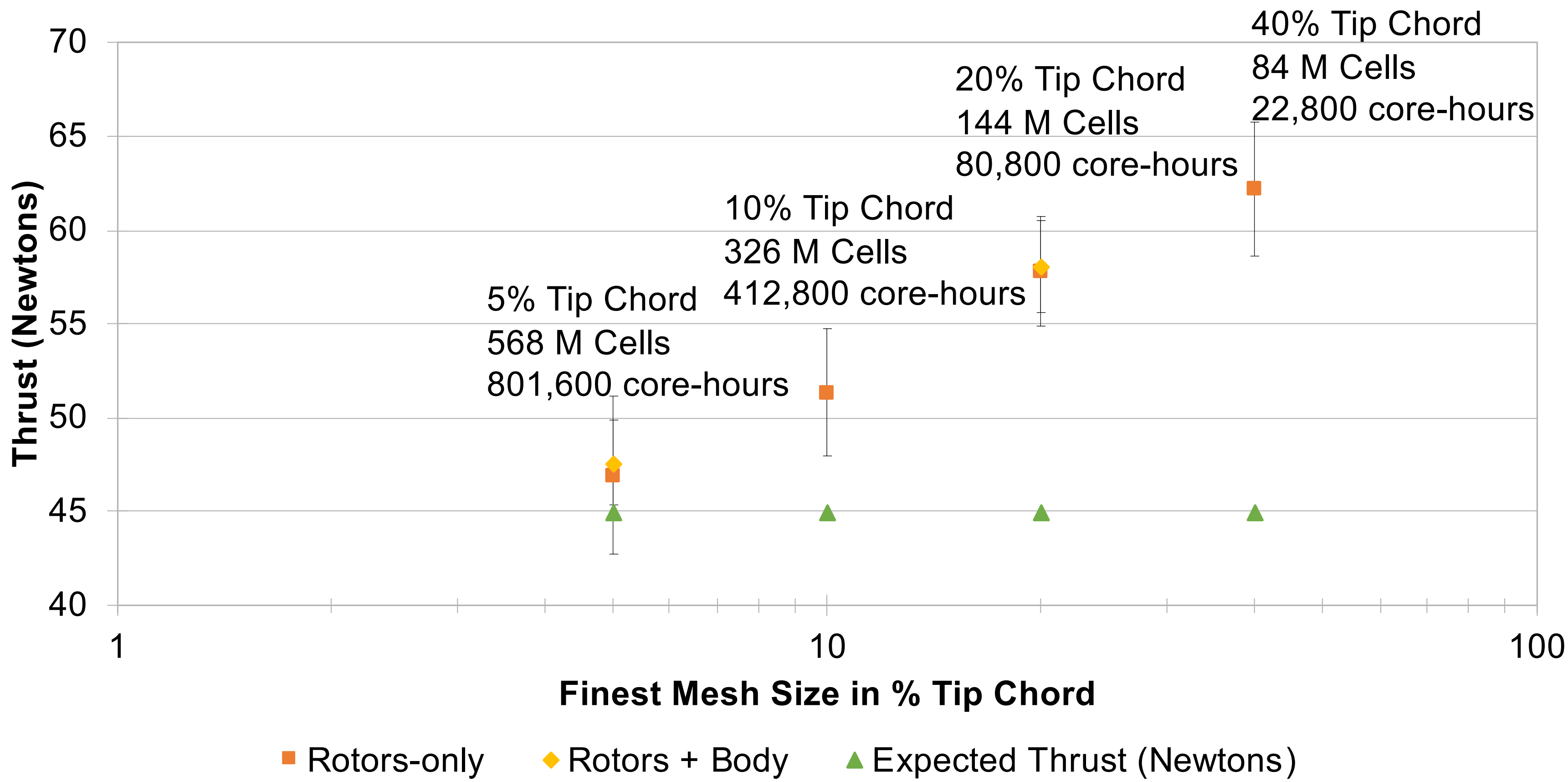
- Right: Isosurfaces of Q-Criterion colored by vertical velocity

Numerical Methodology

- d3Q27 with Entropic Multiple-Relaxation Time (EMRT) collision model
- Slip boundary condition on rotors and fuselage
  - $Re_c = \frac{\rho c_t 2\Pi R\Omega}{\mu} \approx 50{,}000$ → tiny laminar and maybe transitional boundary layer on rotor
  - body-fitted RANS results for isolated rotor show the pressure forces dominate over viscous by nearly 3 orders of magnitude
- Set finest level of mesh on 4 cylinders to cover each rotor
- Regrid every ~45 degrees of slowest rotor to follow areas of high $\langle p'p' \rangle$ and $\langle u_i' u_i' \rangle$ based on on-the-fly statistics
- Set maximum mesh spacing to 40% tip chord resolution everywhere within the FWH surface to ensure we can capture waves up to 18 kHz

Animation Credit: Timothy Sandstrom

Mesh Convergence of Thrust



*Error bars on CFD represent RMS of thrust, not a measure of discretization error

LBM Performance For Quadcopter

Simulation	Resolution (% tip chord)	# of cells	# of time steps performed	Wallclock time (hours)	Core Hours	Cells updated per second	Cells updated per second per core
Rotors + Body	40	8.37E+07	67793	28.5	22800	5.53E+07	6.91E+04
Rotors + Body	20	1.44E+08	135587	50.5	80800	1.07E+08	6.70E+04
Rotors + Body	10	3.26E+08	273408	129	412800	1.92E+08	5.99E+04
Rotors + Body	5	5.68E+08	542347	125.25	801600	6.83E+08	1.07E+05

*Performance is limited by output to disk (volume files are large and slow to write), and writing out surfaces of 1.3 Million triangles often is costly too

