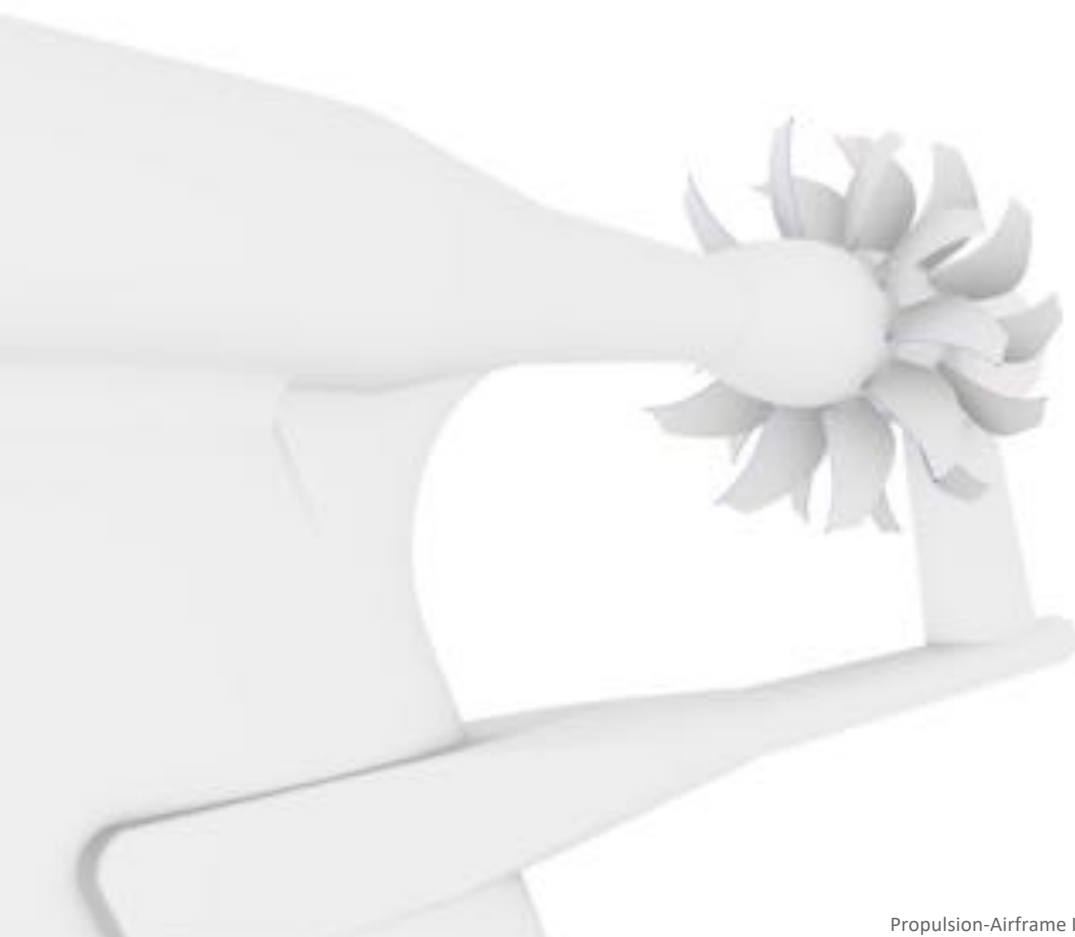
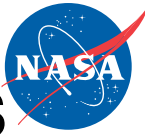
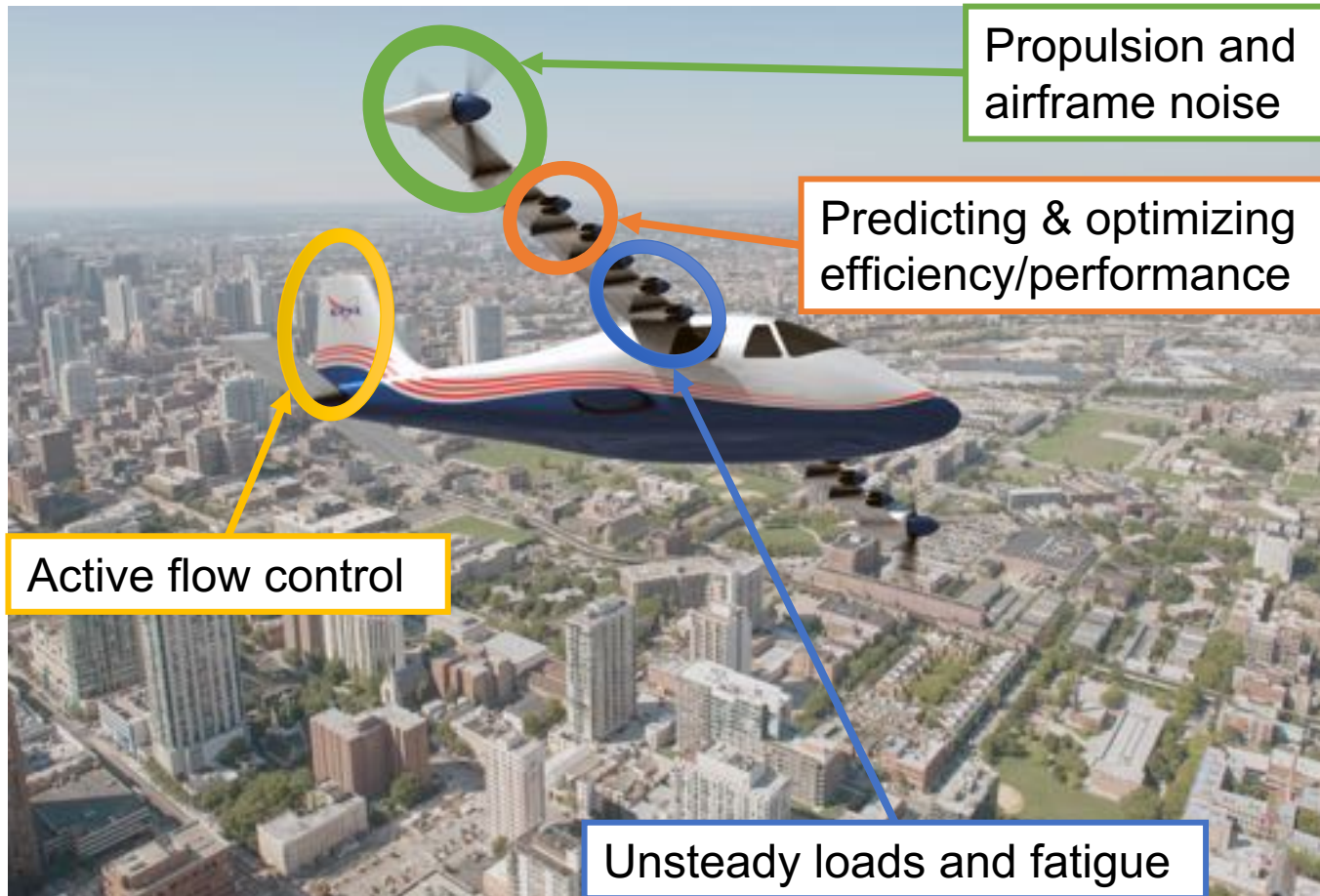


# COMPUTATIONAL STRATEGIES TO SUPPORT PROPULSION-AIRFRAME INTEGRATION APPLICATIONS



**Francois Cadieux**  
**Cetin Kiris**  
Computational  
Aerosciences  
Branch, NASA  
Ames Research  
Center

# Challenges of PAI

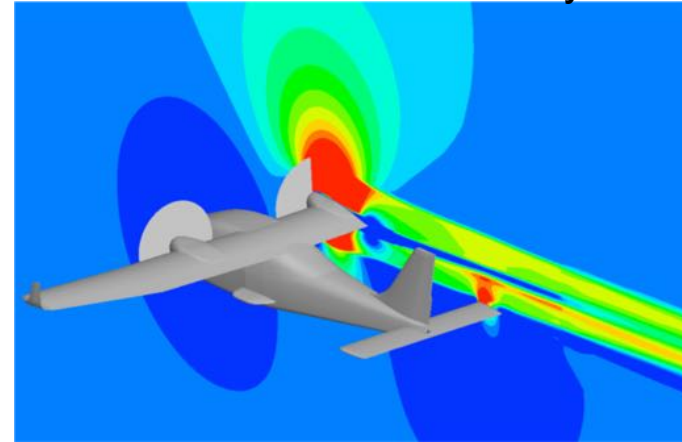


# Choosing the Right Strategy

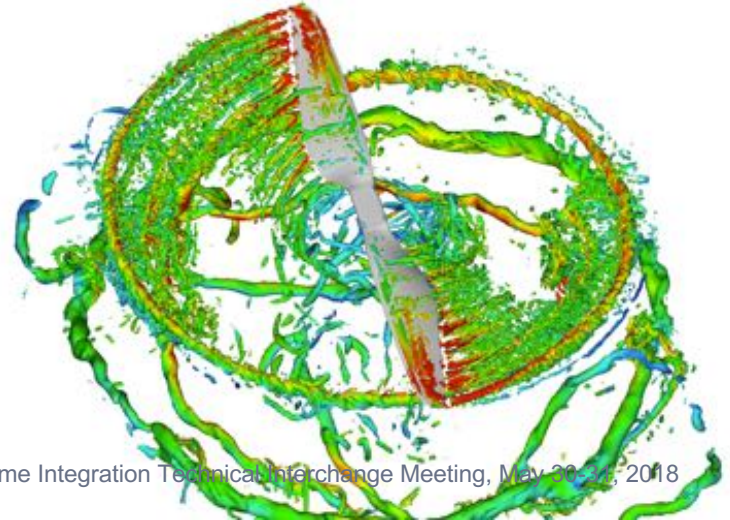


- Fidelity changes with design stage
  - Conceptual/preliminary/detailed design
  - Performance analysis versus noise prediction
- Grid paradigm
  - Grid generation time
  - Boundary layer resolution
- Delivering “on time and on budget”
  - Understand computational req’s of different tools
  - Limit scope of trade studies, design optimizations, and aero-databases

## Viscous Performance analysis

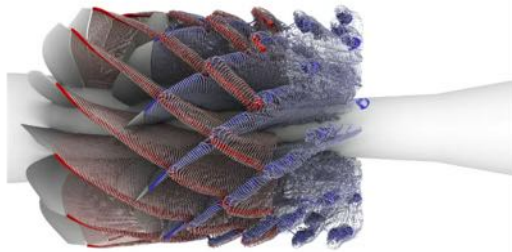
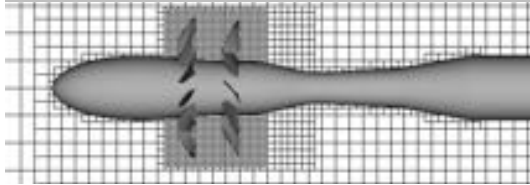


## Noise Prediction



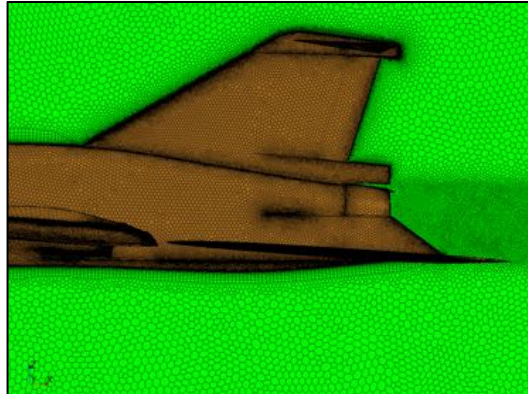
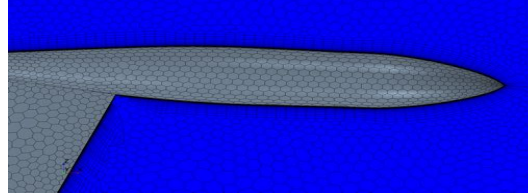
# Choosing The Best Grid Paradigm

