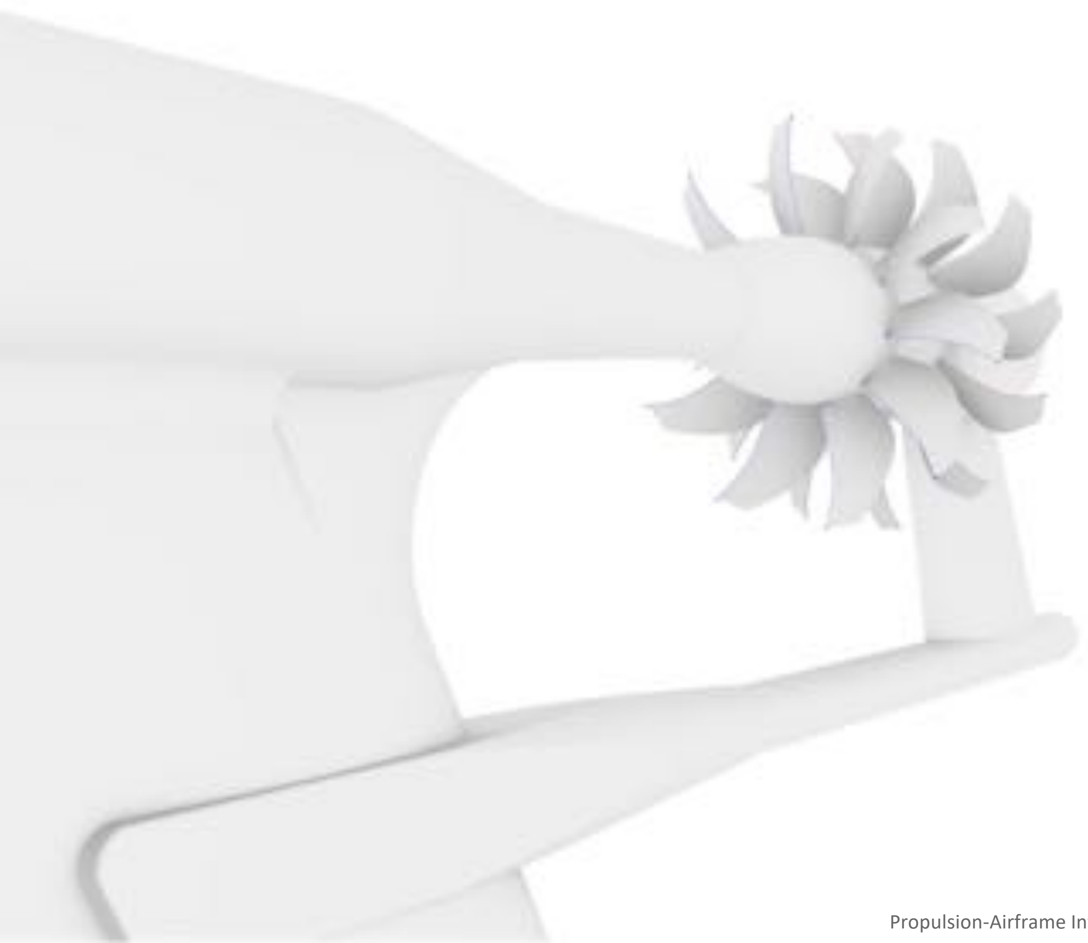
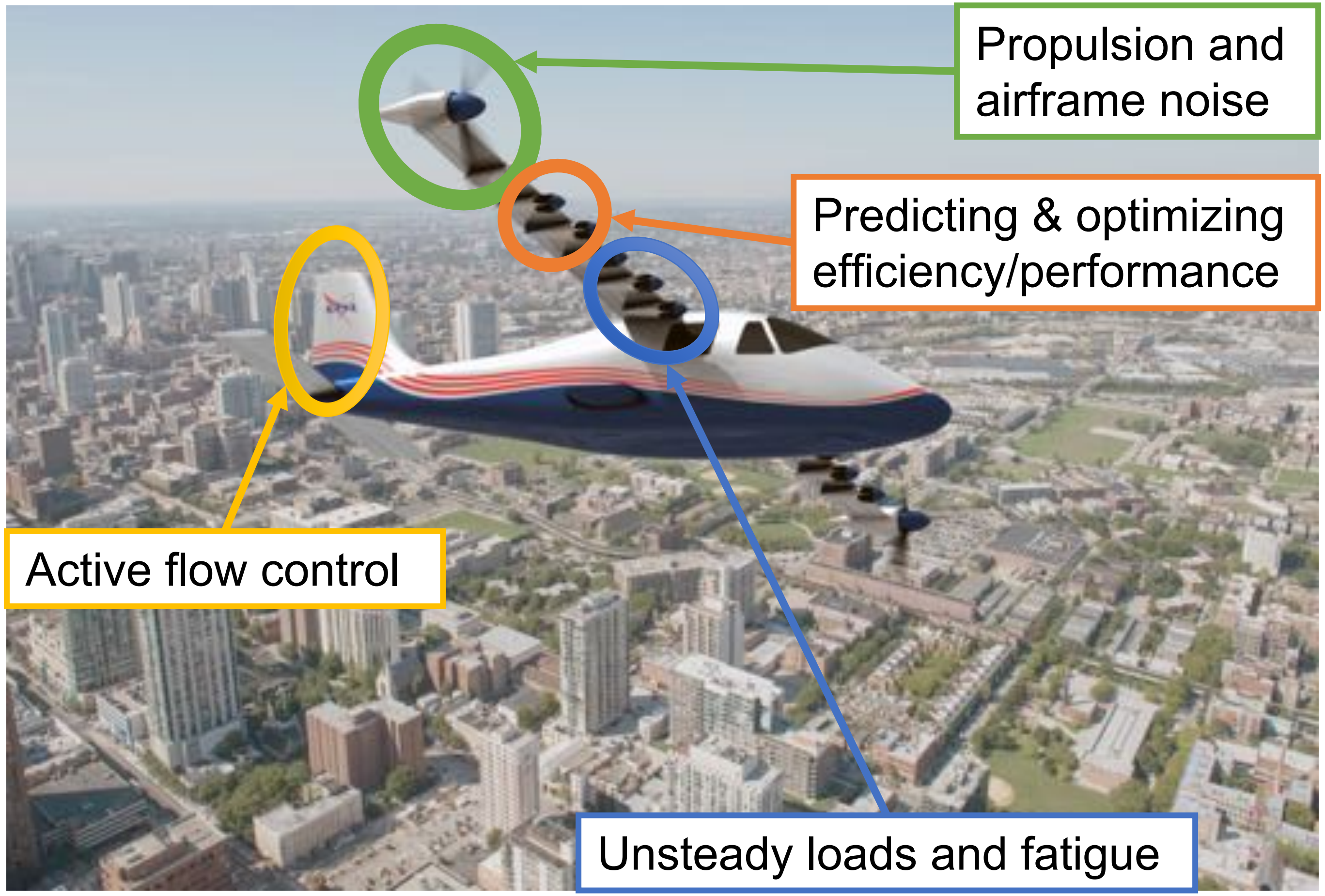
COMPUTATIONAL STRATEGIES TO SUPPORT PROPULSION-AIRFRAME INTEGRATION APPLICATIONS