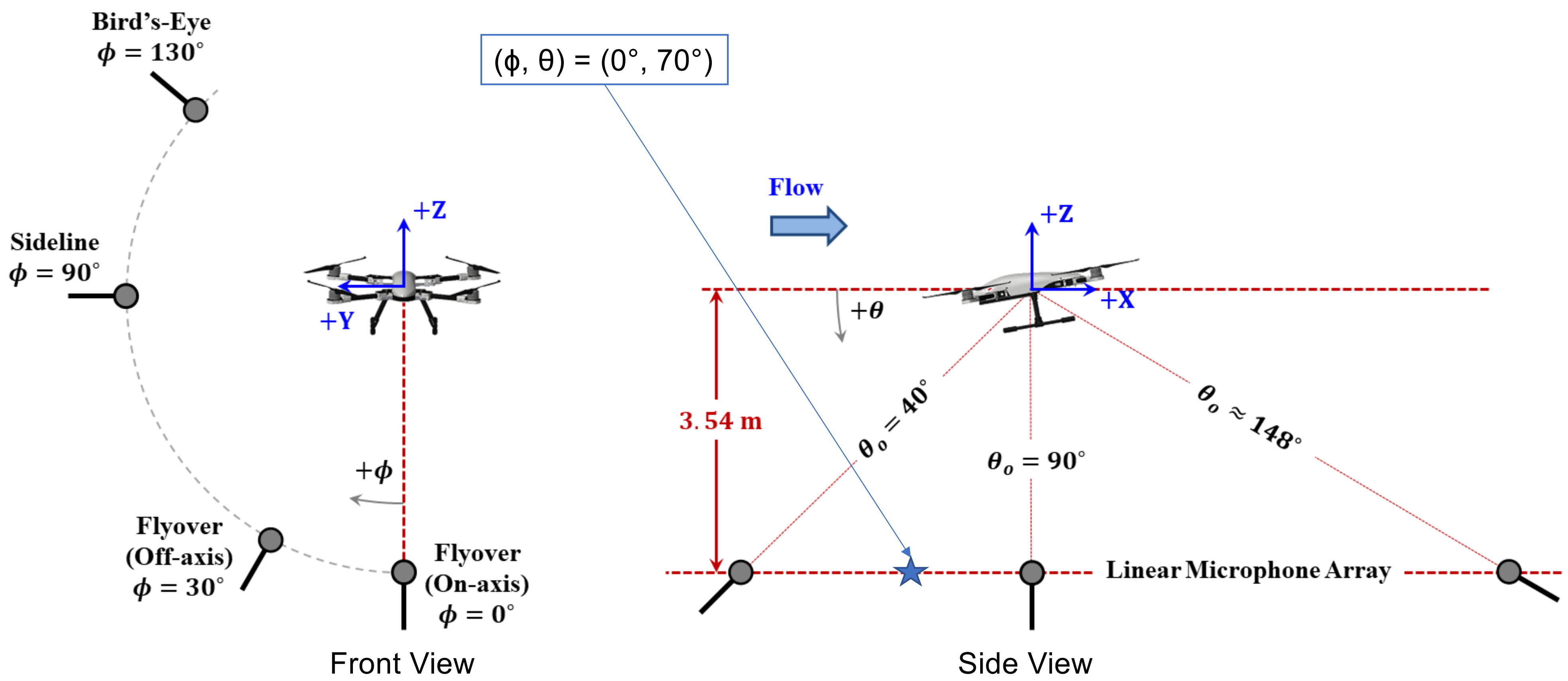
Acoustic Prediction Methodology

- Perform simulation for 4 revolutions of slowest rotor (~4000 RPM) to flush out transient, then continue an additional 0.4 seconds (~30 revolutions) for acoustics

- Interpolate solution onto FWH surface triangulation and save it to disk at regular time interval allowing for ~ 20kHz maximum frequency

- Propagate to observers using fully parallelized FWH integrand in frequency domain for intervals of 0.2 seconds (Δf = 5 Hz) with 75% overlap using Hanning window (parameters chosen to match experiment)