*Structured Cartesian*



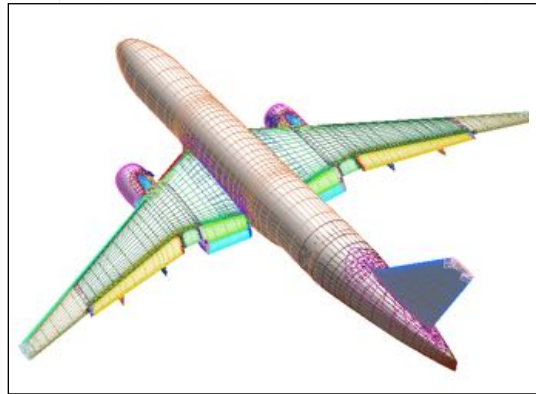
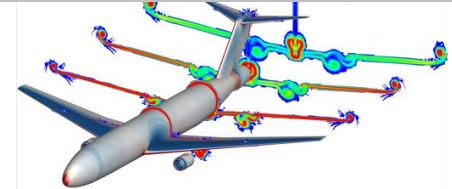
- Automatic grid generation with Adaptive Mesh Refinement
- Low computational cost
- Reliable higher order methods
- **Non-body fitted → Resolution of boundary layers inefficient**

*Unstructured Arbitrary Polyhedral*



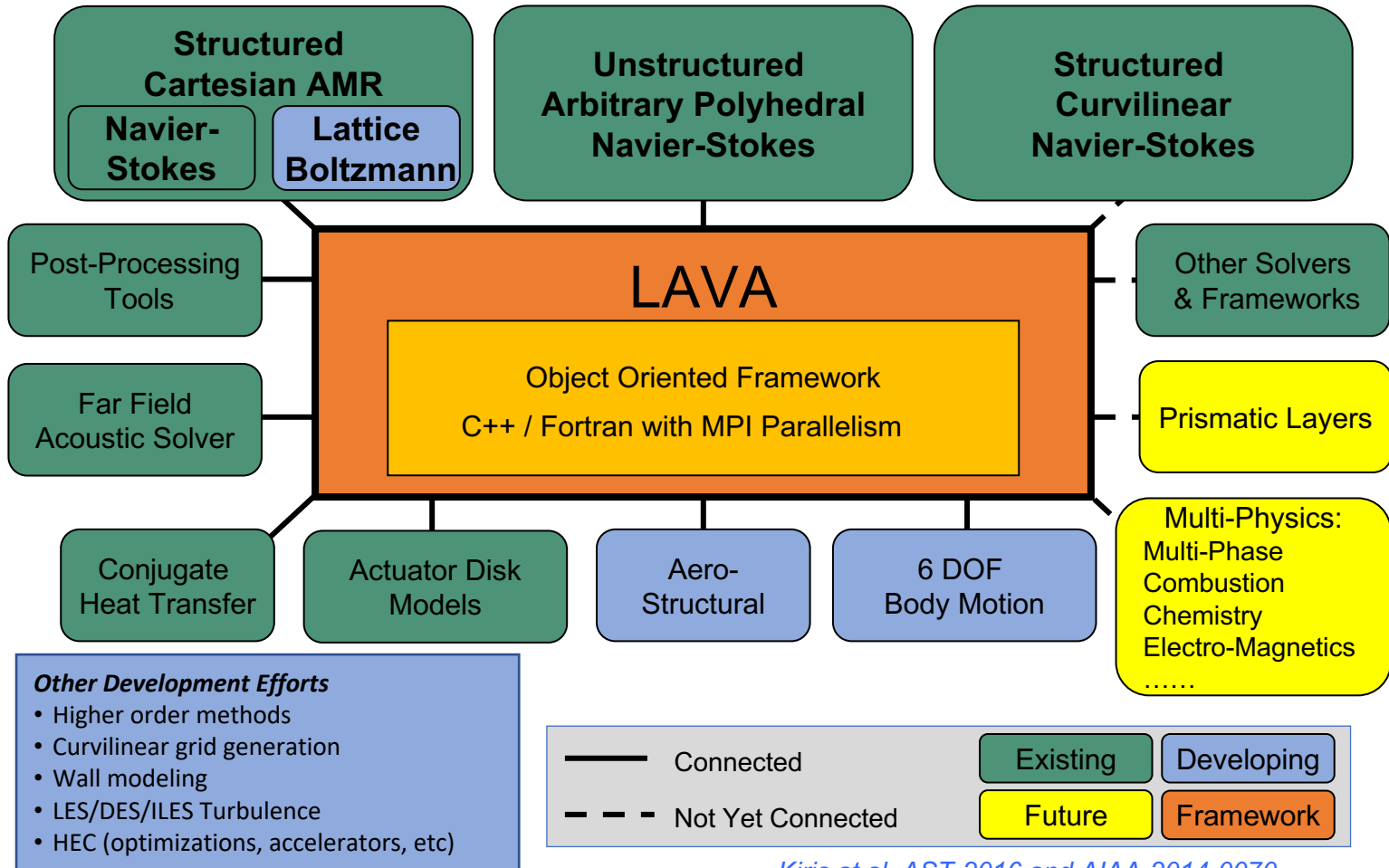
- Partially automated grid generation
- Body fitted grids
- **Grid quality can be challenging**
- **High computational cost**
- **Higher order methods yet to fully mature**

*Structured Curvilinear*



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

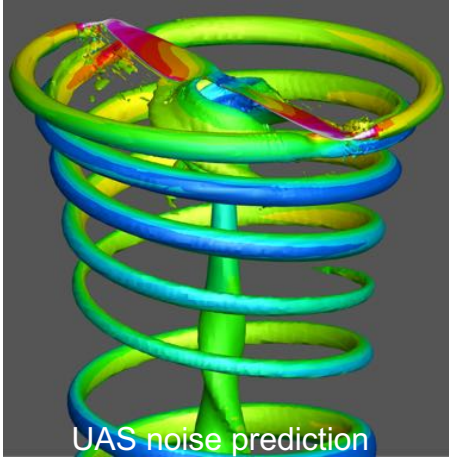
# Launch, Ascent, and Vehicle Aerodynamics (LAVA)



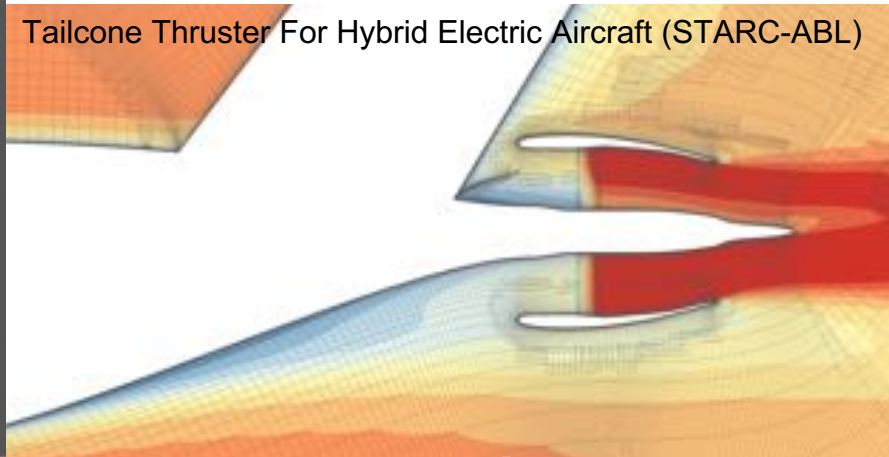
*Kiris at al. AST-2016 and AIAA-2014-0070*



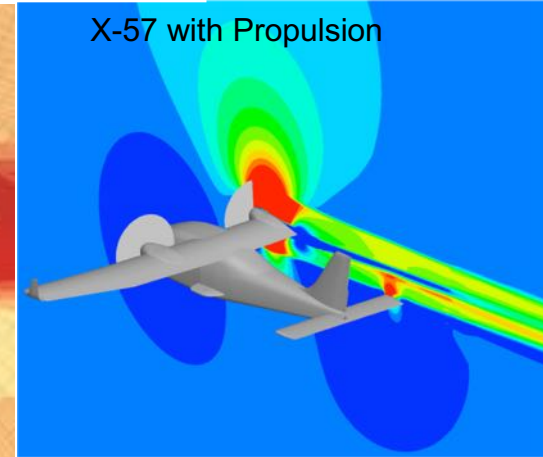
# Recent Examples of Performance Analysis, Design Optimization and Noise Prediction with LAVA



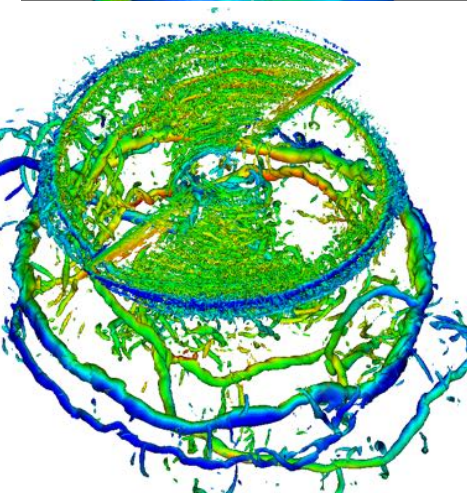
UAS noise prediction



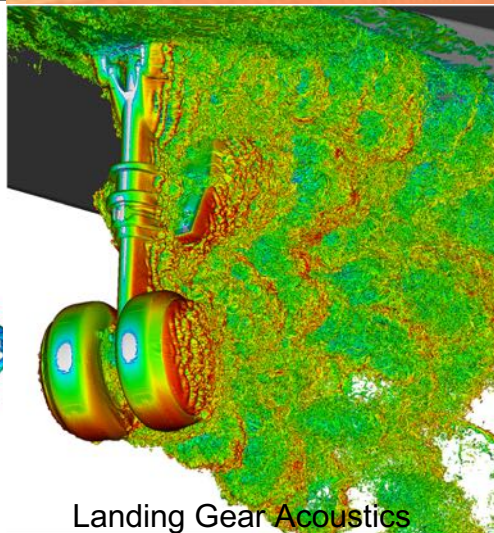
Tailcone Thruster For Hybrid Electric Aircraft (STARC-ABL)