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

Propulsion-Airframe Integration Technical Interchange Meeting, May 30-31, 2018

Challenges of PAI



Propulsion and airframe noise

Predicting & optimizing efficiency/performance

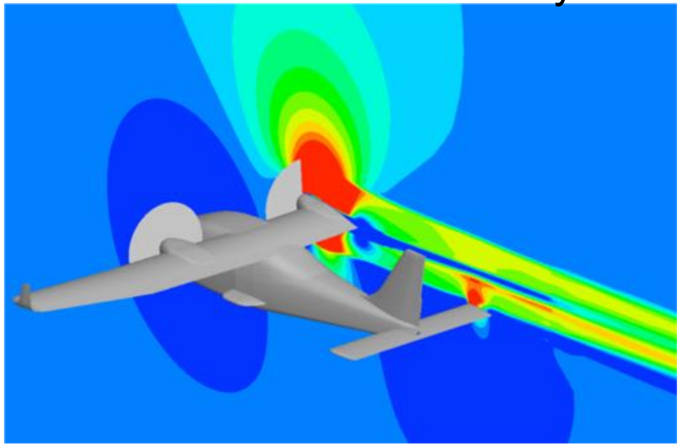
Active flow control

Unsteady loads and fatigue

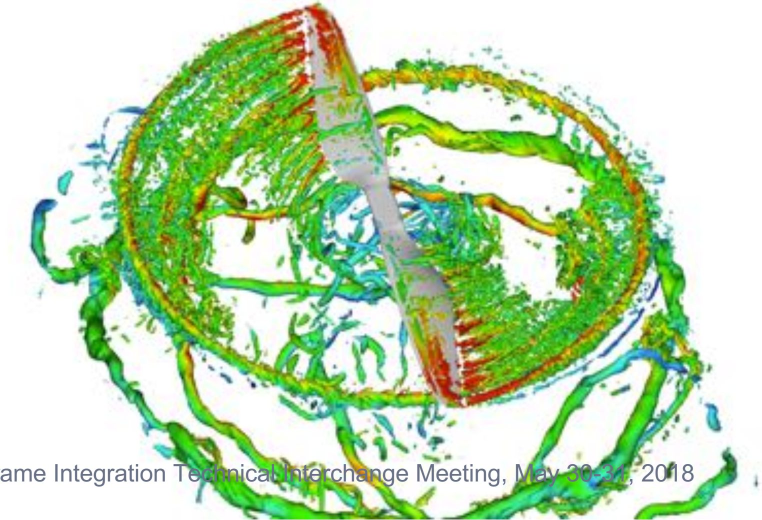
Choosing the Right Strategy

- 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

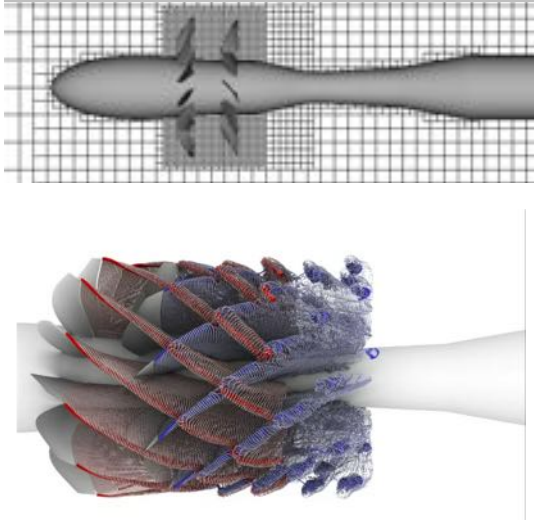


Noise Prediction



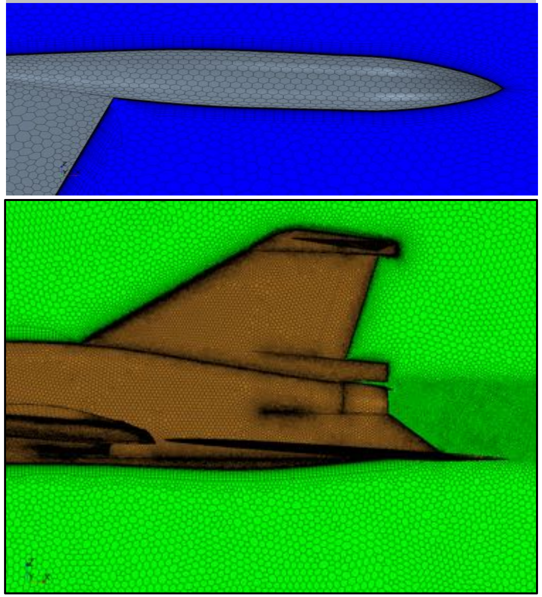
Choosing The Best Grid Paradigm

Structured Cartesian



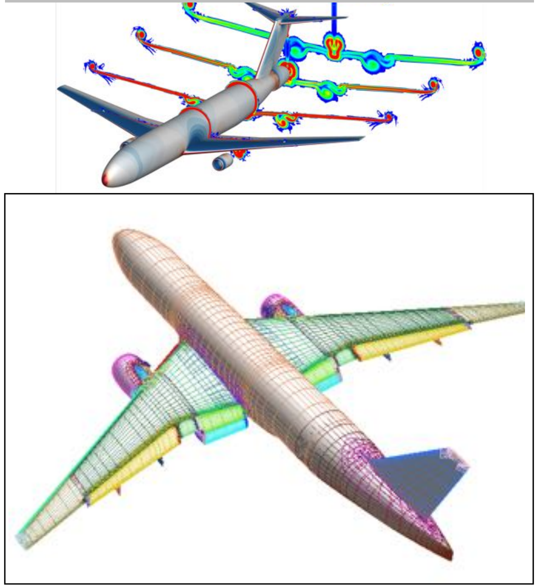
- Automatic grid generation with Adaptive Mesh Refinement
- Low computational cost
- Reliable higher order methods
- Non-body fitted → Resolution of boundary layers inefficient

Unstructured Arbitrary Polyhedral



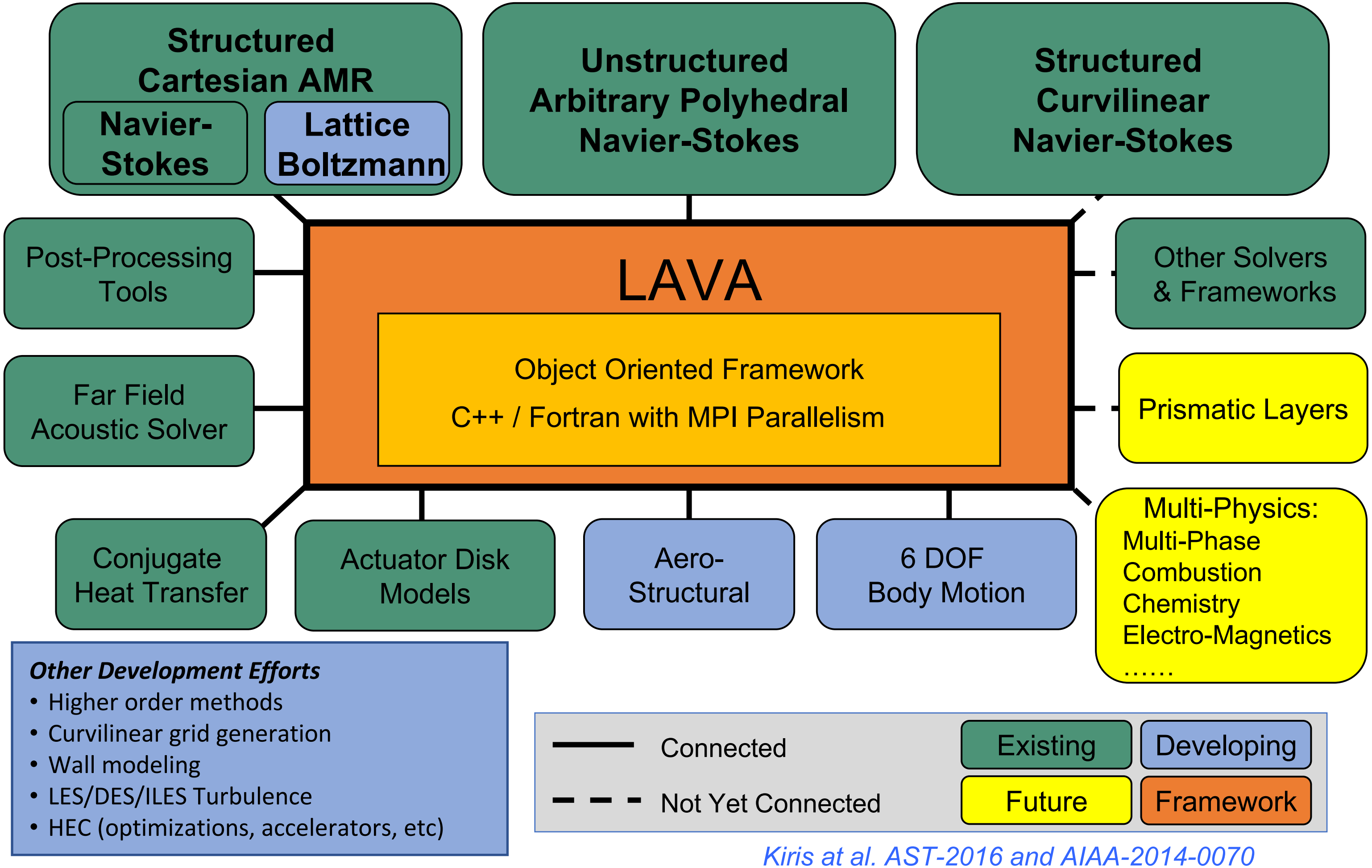
- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