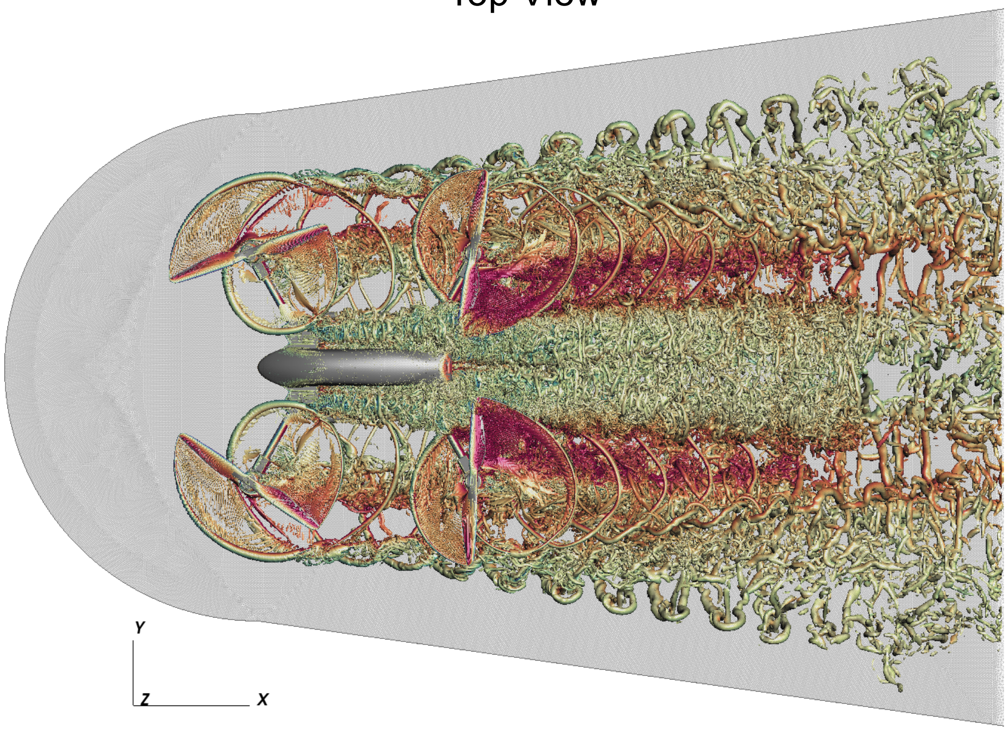
Microphone Location



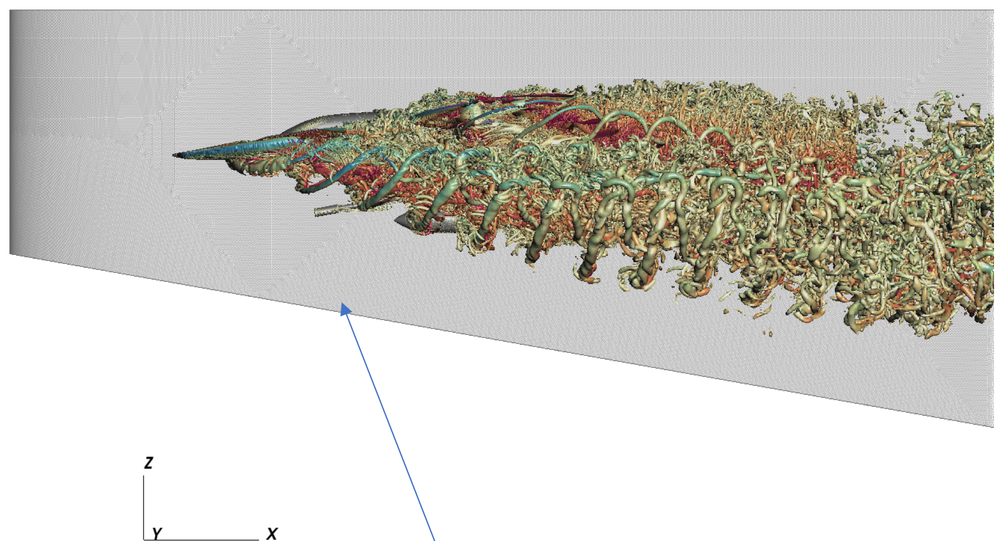
Images courtesy of Nikolas Zawodny

Far-Field Noise Propagation with FWH

Top View



Side View

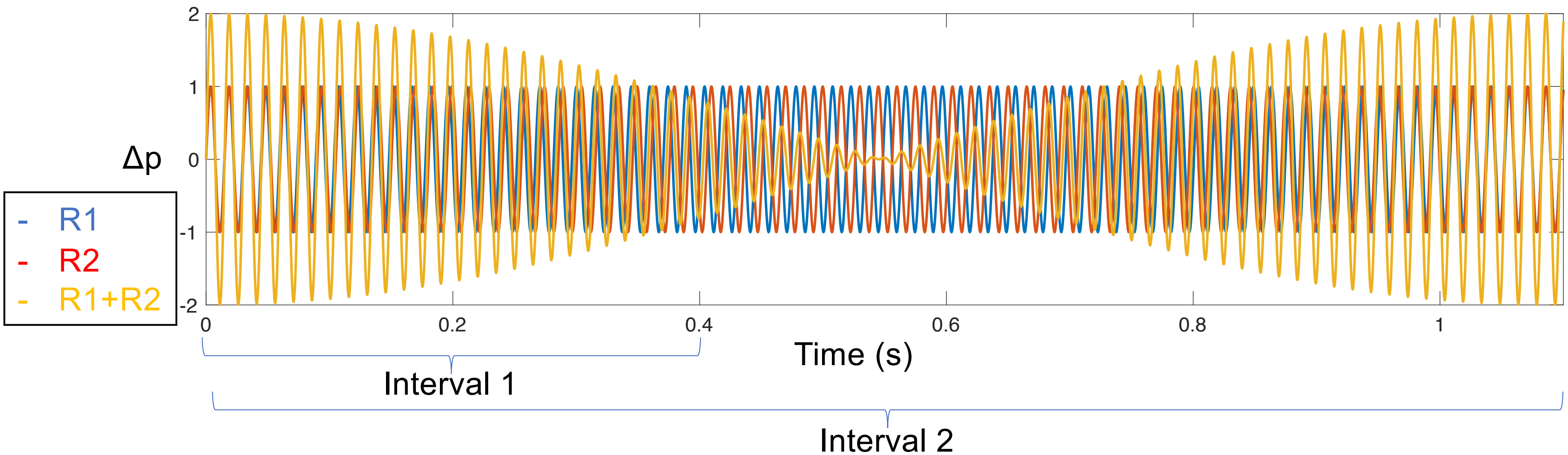


40% tip chord triangle edge length to capture up to 20 kHz

1.37 Million triangles

Differences in Acoustic Spectra Between CFD and Experiment

- Beat phenomenon is observed due to slight differences in rotation rate for front rotor pair (period of ~1.1 seconds), and rear rotor pair (period of ~1.4 seconds)



→Spectra for R1+R2 from interval 1 will be different than interval 2

→For the same reason we expect differences between spectra from 0.4 seconds interval of CFD to be different from 12 seconds of experimental data

→Where non-linear interactions are present, these differences can propagate from BPF to higher frequencies, affecting the broadband content as well

Broadband Noise in Experiment

- Most of the broadband noise comes from rotor self-noise and superposition in R1 + R3, but there is a non-linear increase in broadband noise when both rotors are spinning at the same time in R1 & R3