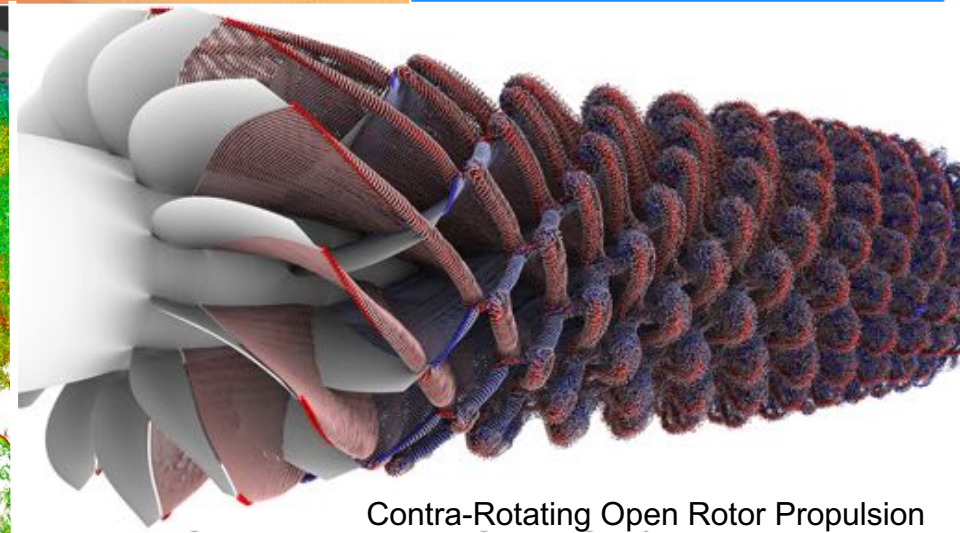
X-57 with Propulsion



UAS noise prediction



Landing Gear Acoustics



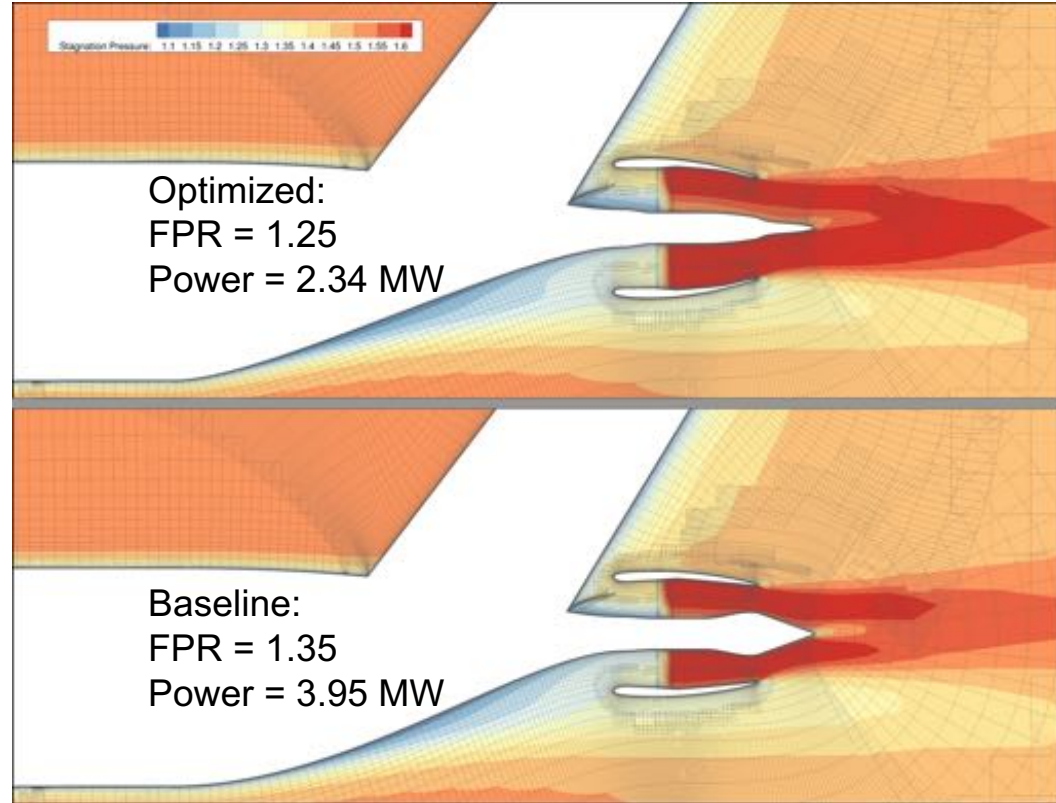
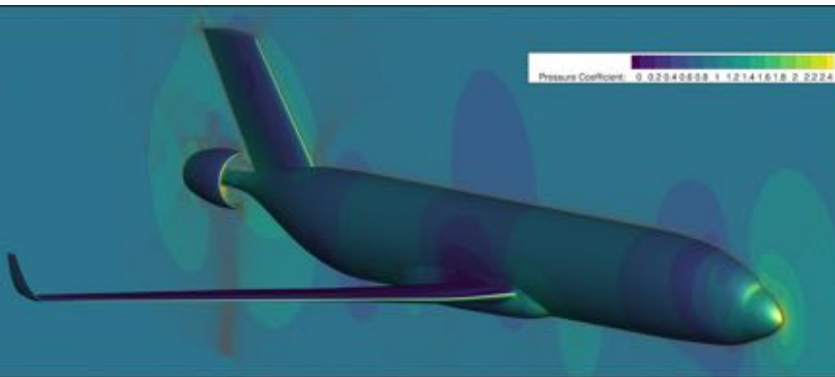
Contra-Rotating Open Rotor Propulsion



**From conceptual to detailed design**

# **HIGH FIDELITY VISCOUS STEADY DESIGN OPTIMIZATION**

# Aeropropulsive Optimization of STARC-ABL with OpenMDAO





# Propulsor Modeling



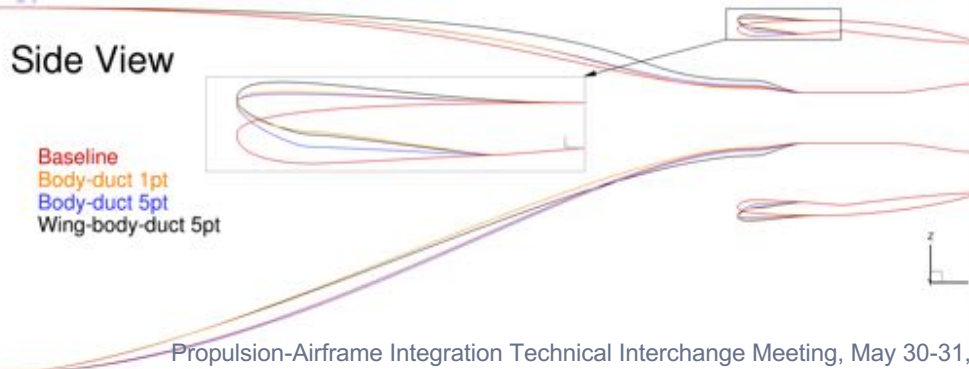
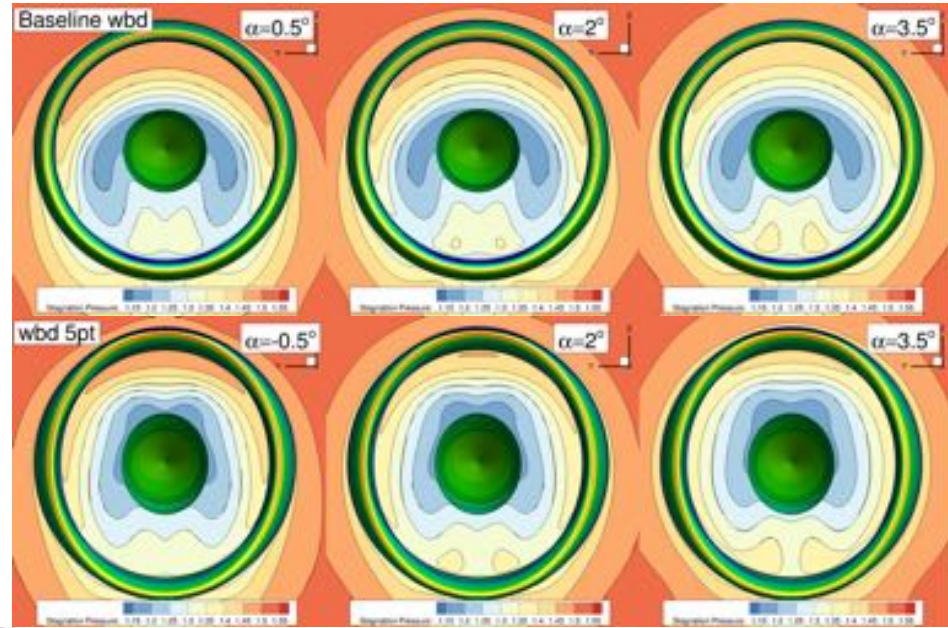
## Actuator zone source term:

- **Equations solved are consistent in space, only add momentum and energy source**
- **Different models for different level of fidelity:**
  - Constant thrust or mass flow rate
  - Torque: Goldstein optimum radially varying tangential force
  - 2D blade element theory with specified loading or airfoil table
  - David Hall model if blade shape and RPM is known
- **Stators can be modeled with zone with no thrust and torque in opposite direction**
- **Input thrust and torque can be tied to NPSS output or other engine model**

# STARC-ABL Shape Optimization To Reduce Inlet Distortion



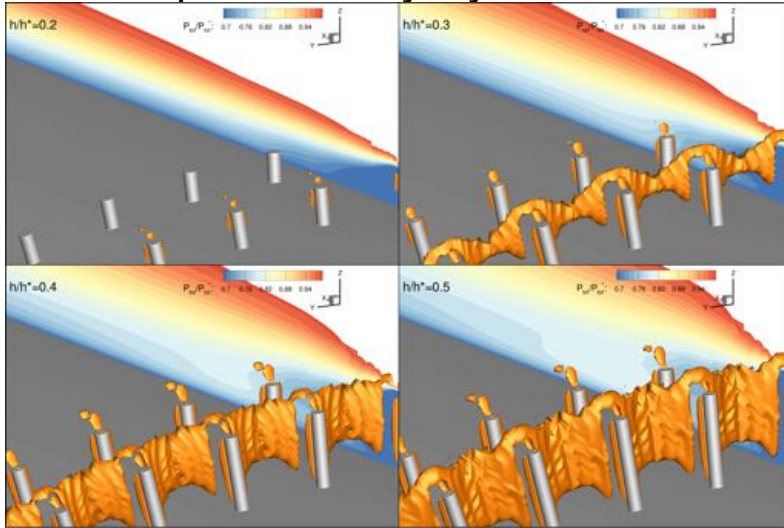
- Parametric description of fuselage and inlet shape with thickness constraints
- Optimized shape reduces distortion by 50% at cruise
- Overset build-up approach helped identify effect of wing on distortion



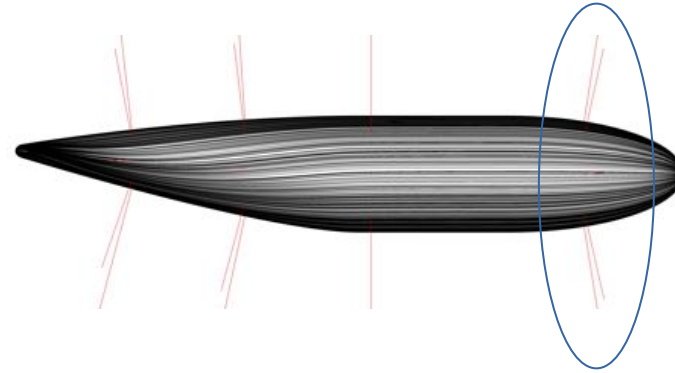
# Tail Cone Thruster (TCT) Wind Tunnel Support



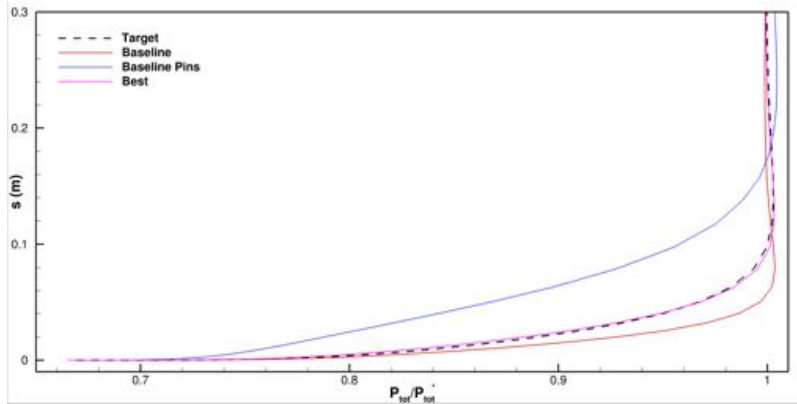
Two-row pin boundary layer thickener



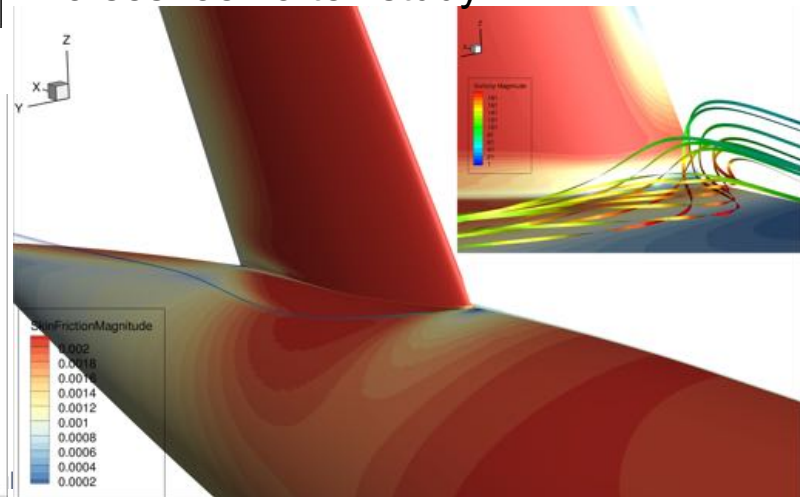
Match total pressure at 5 rake locations