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)



Structured Cartesian AMR

Navier-Stokes

Lattice Boltzmann

Unstructured Arbitrary Polyhedral Navier-Stokes

Structured Curvilinear Navier-Stokes

Post-Processing Tools

Far Field Acoustic Solver

LAVA

Object Oriented Framework

C++ / Fortran with MPI Parallelism

Other Solvers & Frameworks

Prismatic Layers

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

Conjugate Heat Transfer

Actuator Disk Models

Aero-Structural

6 DOF Body Motion

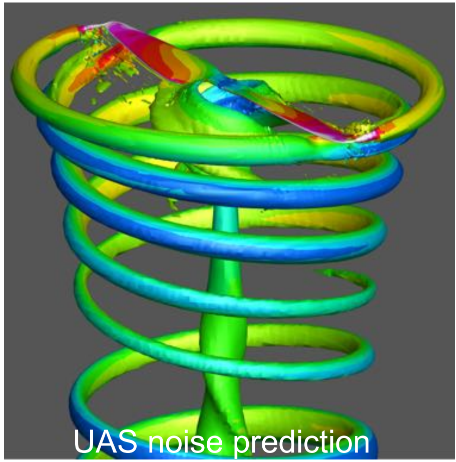
Other Development Efforts
- Higher order methods
- Curvilinear grid generation
- Wall modeling
- LES/DES/ILES Turbulence
- HEC (optimizations, accelerators, etc)

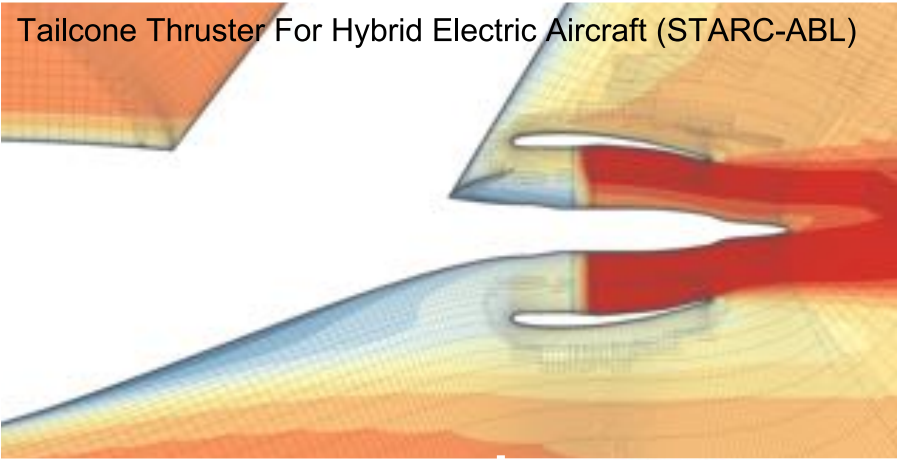
———	Connected
– – –	Not Yet Connected

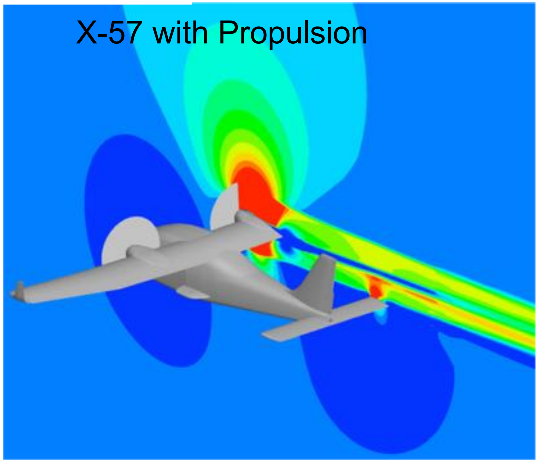
Existing
Developing
Future
Framework

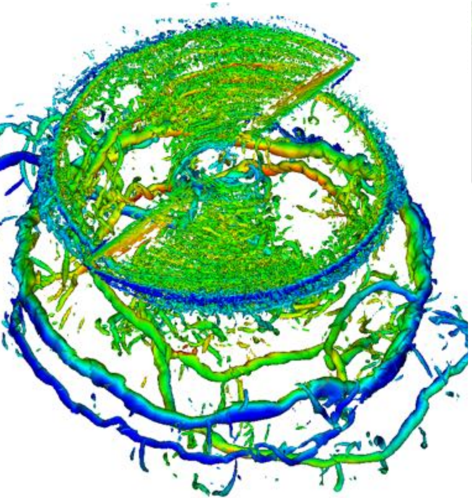
Kiris at al. AST-2016 and AIAA-2014-0070

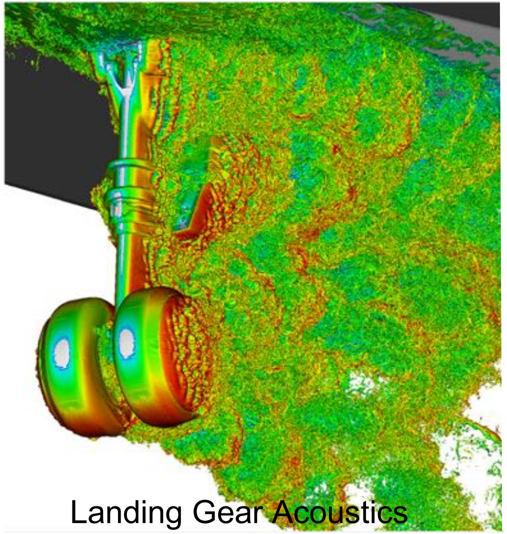
Recent Examples of Performance Analysis, Design Optimization and Noise Prediction with LAVA

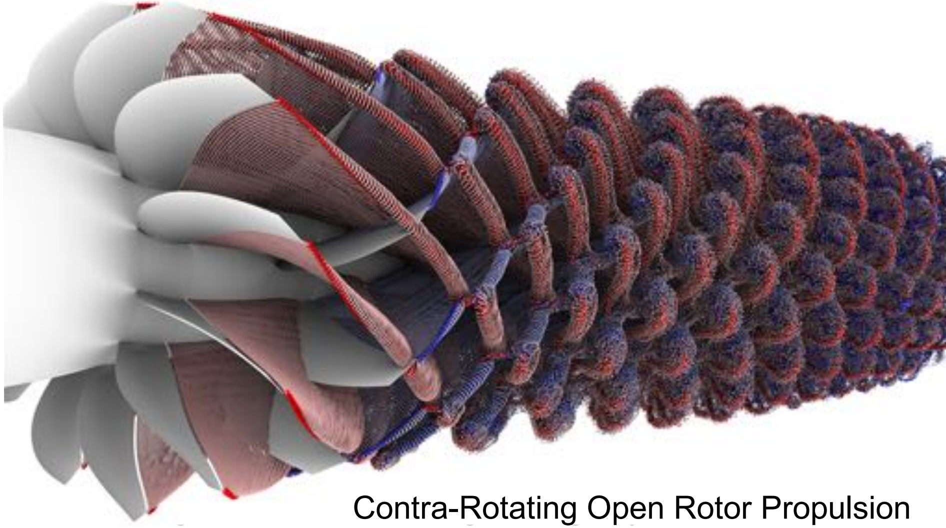

UAS noise prediction


Tailcone Thruster For Hybrid Electric Aircraft (STARC-ABL)