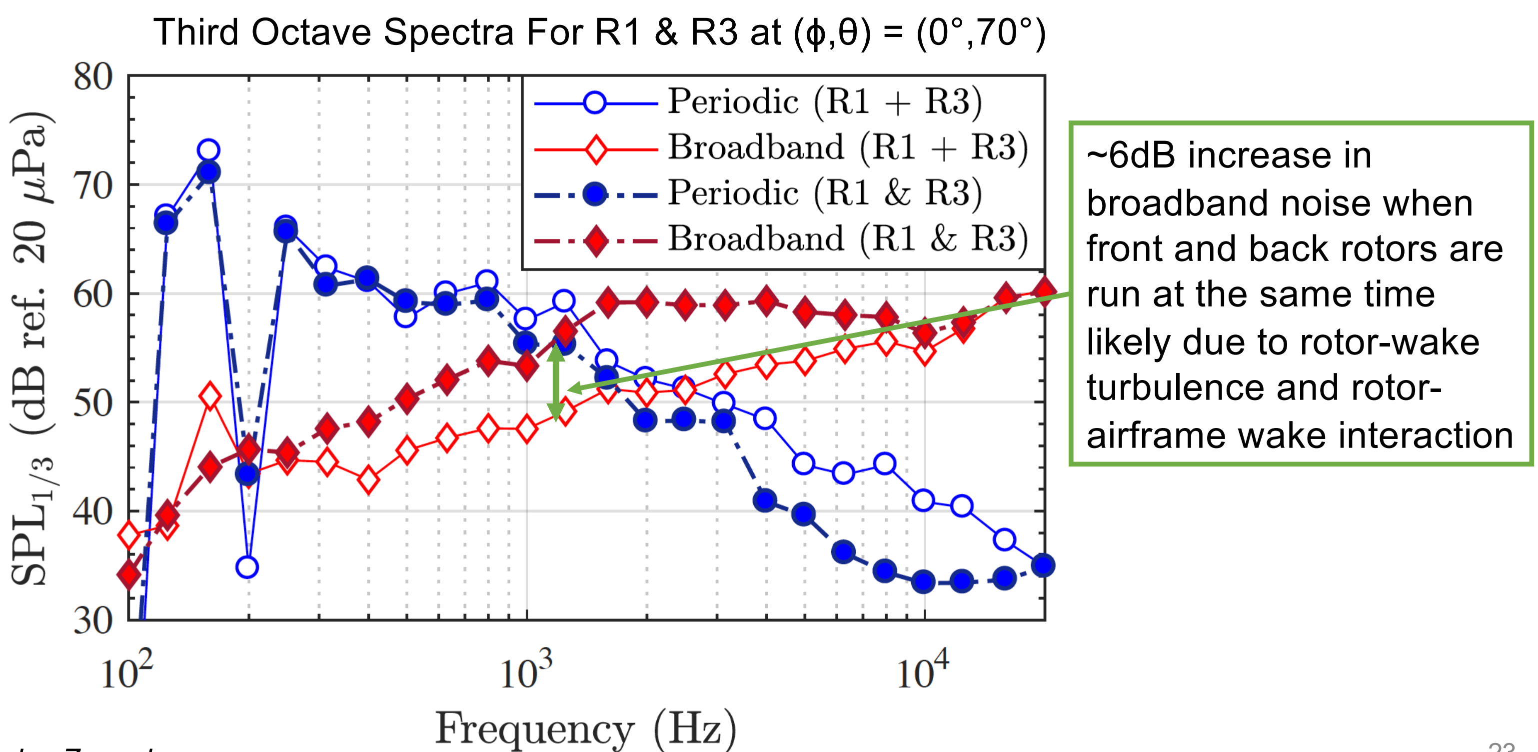
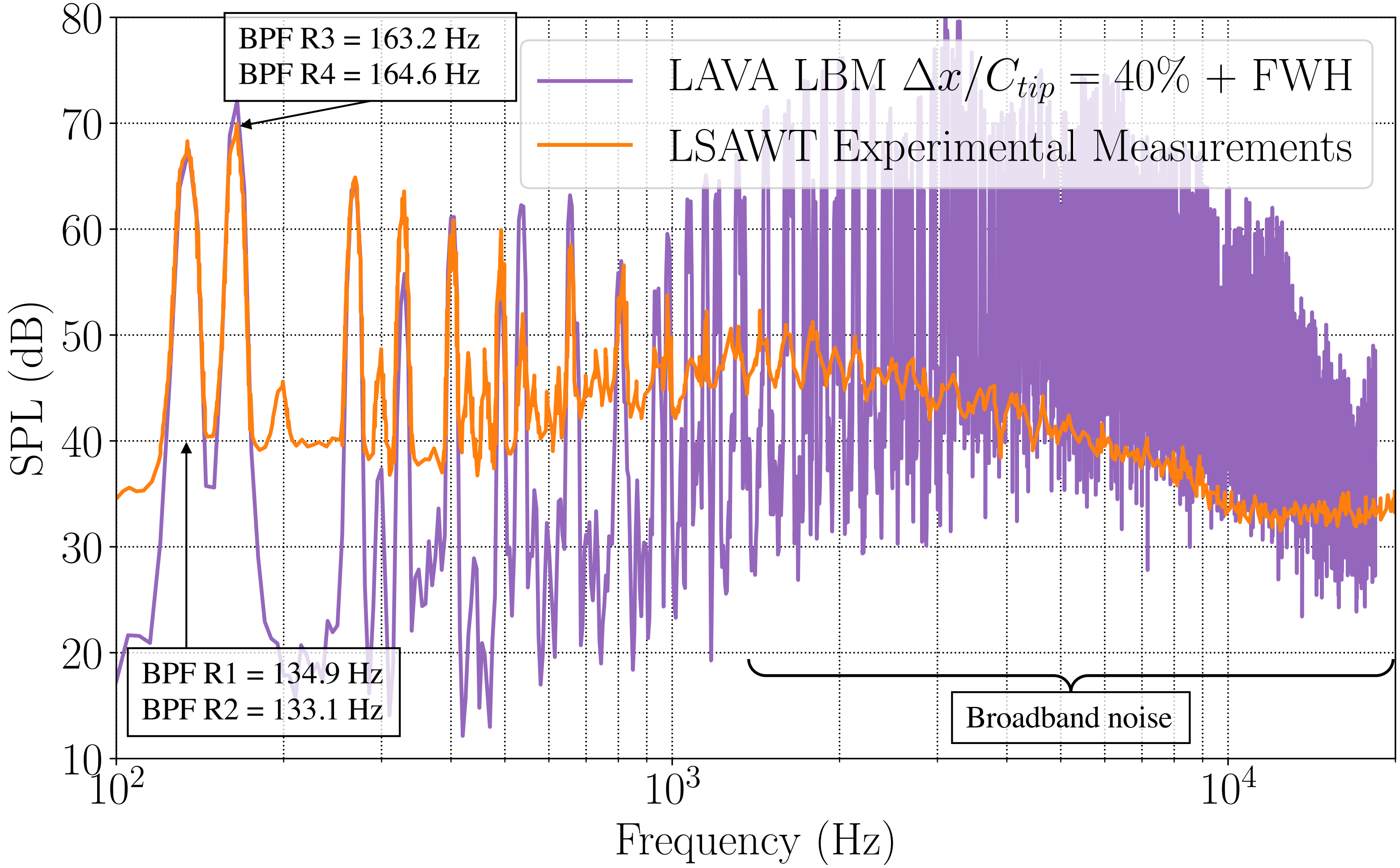
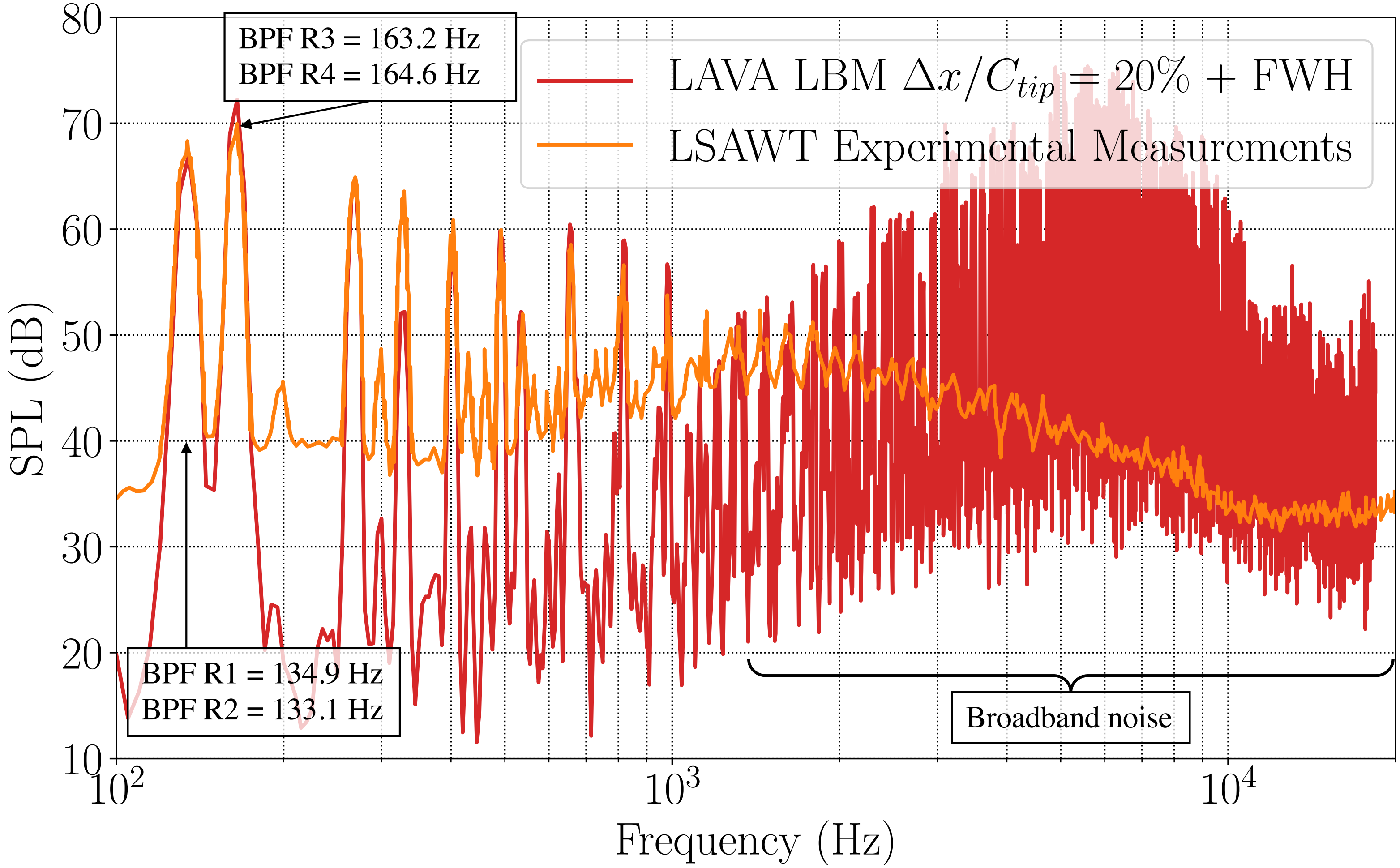