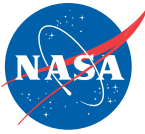


We are able to match target boundary layer



Horseshoe vortex study





**From preliminary to detailed design**

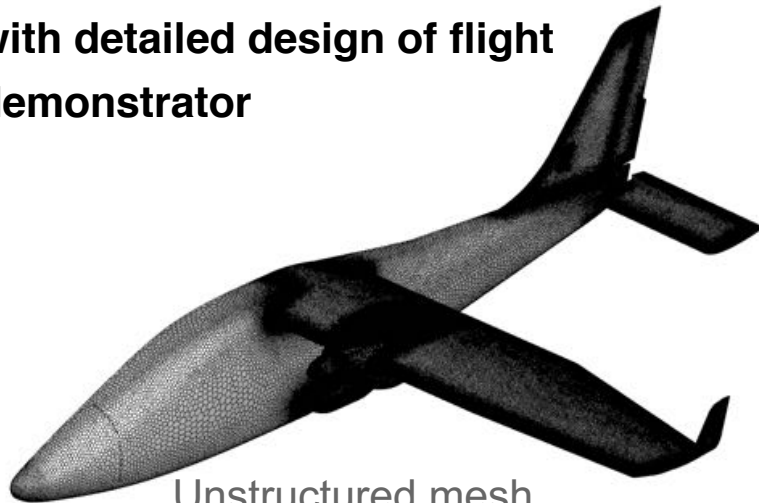
# **HIGH FIDELITY VISCOUS STEADY PERFORMANCE ANALYSIS**



# X-57 Electric Research Aircraft



- **Predict X-57 performance for a variety of flight scenarios and propulsion configurations**
- **Validate CFD with wind tunnel experiments and across solvers**
- **Help aircraft designers at Armstrong with detailed design of flight demonstrator**

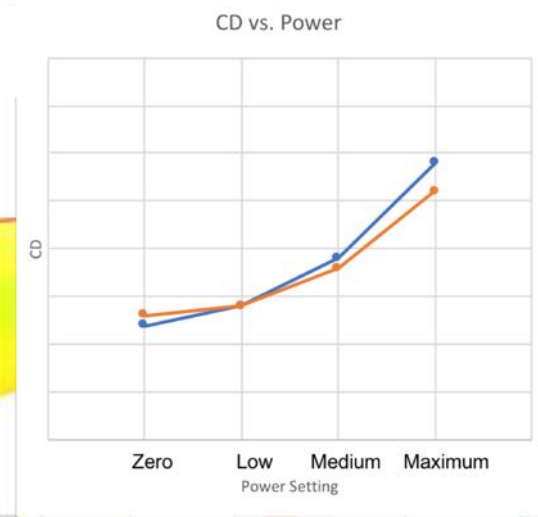
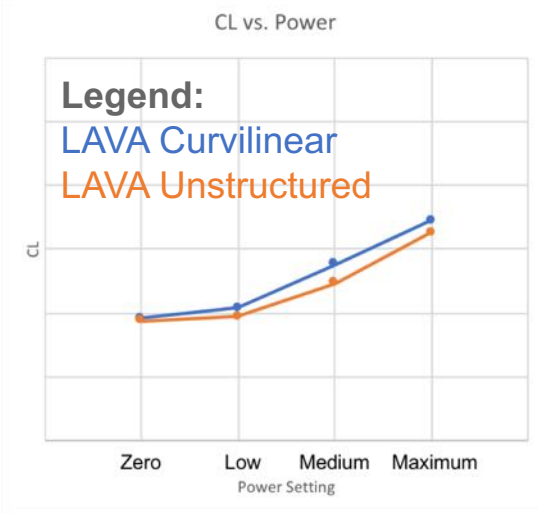
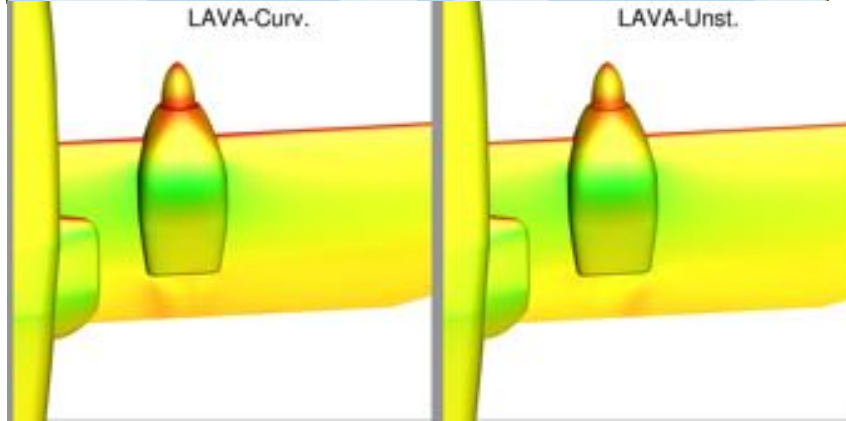
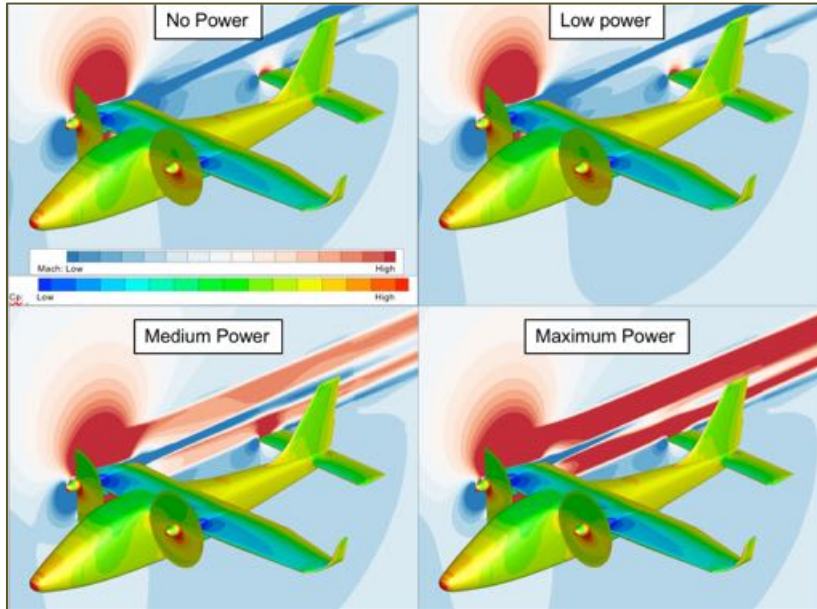


Unstructured mesh



Structured overset mesh

# X-57 Propulsion Performance



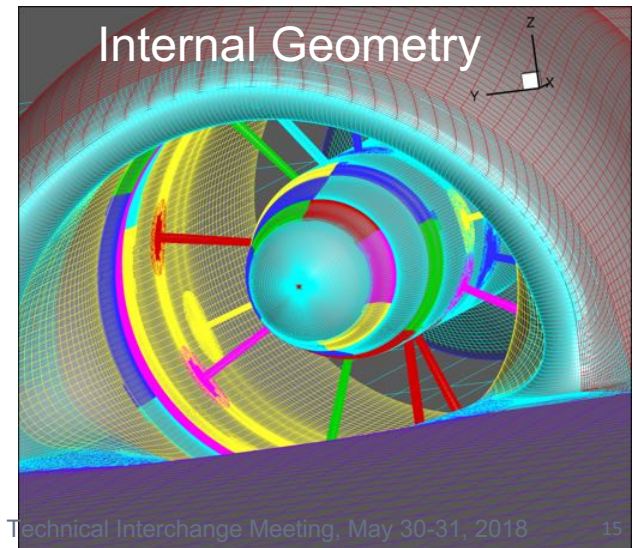
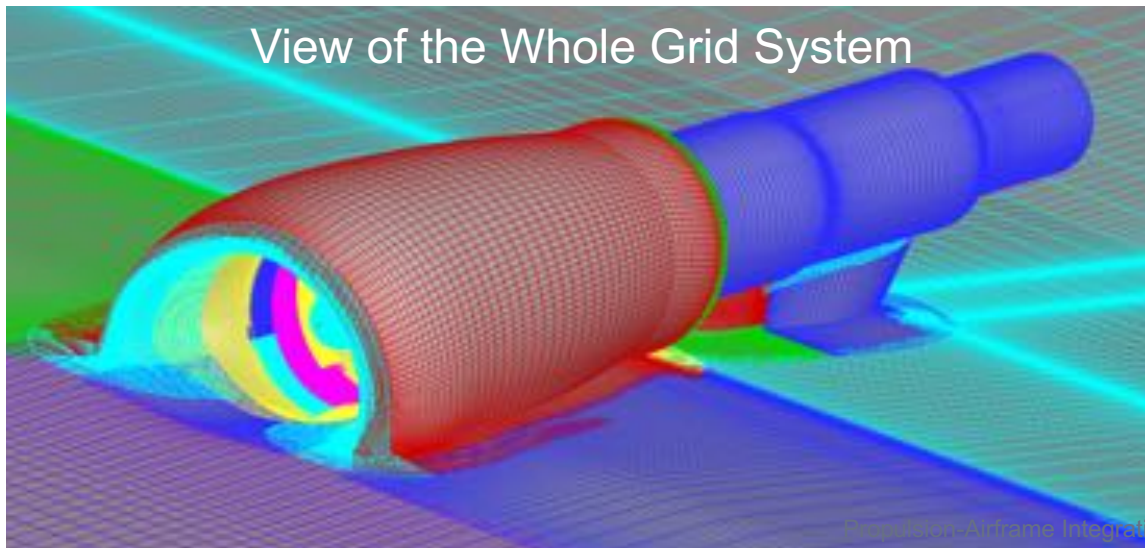
# BLI2DTF: Predicting Fan Face Distortion

## Goal

- Perform validation of CFD with different propulsion models in BLI configurations using comparisons with the experiment