X-57 with Propulsion


UAS noise prediction

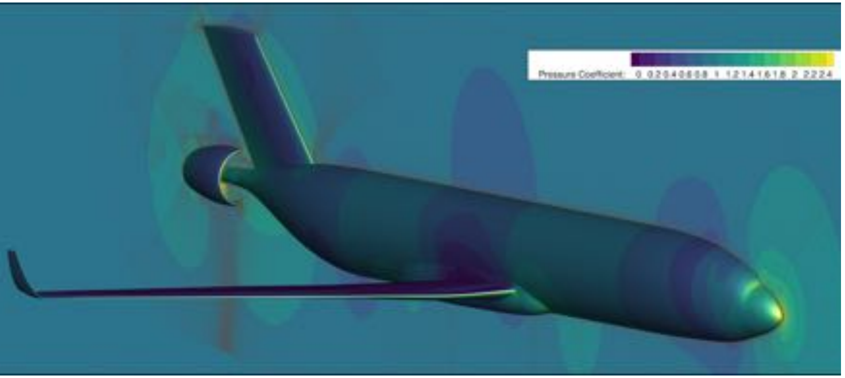

Landing Gear Acoustics

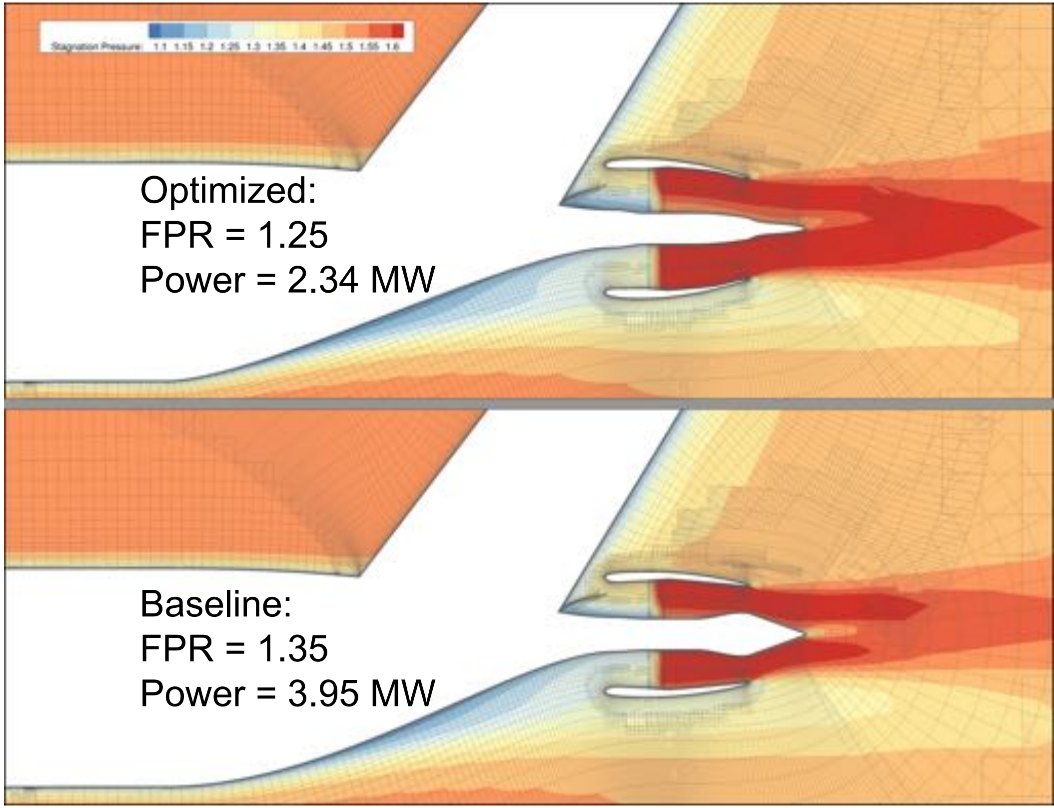

Contra-Rotating Open Rotor Propulsion

From conceptual to detailed design

HIGH FIDELITY VISCOUS STEADY DESIGN OPTIMIZATION

Aeropropulsive Optimization of STARC-ABL with OpenMDAO





Optimized:
FPR = 1.25
Power = 2.34 MW

Baseline:
FPR = 1.35
Power = 3.95 MW

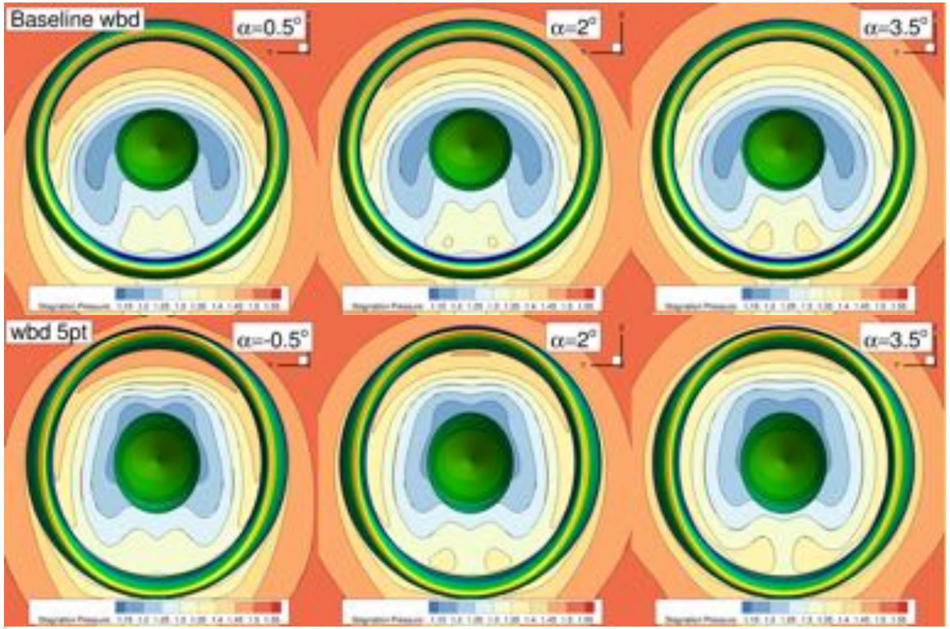
Propulsor Modeling

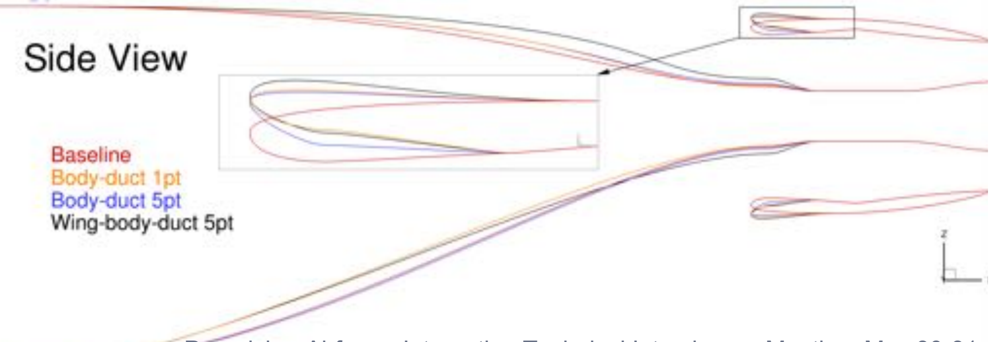
Actuator zone source term:

- **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 tangeantial 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

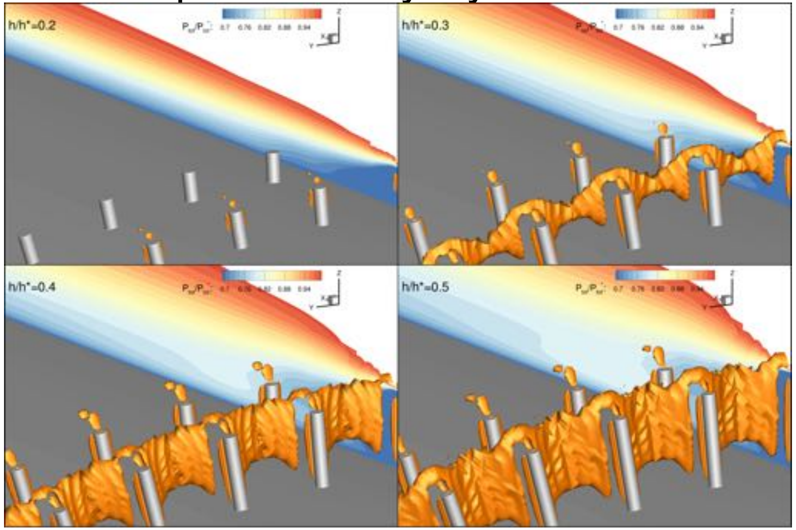
- **Parametric description of fuselage and inlet shape with thickness constraints**
- **Optimized shape reduces distortion by 50% at cruise**
- **Overset build-up approach helped identify effect of wing on distortion**