Image courtesy of Nikolas Zawodny

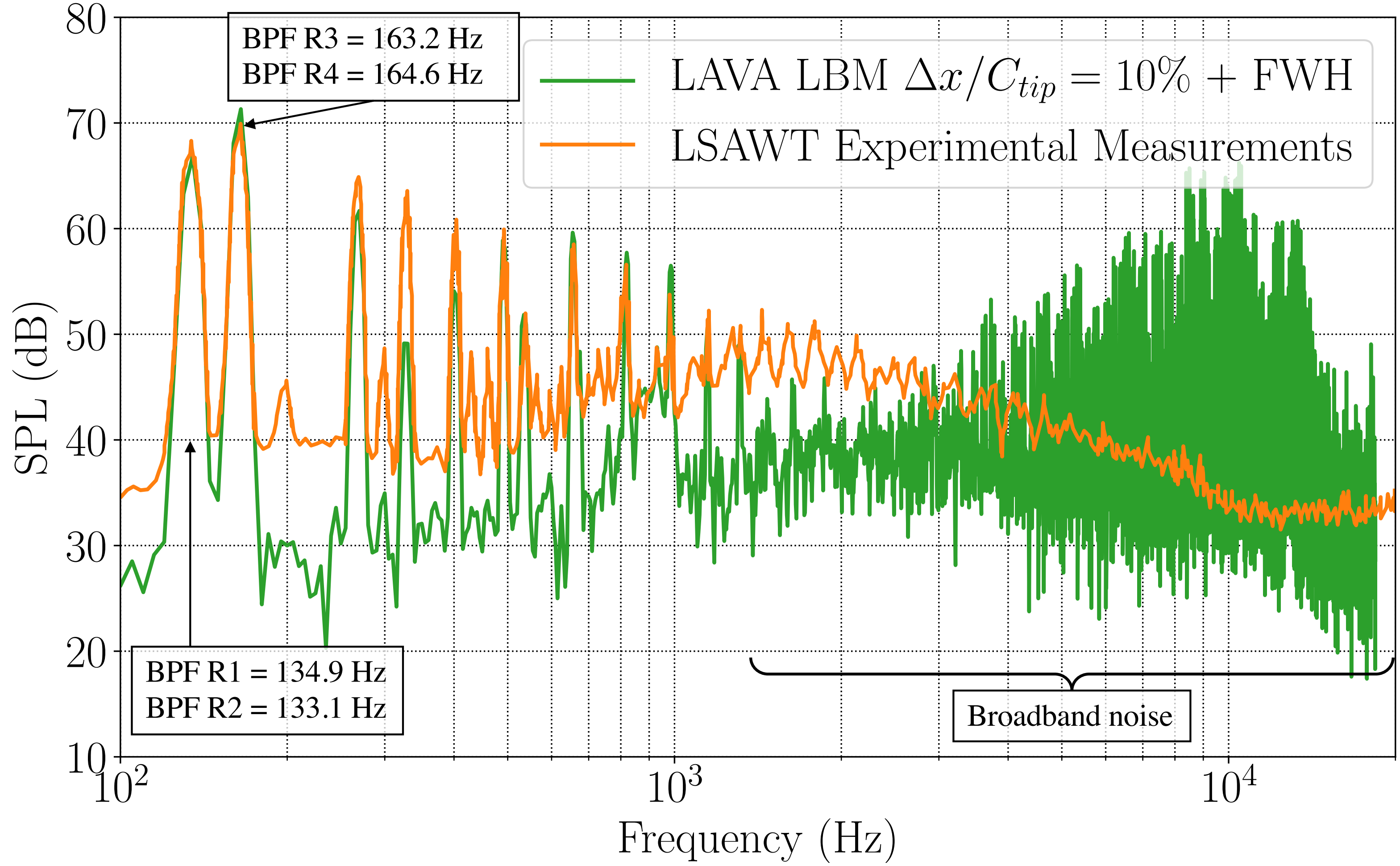
FWH Narrow-Band Spectra at (ϕ,θ) = (0°,70°)



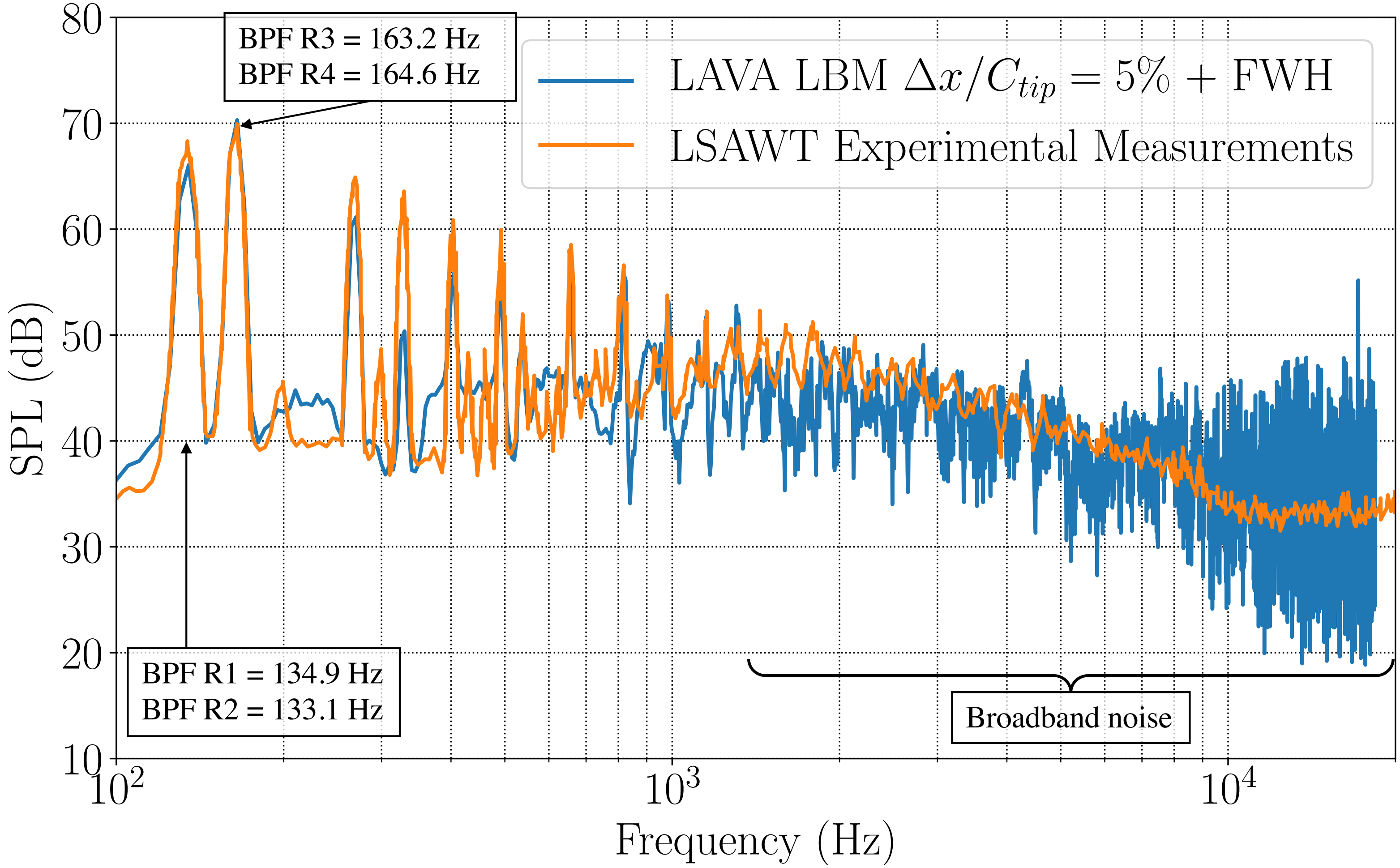
FWH Narrow-Band Spectra at (ϕ,θ) = (0°,70°)