## Progress Summary

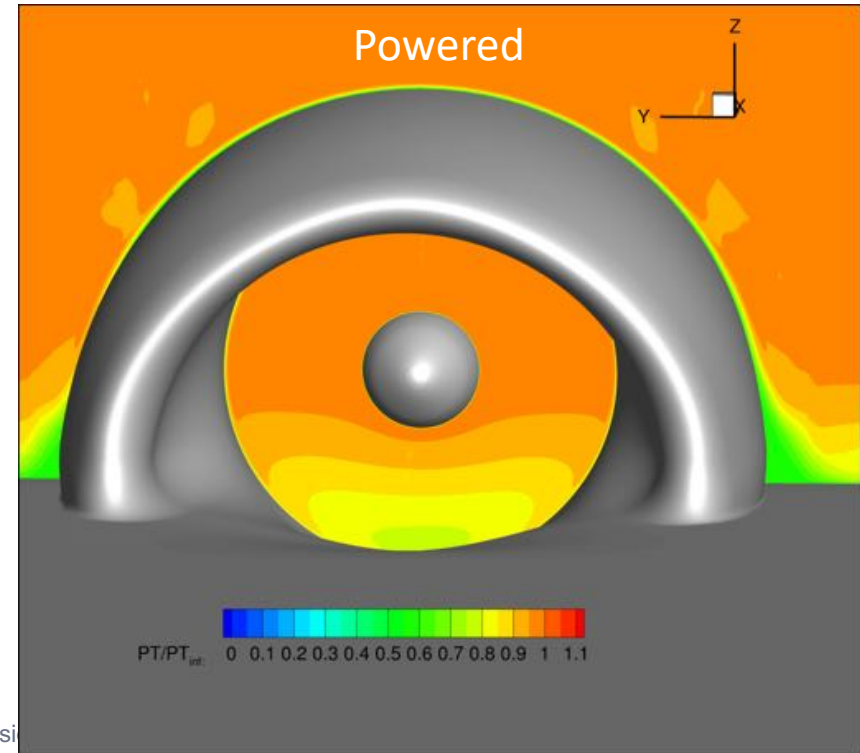
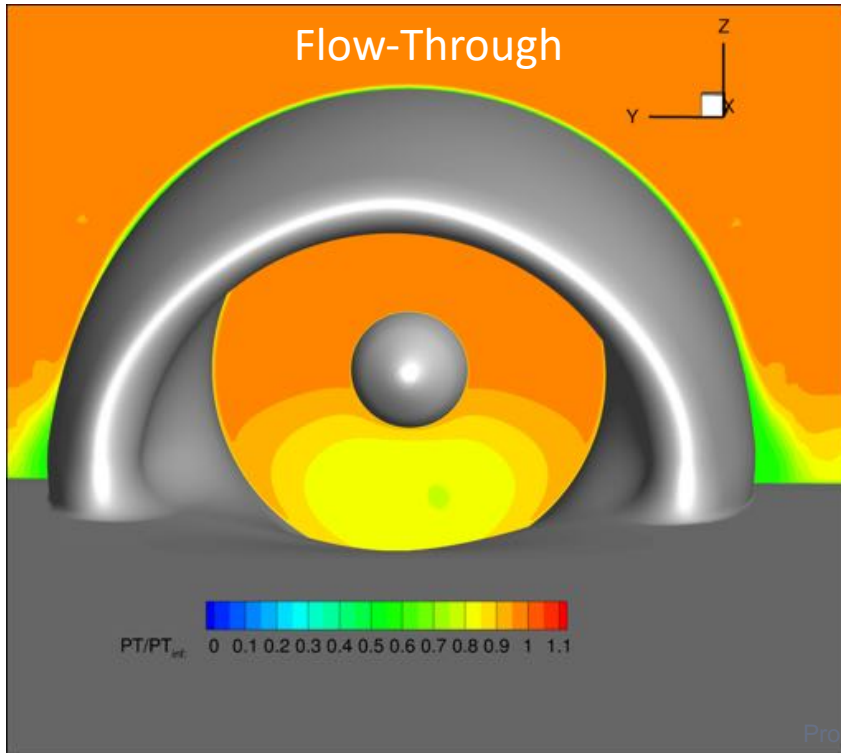
- Generated an overset, structured grid system
- Ran initial flow-through case for reference
- Ran initial powered case using a 3D actuator zone and targeting the experimental mass flow



# BLI2DTF: Predicting Fan Face Distortion



- Comparisons are between flow-through and powered case with the mass flow targeted to 110.66 lb/s (100.23 lb/s corrected).
- The figures below are plots of the total pressure ratio at the fan face

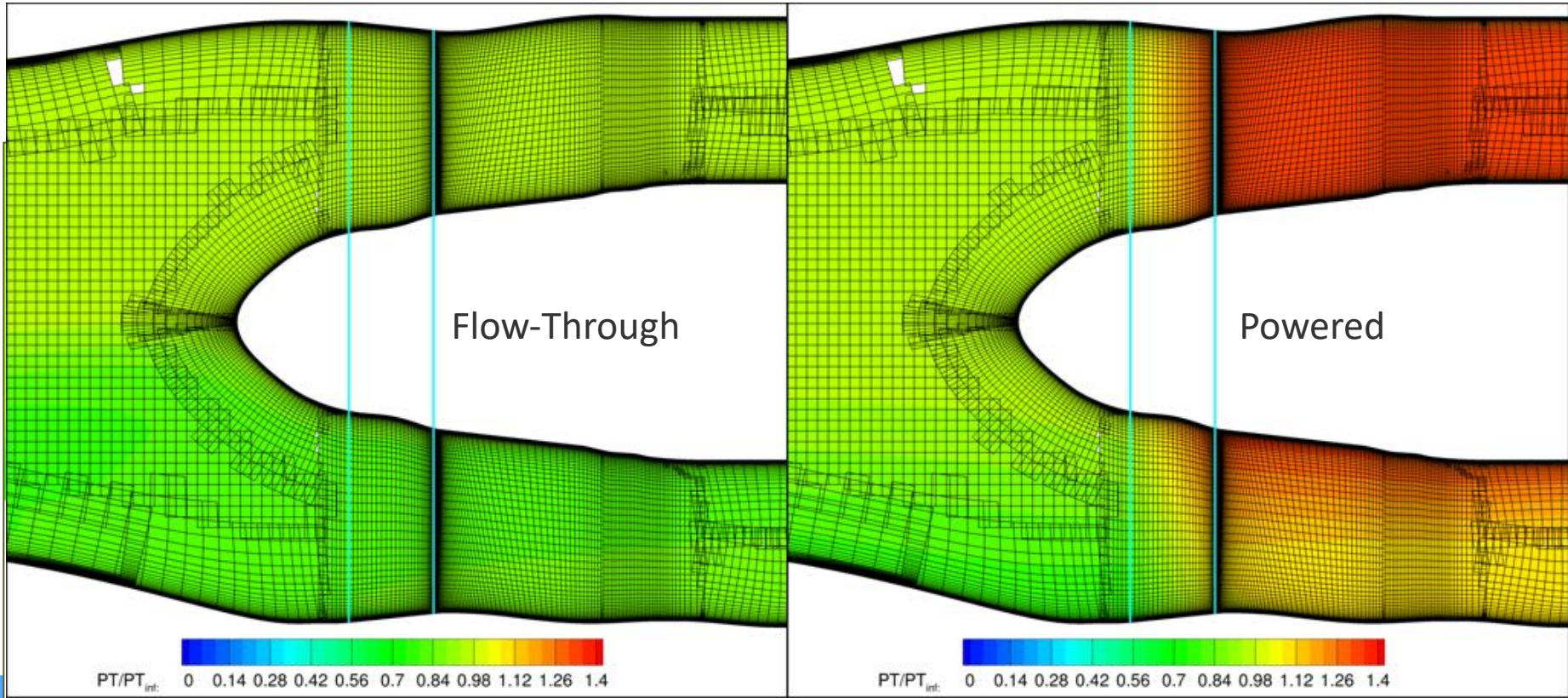




# BLI2DTF: Predicting Fan Face Distortion



- Comparisons are between flow-through and powered case with the mass flow targeted to 110.66 lb/s (100.23 lb/s corrected). Will compare with experiment once we match geometry.
- Below plots are slices through the centerline of the nacelle with the total pressure ratio; teal lines are where the actuator zone starts and ends