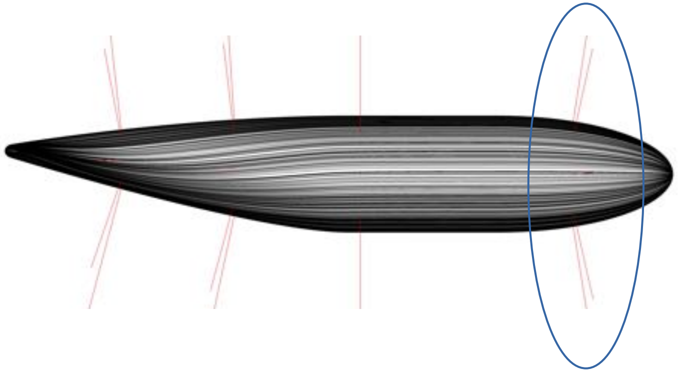


Tail Cone Thruster (TCT) Wind Tunnel Support

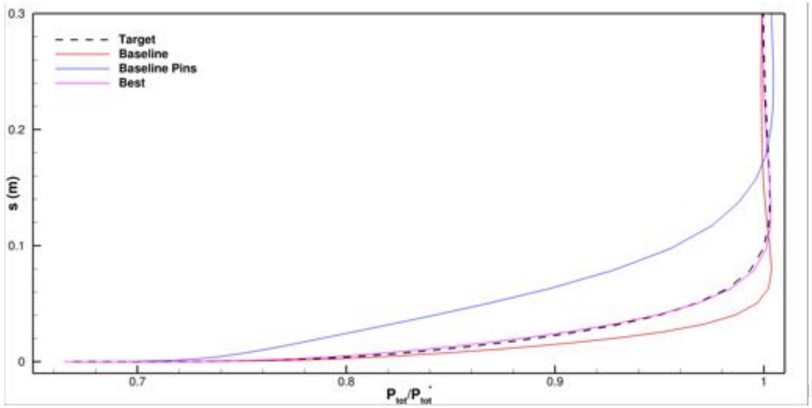
Two-row pin boundary layer thickener



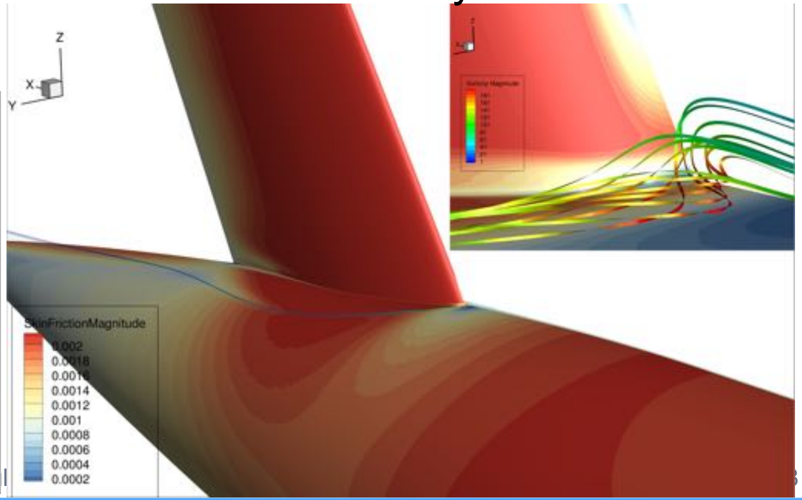
Match total pressure at 5 rake locations



We are able to match target boundary layer



Horseshoe vortex study

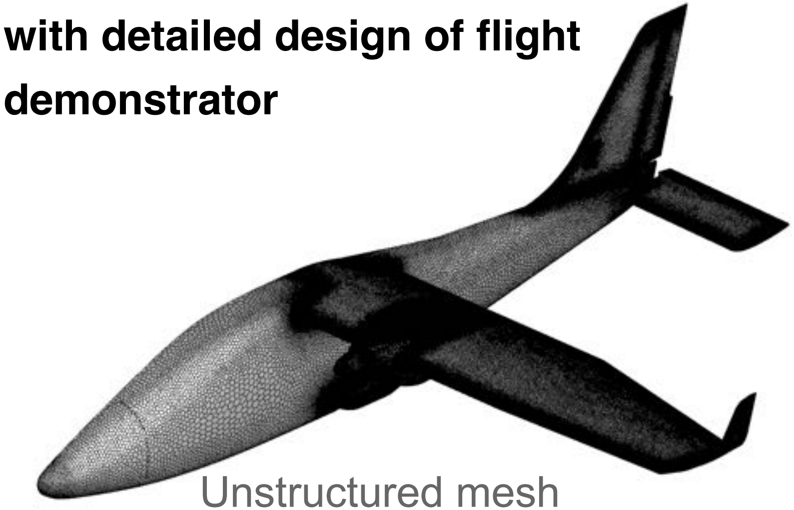


From preliminary to detailed design

HIGH FIDELITY VISCOUS STEADY PERFORMANCE ANALYSIS

X-57 Electric Research Aircraft

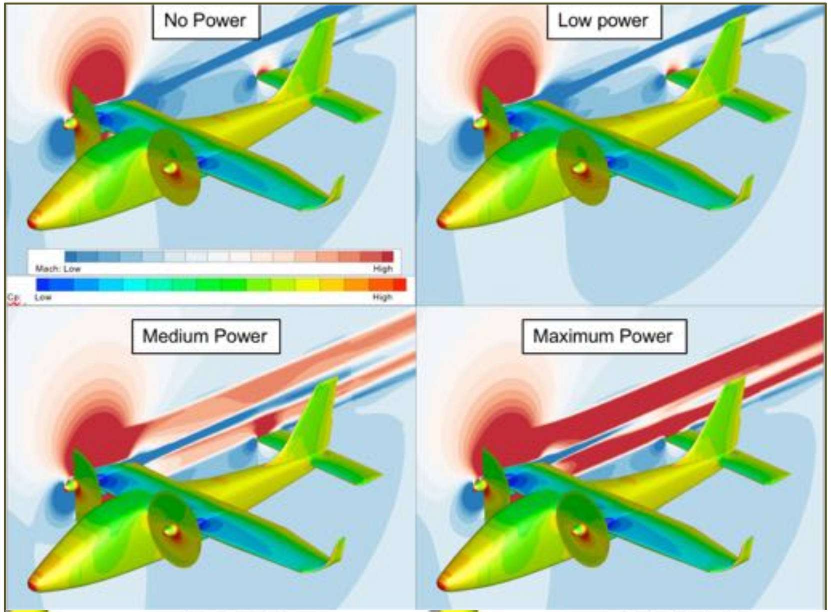
- Predict X-57 performance for a variety of flight scenarios and propulsion configurations
- Validate CFD with wind tunnel experiments and across solvers
- Help aircraft designers at Armstrong with detailed design of flight demonstrator