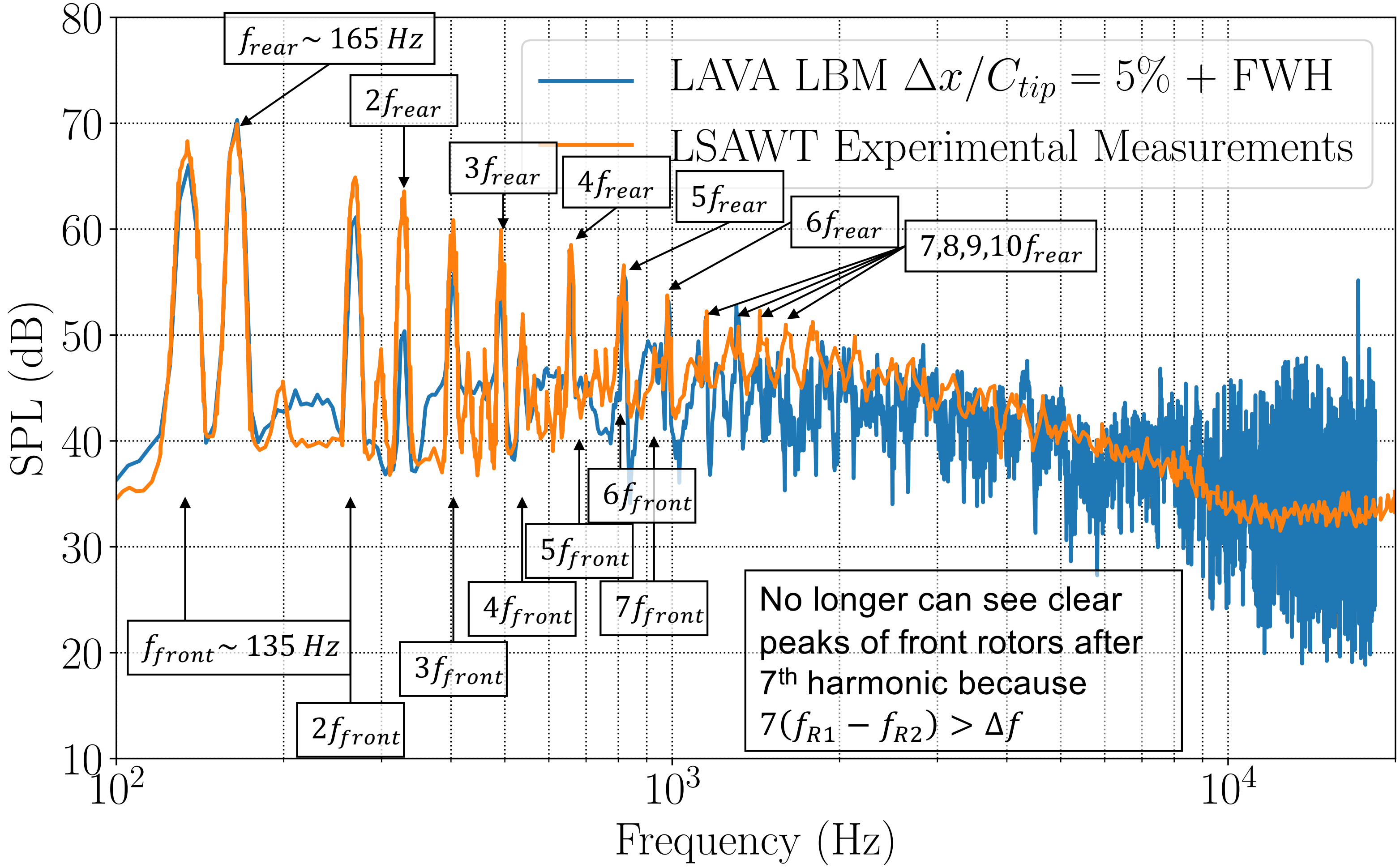
FWH Narrow-Band Spectra at (ϕ,θ) = (0°,70°)



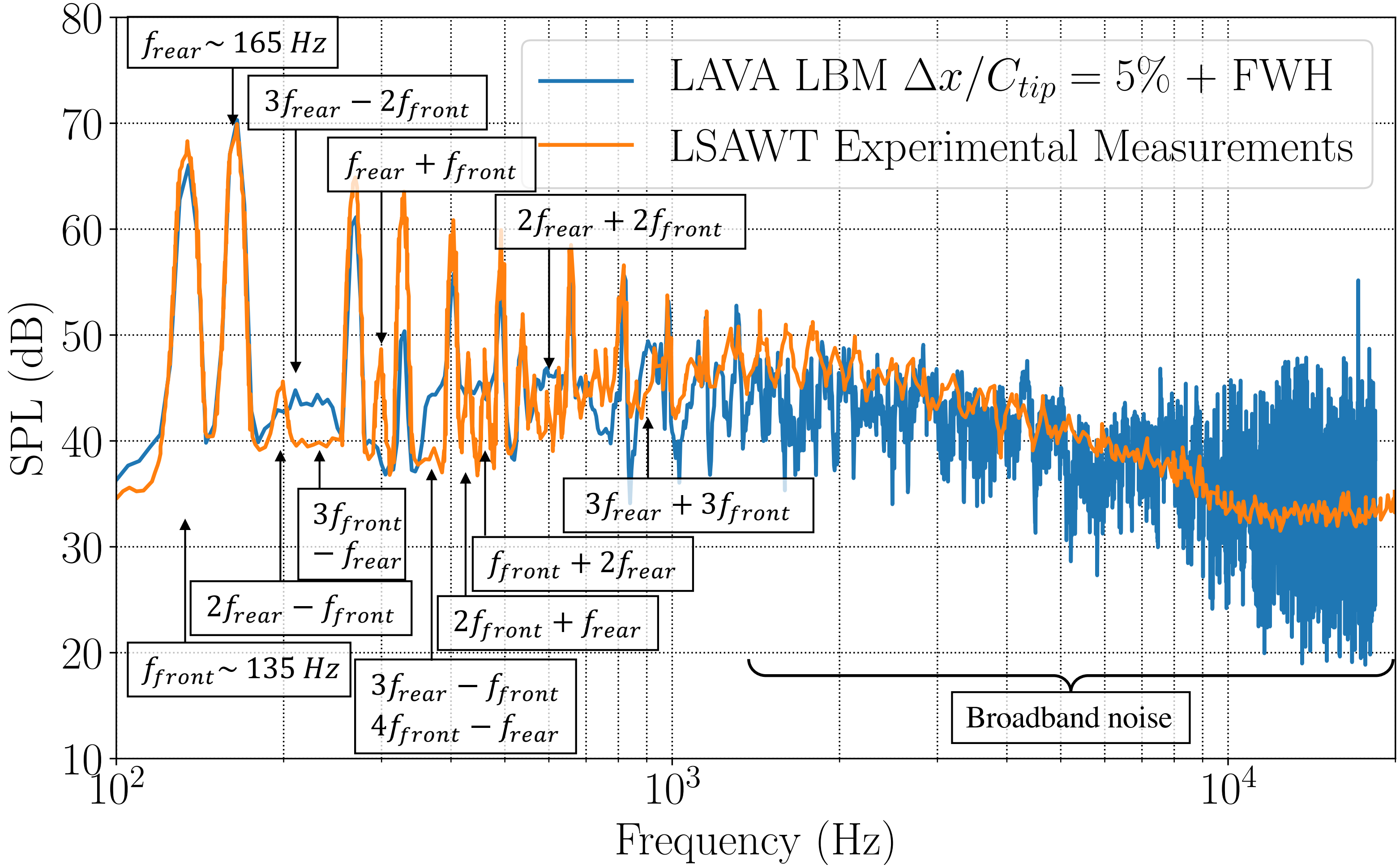
FWH Narrow-Band Spectra at (ϕ,θ) = (0°,70°)