**Toward detailed design**

# **PROPULSION AND AIRFRAME NOISE PREDICTION**

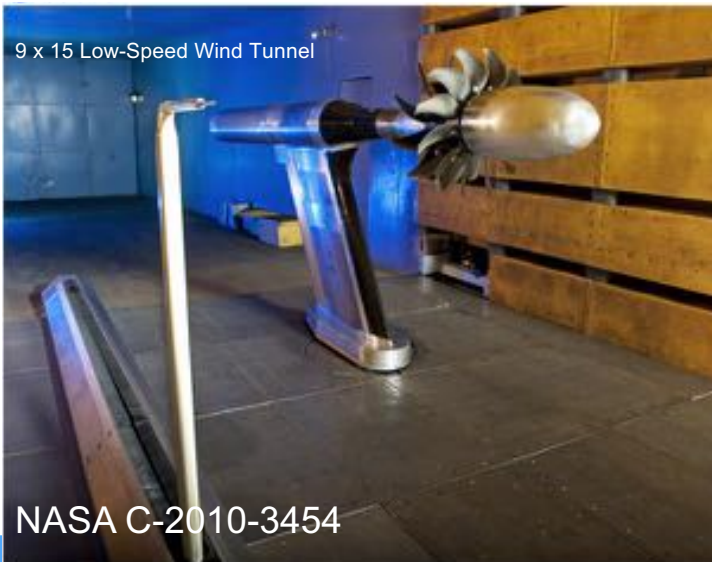
# Predicting Noise: Open Rotor



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



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

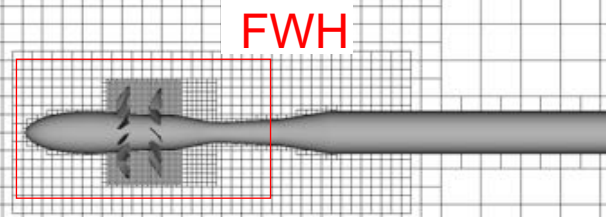




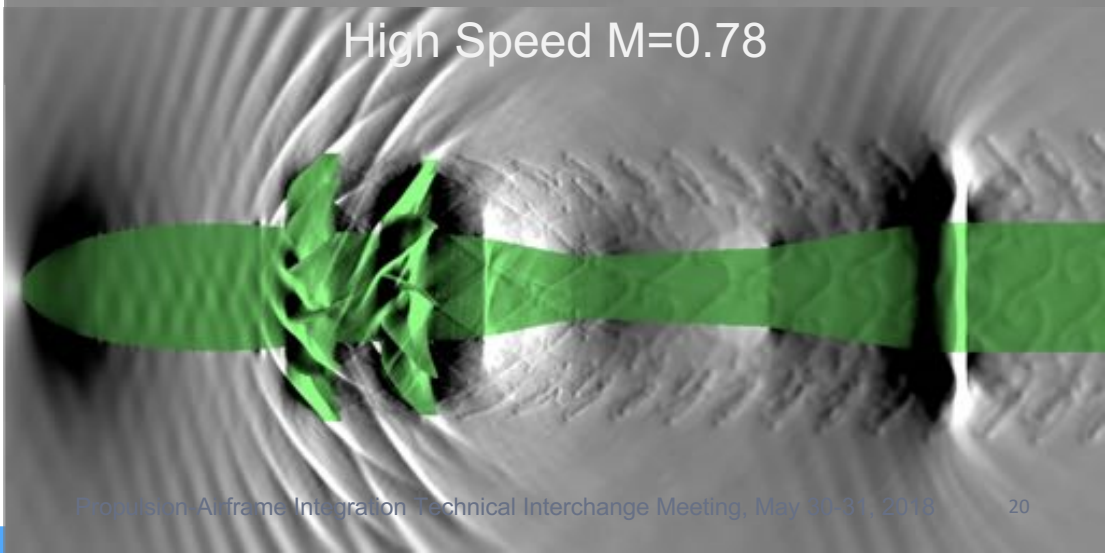
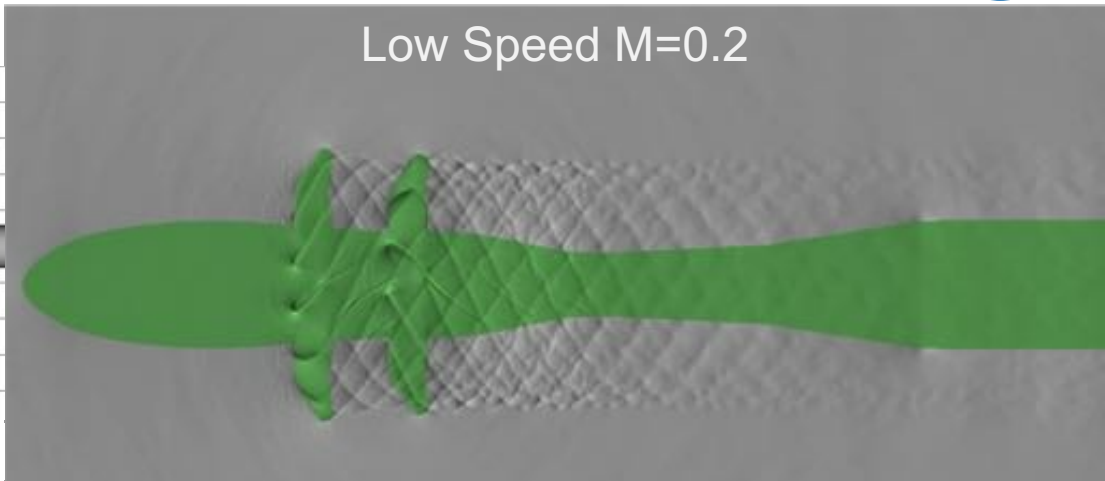
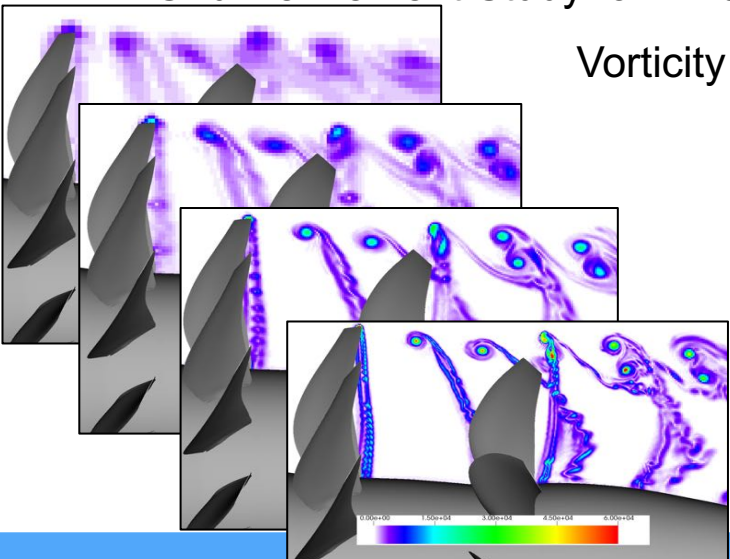
# Numerical Schlieren of Unsteady Flow Field



Structured Cartesian AMR



Each box contains  $16^3$  grid points  
Grid Refinement Study for  $M=0.2$ :

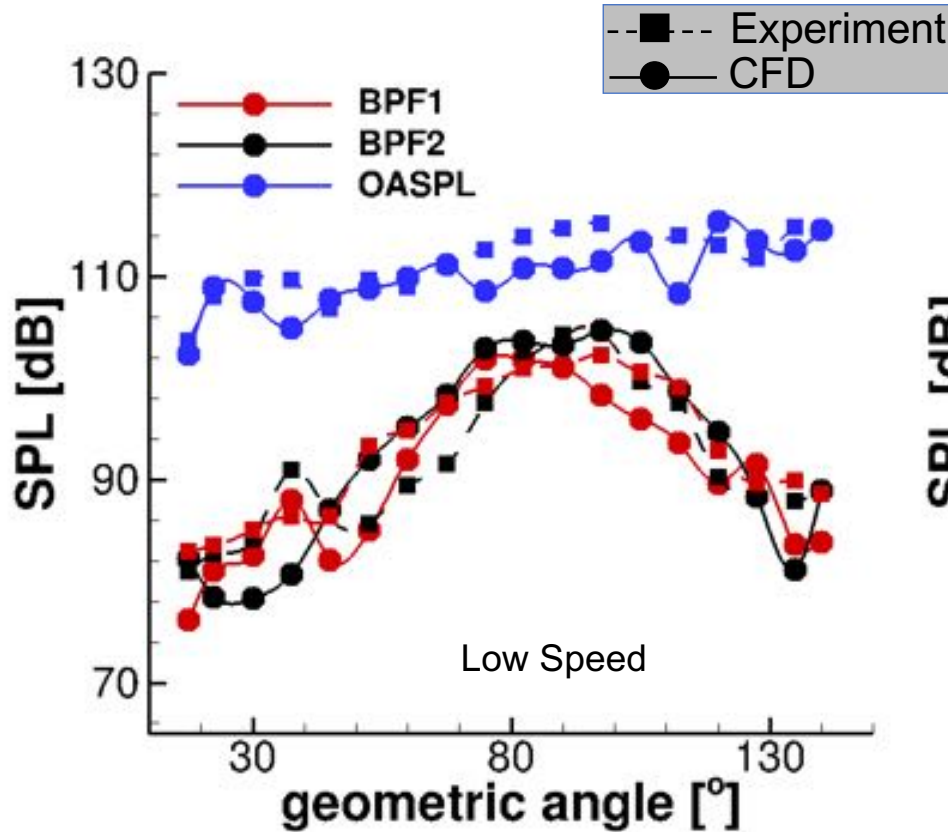




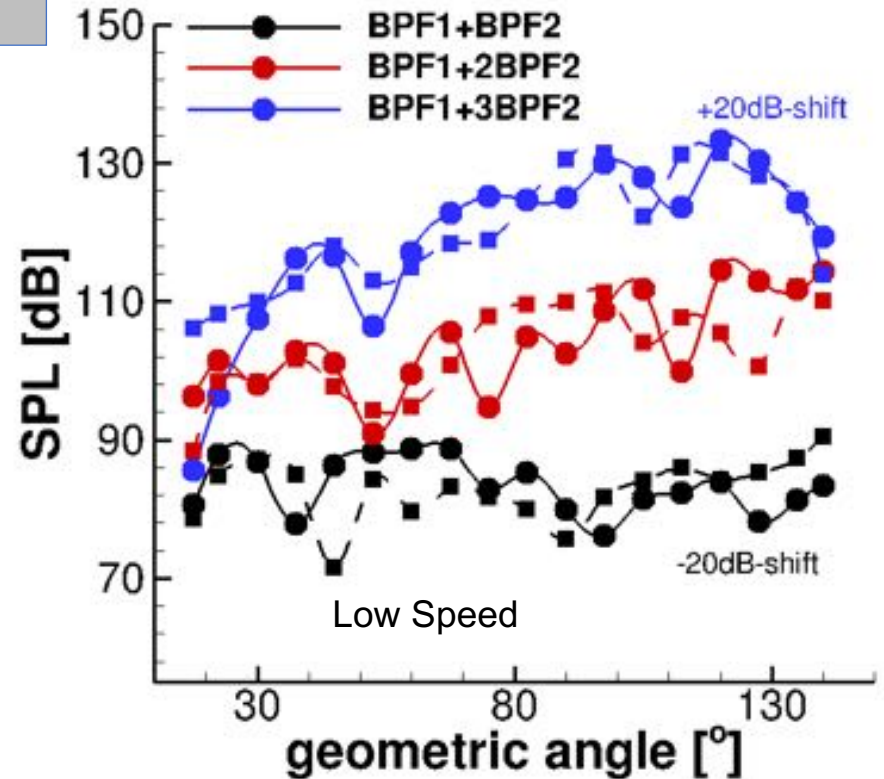
# Experimental Validation of Open Rotor Noise



## Fundamental Tones



## Higher-Order Interactions

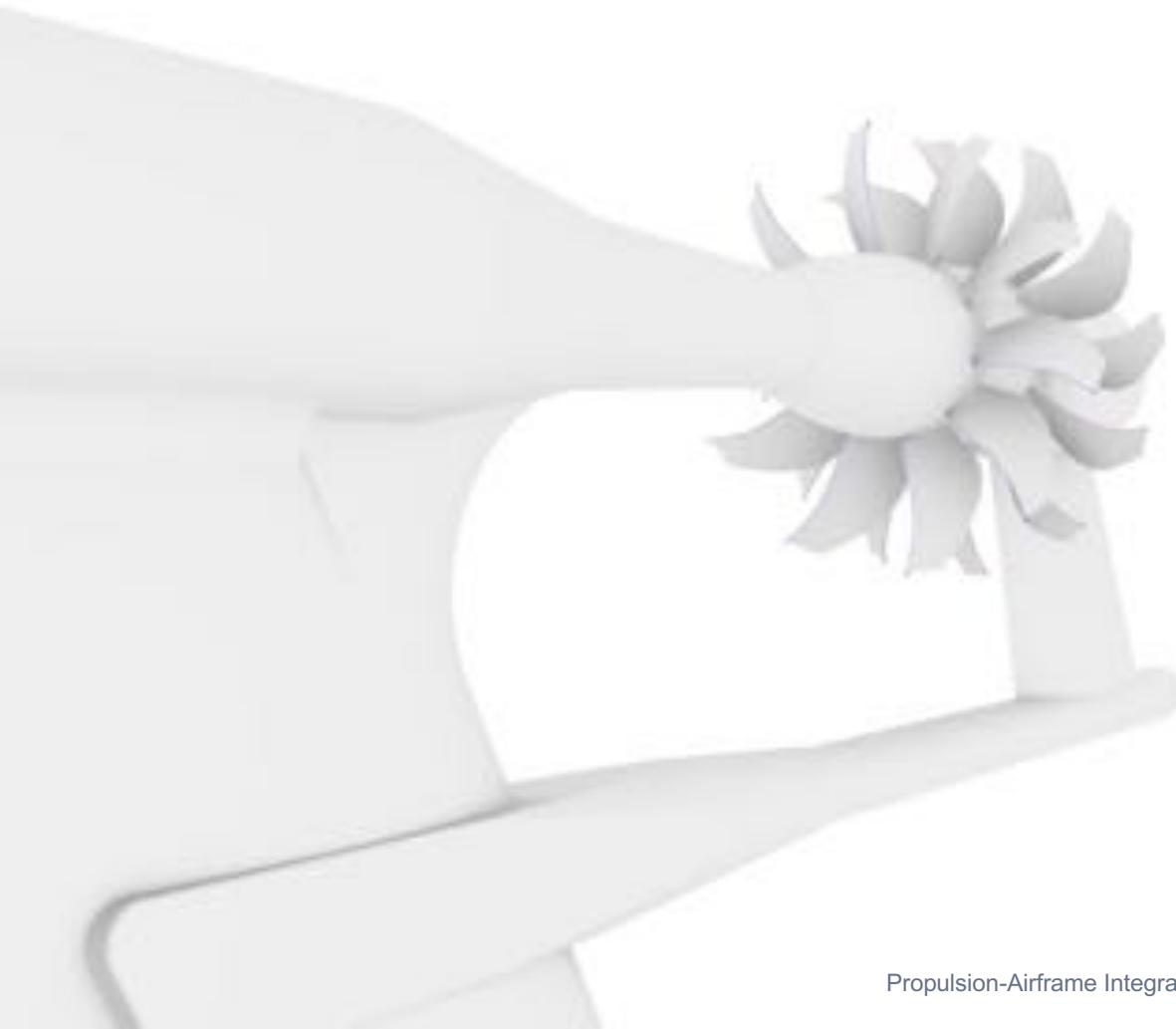


# Investigating Installation Effects



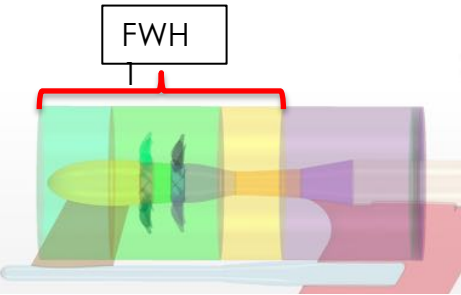
Seed colors:

- **Green** = Pylon Edge
- **Red** = FWD Blade Edges
- **Blue** = AFT Blade Edges



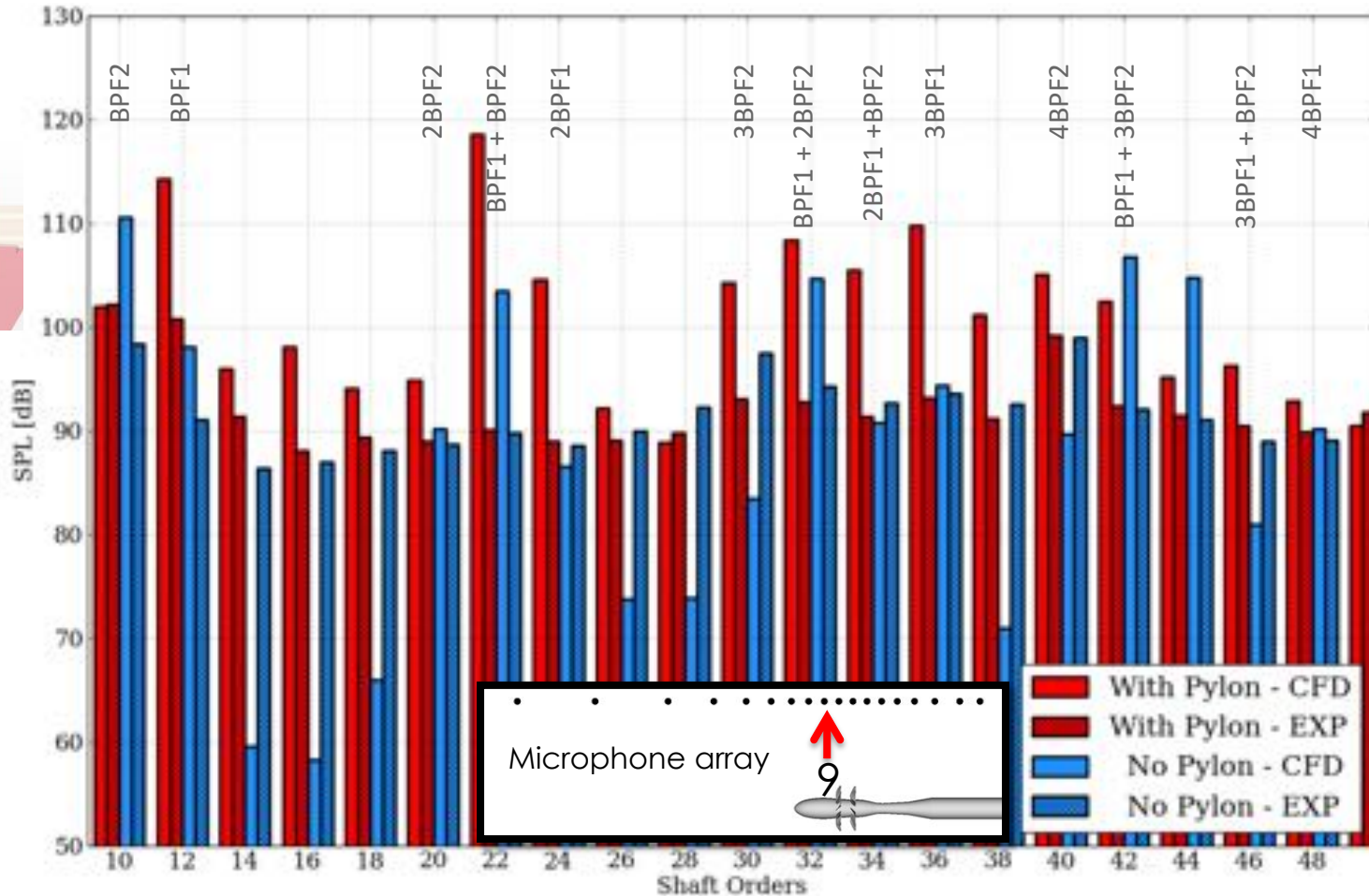
# Investigating Installation Effects

## FWH Surface:



### 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



# Predicting Urban Air Mobility Noise



- **Potential Noise Annoyances**

- Rotor tones
- Rotor-rotor interaction
- Rotor-airframe interaction

- **Experimental validation with UAS**

- Create best practices
- Assess pros and cons of different methods



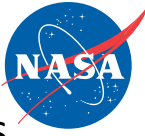
eVTOL aircraft concepts



SUI Endurance drone



# Predicting SUI Isolated Rotor Noise



- **Build-up approach**

- Single rotor first
- Add other rotors
- Add fuselage

- **Computational Methodology**

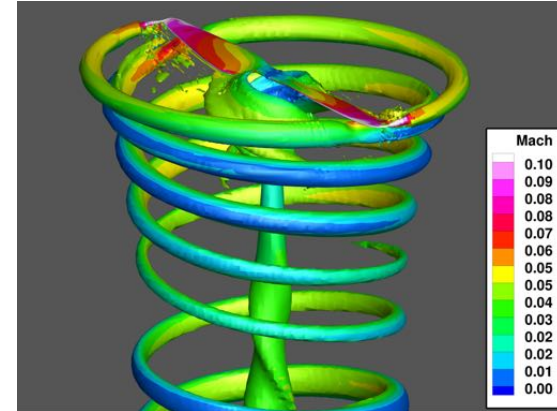
- Overset Structured Grid/Solver
- Cartesian AMR

- **Validation Comparison**

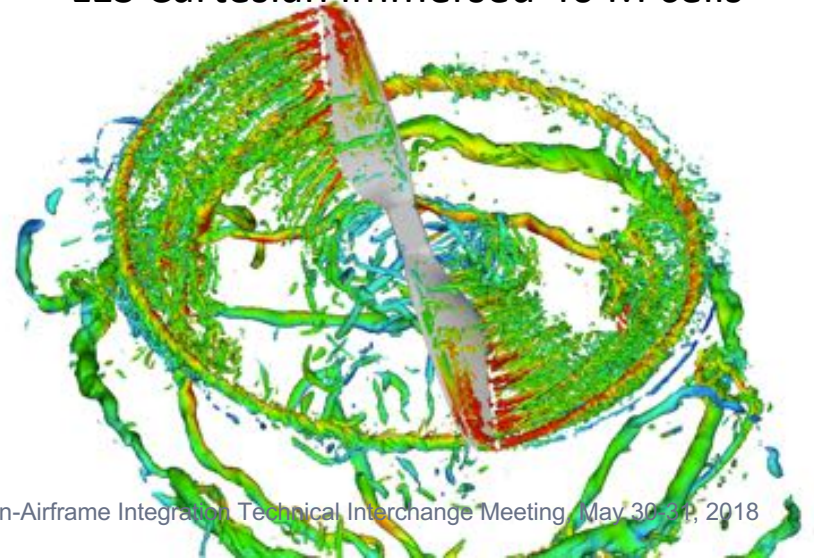
- Integrated Loads
- Far-field Acoustics

*Data From Zawodny and Haskin AIAA-2017-3709*

URANS curvilinear overset 6 M cells



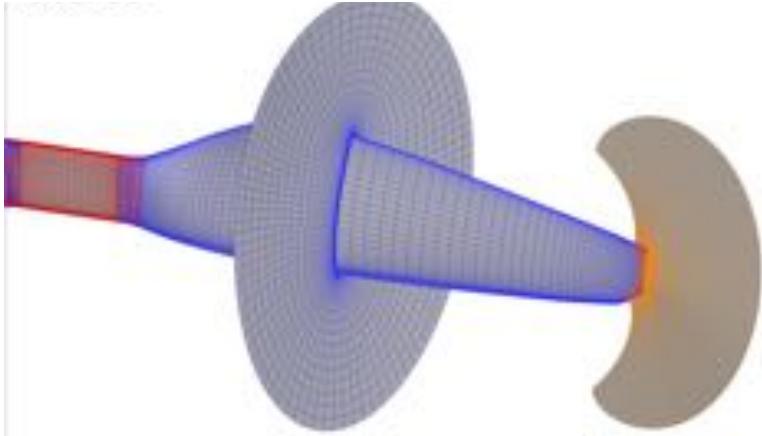
LES Cartesian immersed 40 M cells



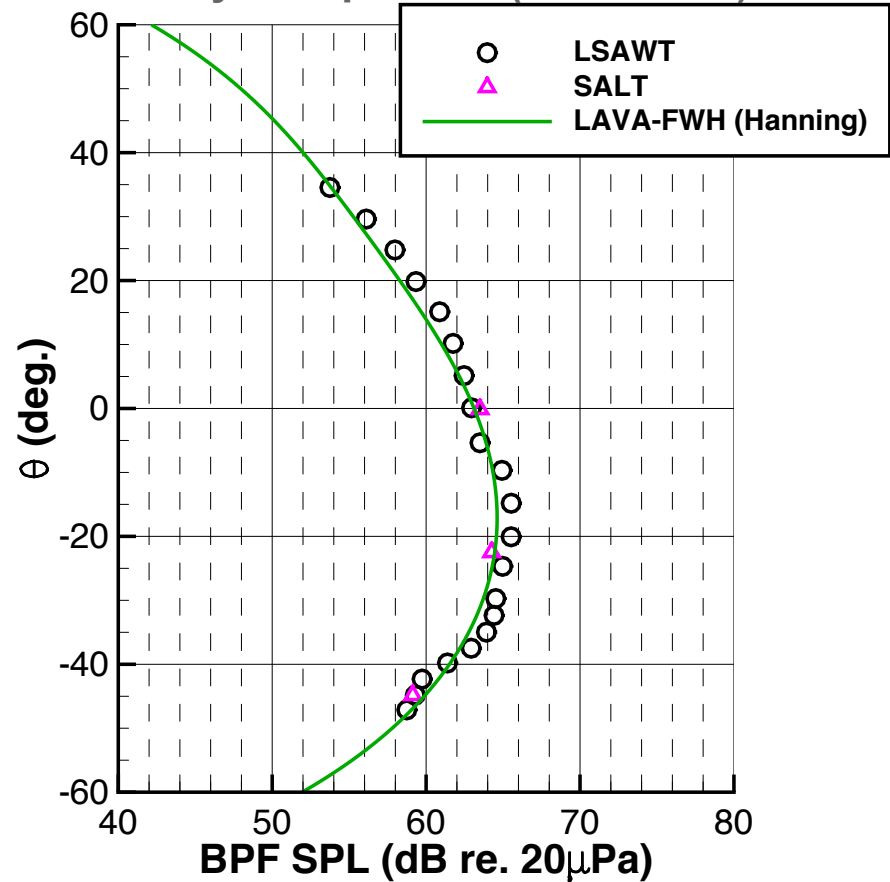
# Experimental Validation of SUI Rotor Noise Predictions



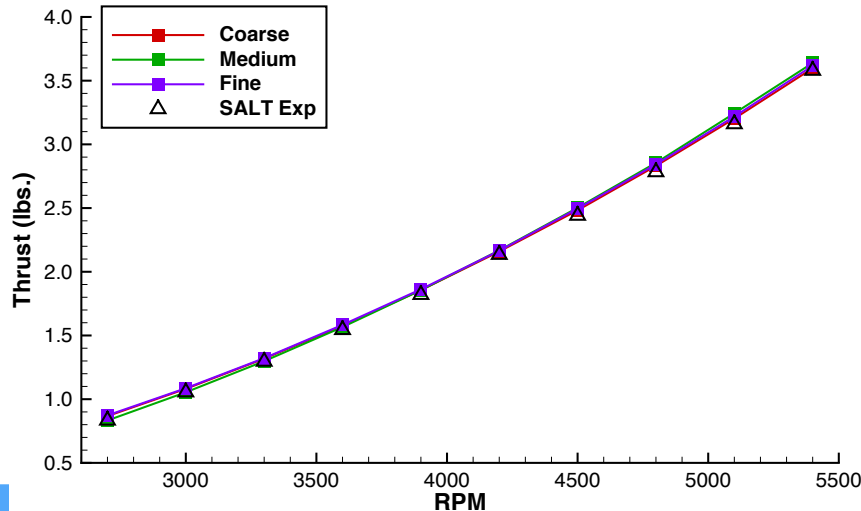
Structured Overset Grid



BPF Directivity Comparison (RPM=5400)