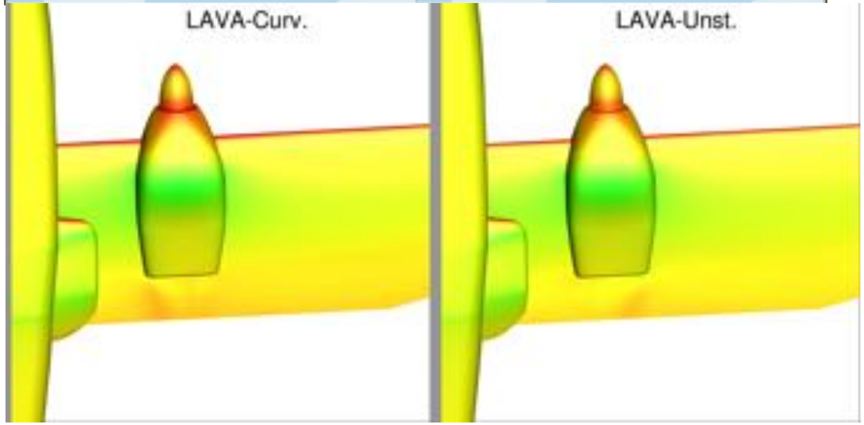


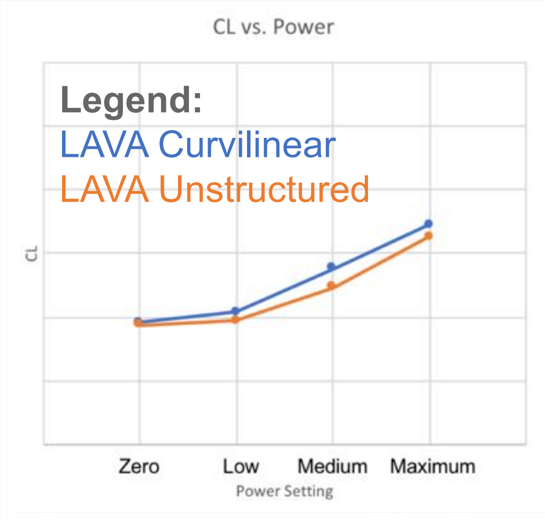
Unstructured mesh

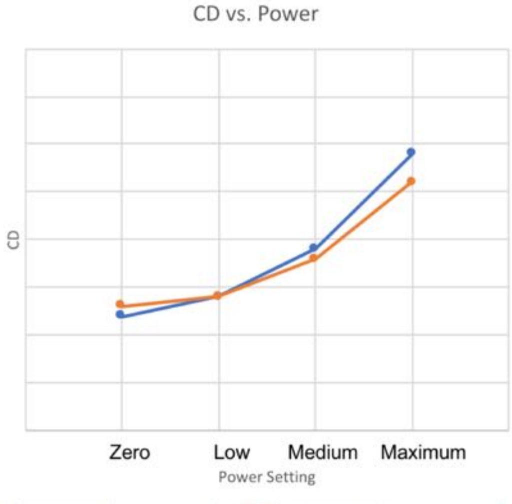
Structured overset mesh

X-57 Propulsion Performance









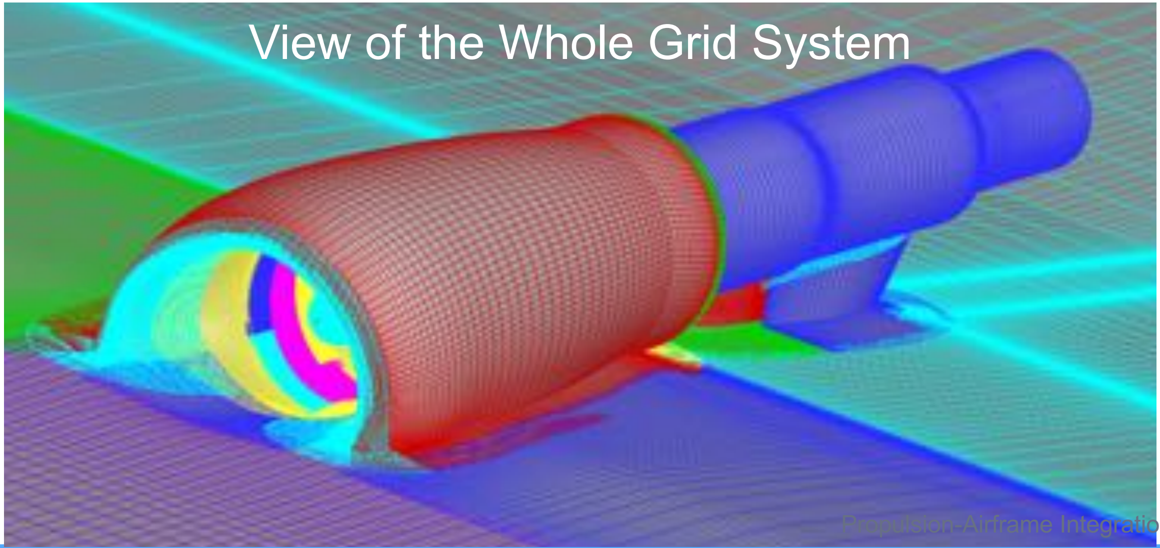
BLI2DTF: Predicting Fan Face Distortion

Goal

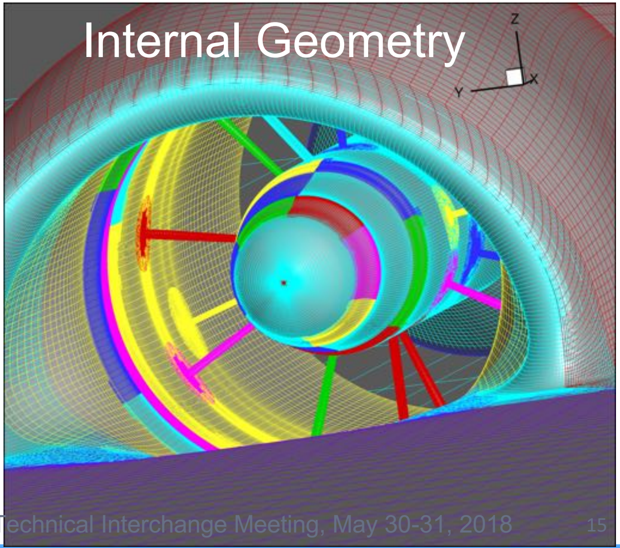
- Perform validation of CFD with different propulsion models in BLI configurations using comparisons with the experiment