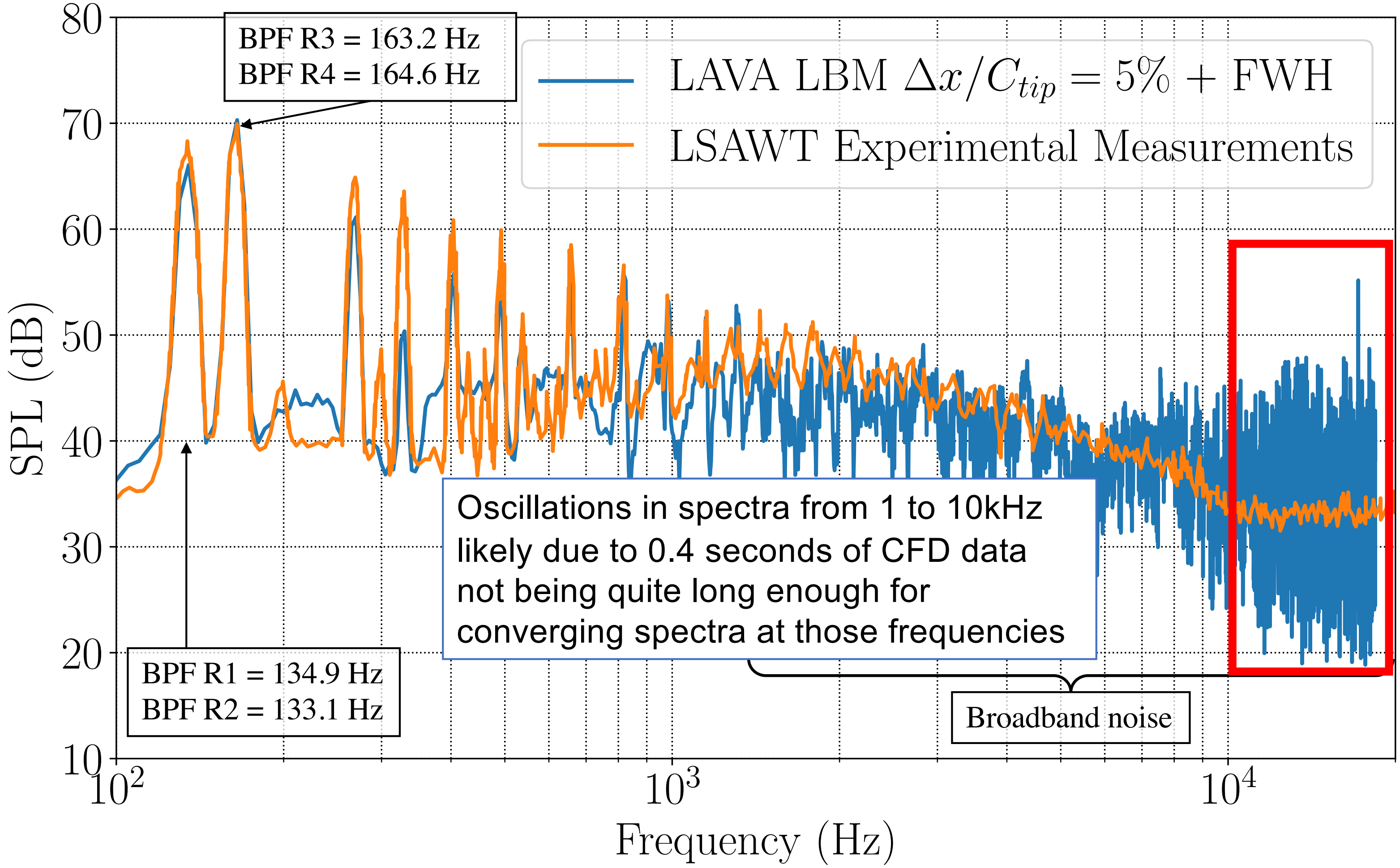
Harmonics for (ϕ,θ) = (0°,70°)



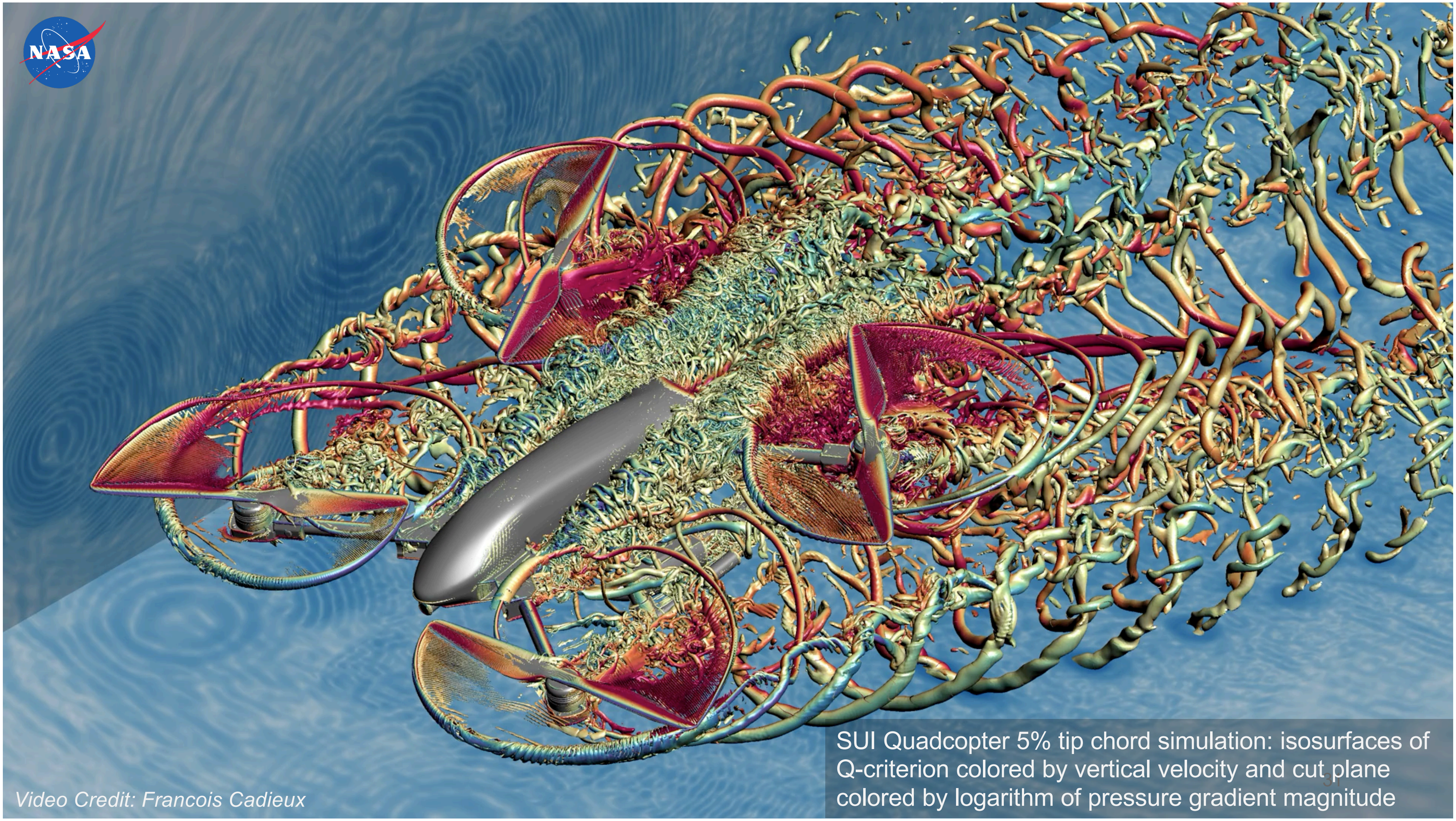
Rotor-rotor Interactions at (ϕ,θ) = (0°,70°)