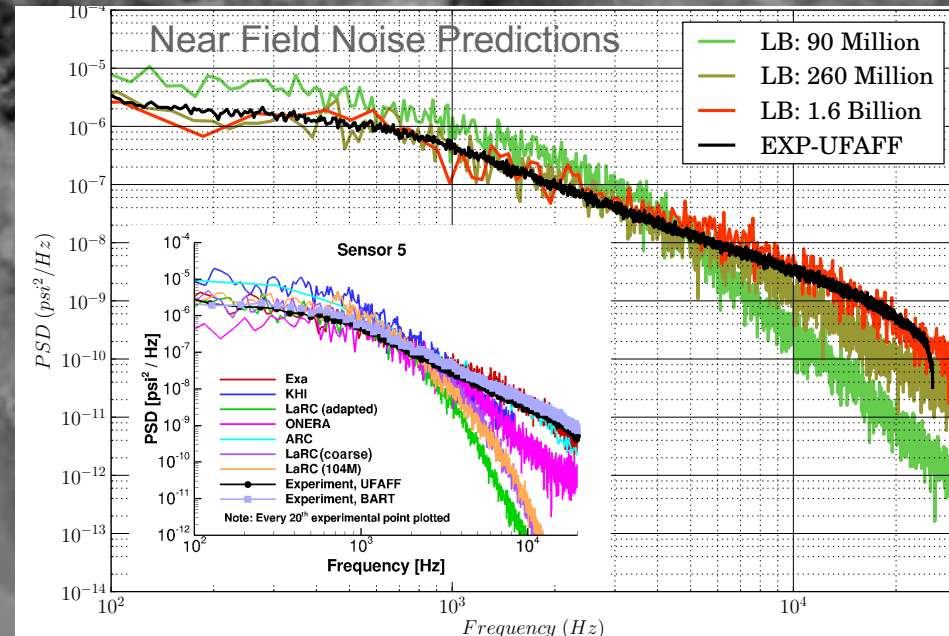
Integrated Loads: Thrust versus RPM



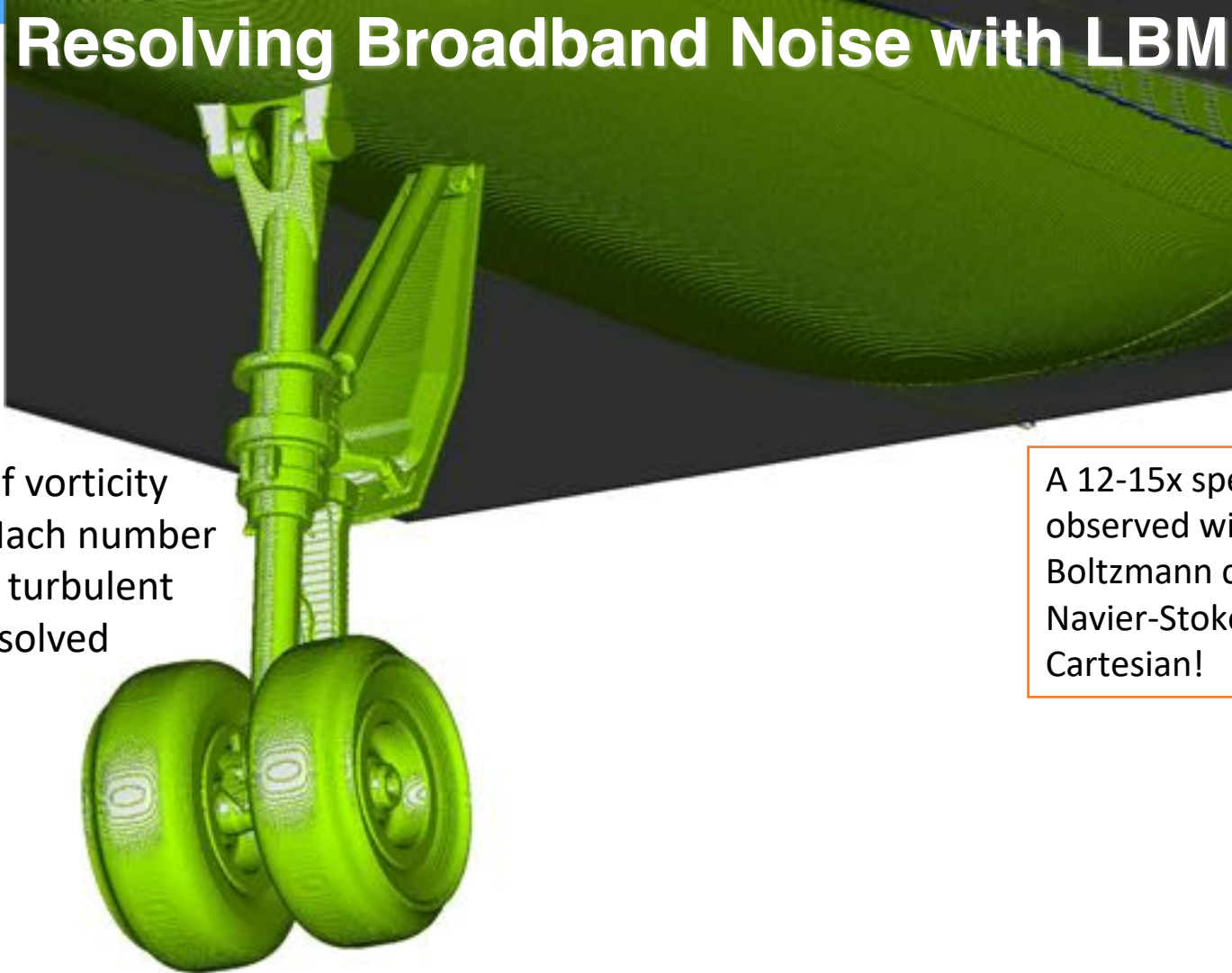
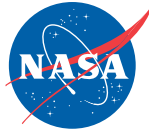
# Predicting Landing Gear Broadband Noise



“Lattice Boltzmann and Navier-Stokes Cartesian CFD Approaches for Airframe Noise Predictions”,  
Barad, Kocheemoolayil, Kiris, AIAA 2017-4404



# Resolving Broadband Noise with LBM



Isosurfaces of vorticity colored by Mach number showing fine turbulent structures resolved

A 12-15x speedup was observed with Lattice-Boltzmann compared to Navier-Stokes within LAVA Cartesian!

# Summary



- **Different PAI challenges call for different strategies**
- **LAVA strives to provide flexibility**
  - **Structured curvilinear overset approach:**
    - High-fidelity viscous performance analysis (X-57)
    - Tonal noise predictions (SUI rotor)
    - Design optimization (STARC-ABL, TCT)
  - **Unstructured approach:**
    - High-fidelity viscous performance analysis (X-57)
  - **Cartesian AMR approach:**
    - Tonal noise predictions (open rotor, SUI)
    - Broadband noise predictions (landing gear)
- **It pays off to invest in new technologies like Lattice-Boltzmann**



# Acknowledgements



## **LAVA team:**

- Cetin Kiris (POC)
- Michael Barad
- Jeff Housman
- James Jensen
- Marie Denison
- Joseph Kocheemoolayil
- Gerrit Stich
- Francois Cadieux
- Jared Duensing
- Gaetan Kenway

## **This work was partially supported by the following NASA ARMD projects:**

- Transformational Tools and Technologies (T<sup>3</sup>)
- Advanced Air Transport Technology (AATT)
- Commercial Supersonic Transport (CST)
- Revolutionary Vertical Lift Technology (RVLT)

## **Computer time provided by:**

- NASA Advanced Supercomputing (NAS)

## **Particle and schlieren visualizations provided by:**

- Timothy Sandstrom
- Patrick Moran



# BACKUP SLIDES

# Ongoing Development Efforts

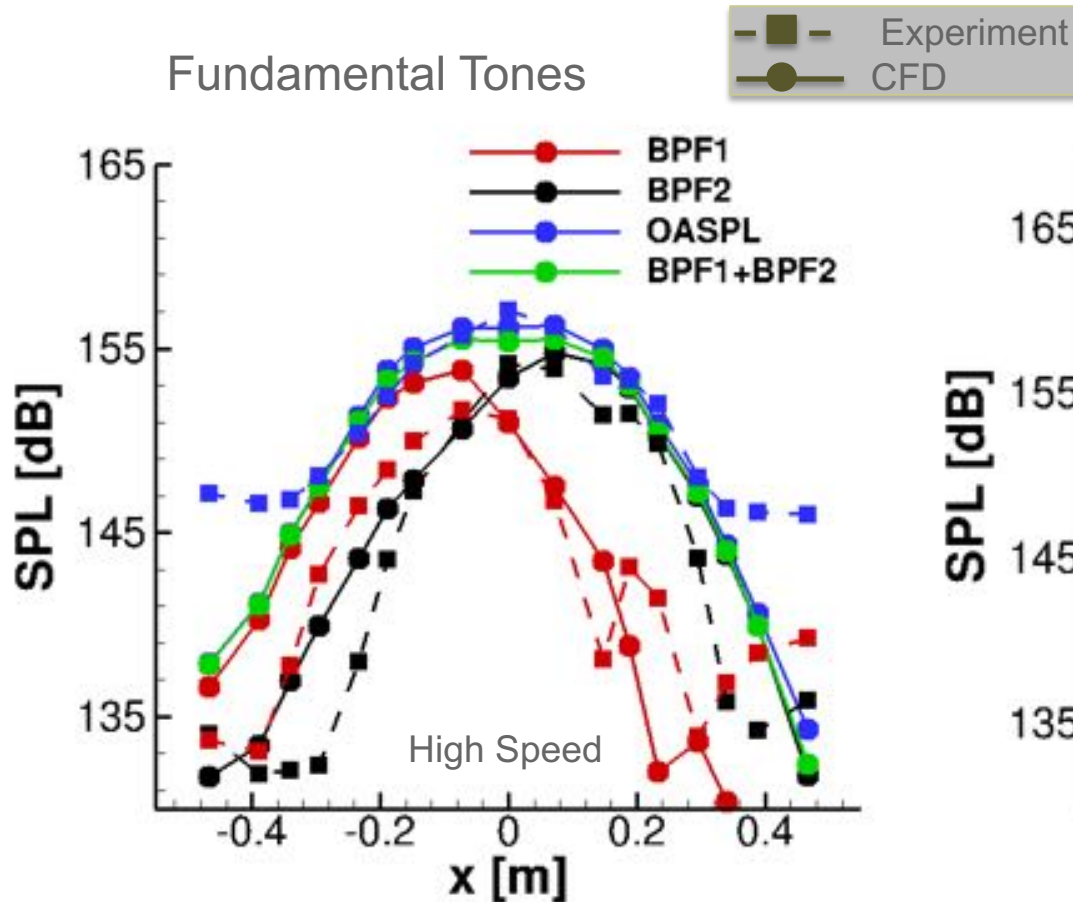


- **Turbulent wall-layer modeling for Cartesian methods**
- **Moving geometry capability for Lattice-Boltzmann**
- **Integration of more multi-disciplinary capabilities in design optimization and in predictive simulations: structural dynamics, fluid-structure interaction**

# Experimental Validation of Open Rotor Noise



### Fundamental Tones



### Higher-Order Interactions