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



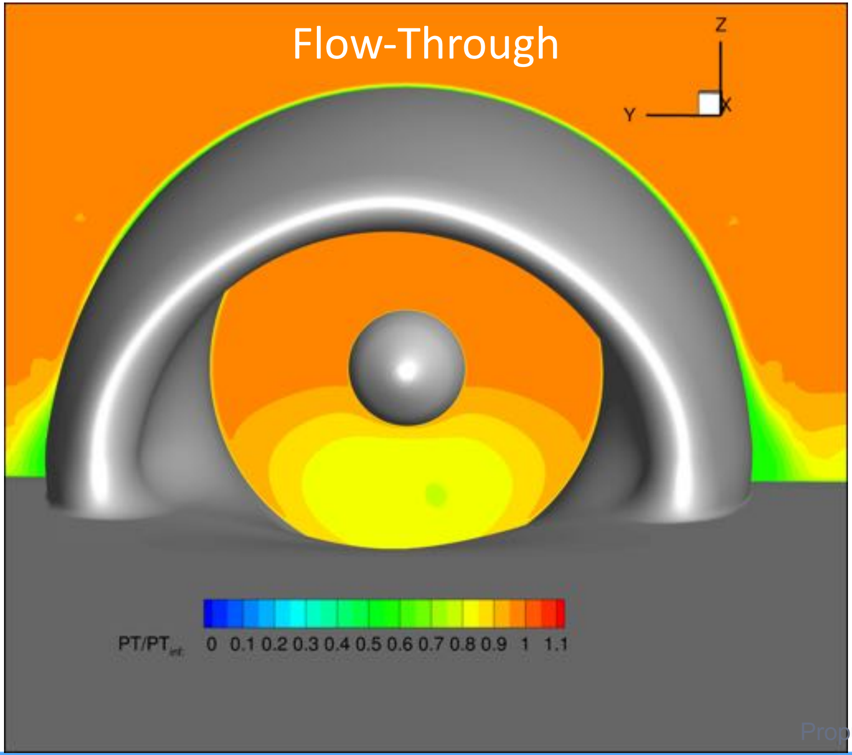
View of the Whole Grid System

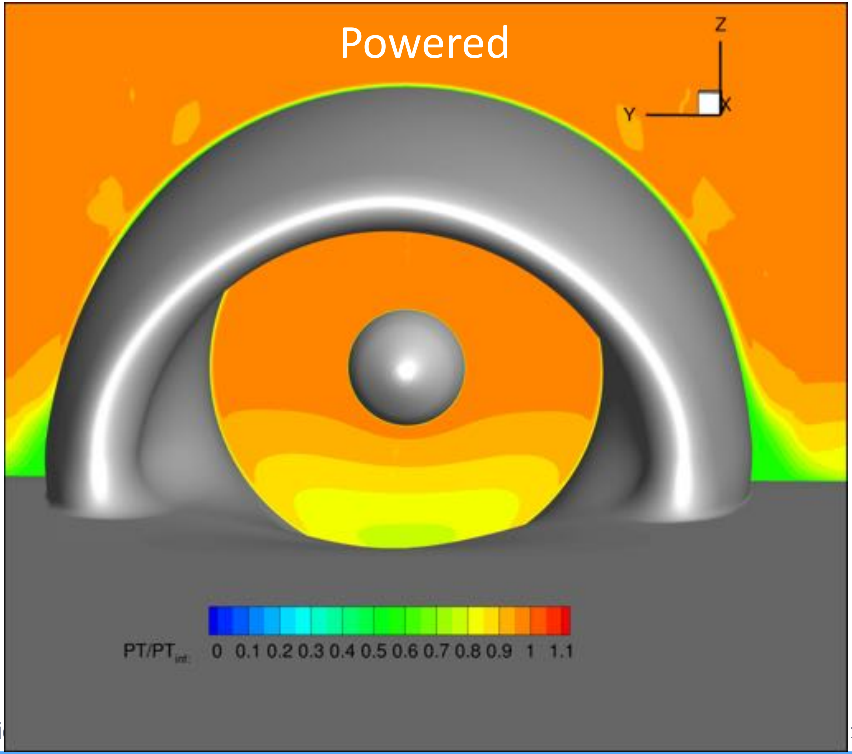


Internal Geometry

BLI2DTF: Predicting Fan Face Distortion

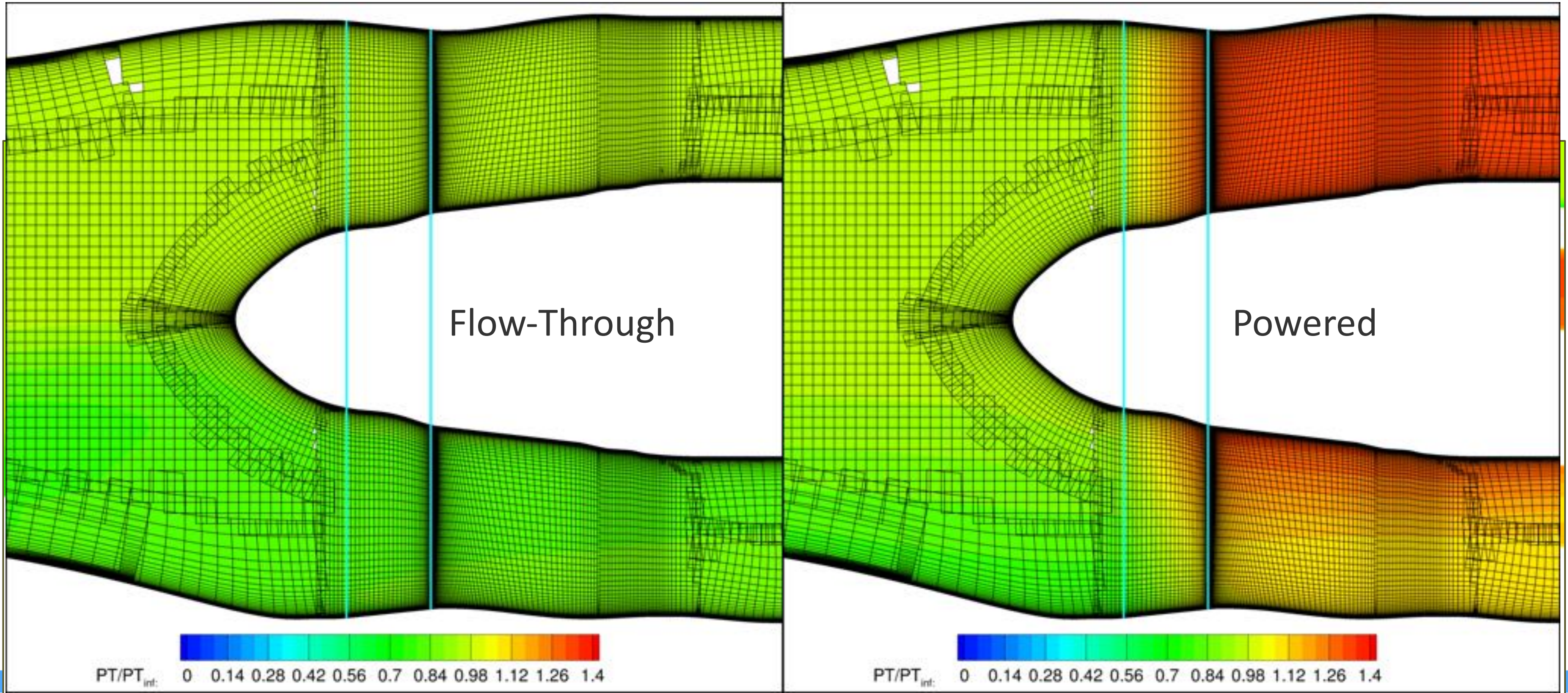
- Comparisons are between flow-through and powered case with the mass flow targeted to 110.66 lb/s (100.23 lb/s corrected).
- The figures below are plots of the total pressure ratio at the fan face





BLI2DTF: Predicting Fan Face Distortion

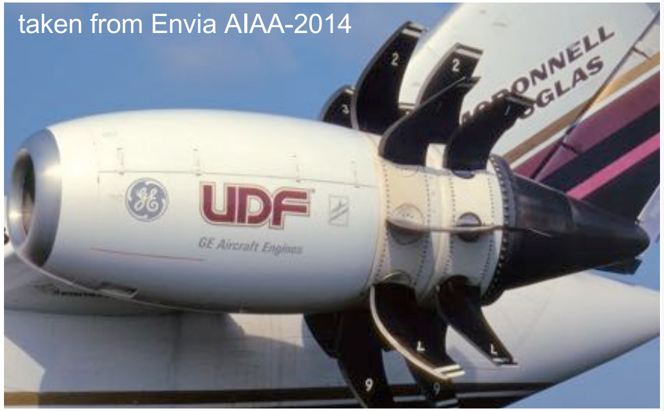
- Comparisons are between flow-through and powered case with the mass flow targeted to 110.66 lb/s (100.23 lb/s corrected). Will compare with experiment once we match geometry.
- Below plots are slices through the centerline of the nacelle with the total pressure ratio; teal lines are where the actuator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



Toward detailed design

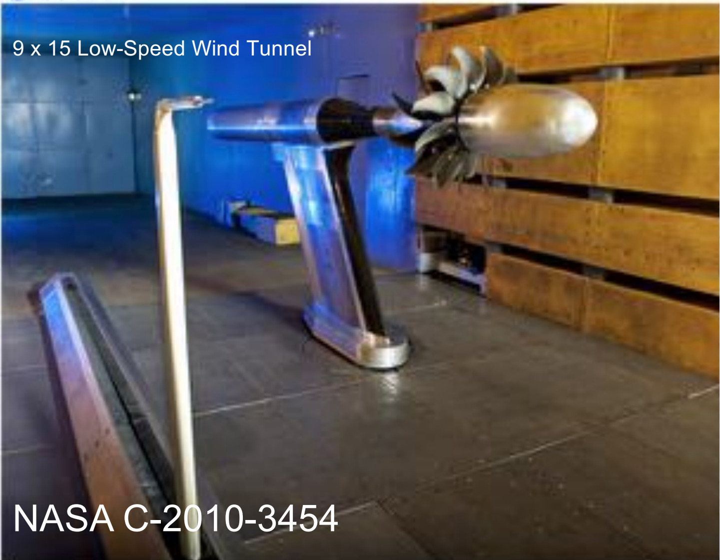
PROPULSION AND AIRFRAME NOISE PREDICTION

Predicting Noise: Open Rotor


taken from Envia AIAA-2014

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


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


9 x 15 Low-Speed Wind Tunnel

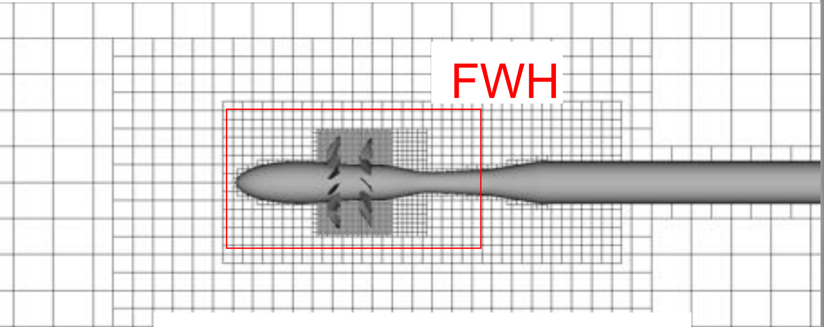
NASA C-2010-3454


8 x 6 Supersonic Wind Tunnel

NASA C-2011-620

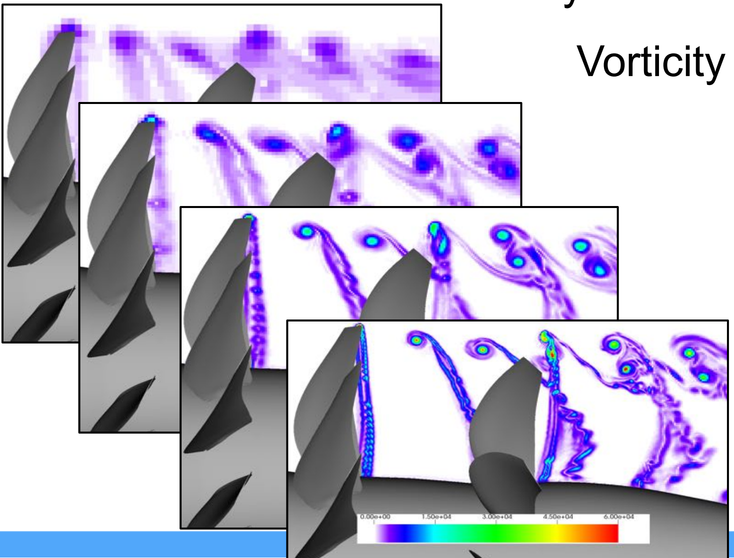
Numerical Schlieren of Unsteady Flow Field