FWH Narrow-Band Spectra at (ϕ,θ) = (0°,70°)



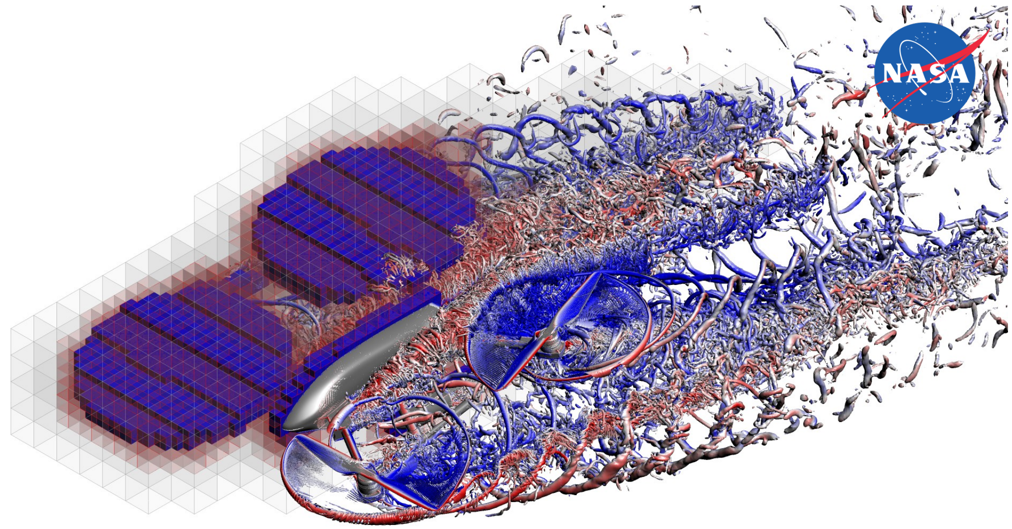
Large oscillations in spectra beyond 10kHz likely due to aliasing because we don't sample every time step (36 kHz in CFD versus 80 kHz in experiment)



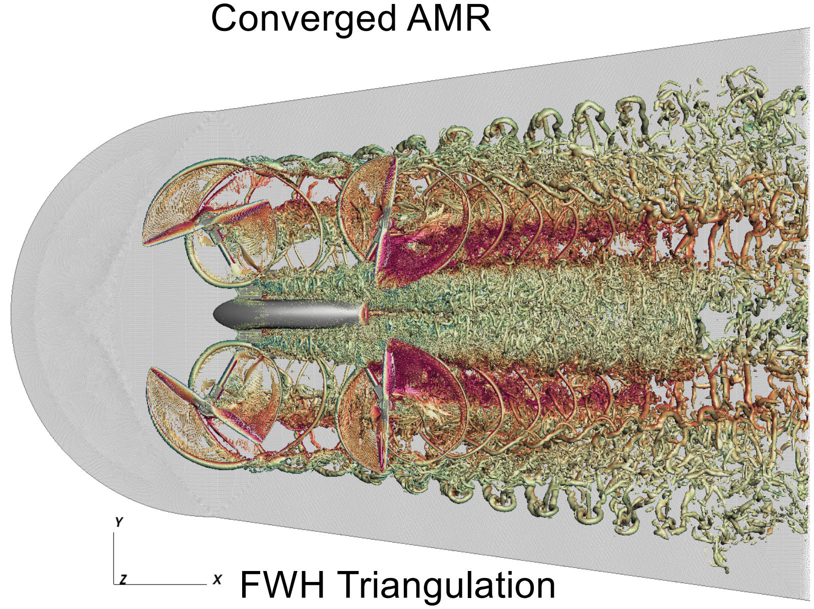
SUI Quadcopter 5% tip chord simulation: isosurfaces of Q-criterion colored by vertical velocity and cut plane colored by logarithm of pressure gradient magnitude

Challenges

- Fine-to-coarse transitions can affect acoustics because numerical dissipation is related to the grid size
- AMR is great as long as it converges quickly in time average, otherwise, it can affect acoustics rather unpredictably
- FWH surface shape and placement is still based on experience rather than physics → need a tool to use simulation statistics to automatically design FWH surface based on solution and CFD mesh size



Converged AMR



FWH Triangulation

Ongoing & Future Work

- Compare predictions to other microphone locations once we receive experimental data

- Improve slip boundary condition (higher order) to converge thrust more quickly while remaining robust for under-resolved curvature

- Complete 2.5% tip chord simulation with higher sampling rate and better boundary condition (contingent on funding and/or computer time)

Concluding Remarks

- Coupled with far-field acoustic propagation in the Launch, Ascent and Vehicle Aerodynamics (LAVA) framework, ***LBM successfully predicted tonal noise levels and captured broadband noise trends accurately for the first time*** *for small multi-rotor vehicle with a complex fuselage*

- Key to this success was ***high resolution in space and time, low dissipation****, and* ***conservative coarse-fine interfaces***

- ***LBM is attractive because it is the only tool to demonstrate it can capture complex rotorcraft noise trends at high frequencies so far***, but it's rather expensive for aerodynamic performance and tonal noise

Acknowledgments

- Special thanks to Nikolas Zawodny for a fruitful collaboration, and for providing the quadcopter CAD geometry as tested in the wind tunnel, along with figures describing the experiment for use in this presentation
- Funding was provided by the Revolutionary Vertical Lift Technologies (RVLT) project, and by the Transformational Tools and Technologies (T^3) project
- Gerrit Stich and Jeffrey Housman for helpful discussions and guidance on FWH far-field noise propagation, as well as Gaetan Kenway for reconstructing the rotor geometry