Structured Cartesian AMR

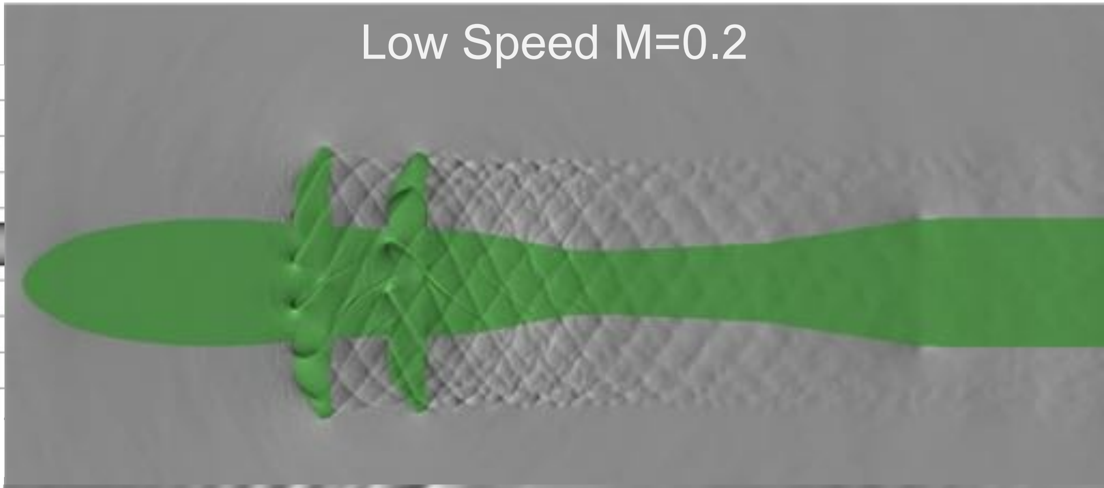


Each box contains 16^3 grid points

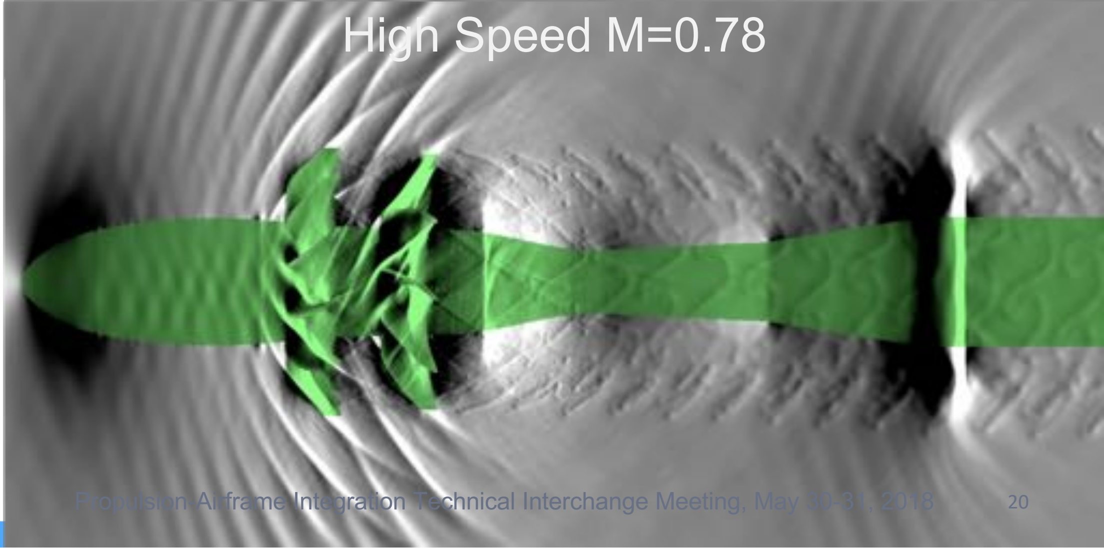
Grid Refinement Study for M=0.2:



Low Speed M=0.2



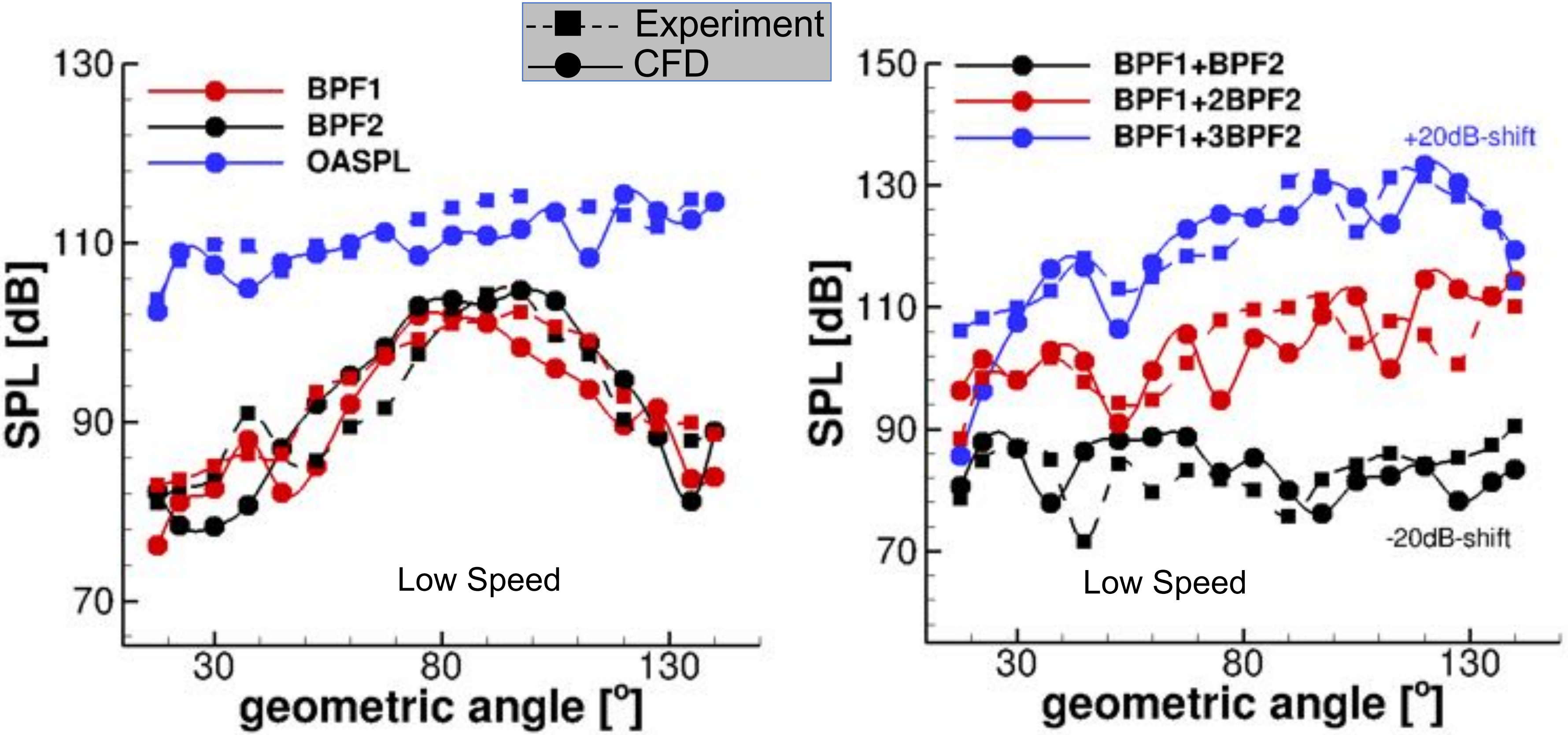
High Speed M=0.78



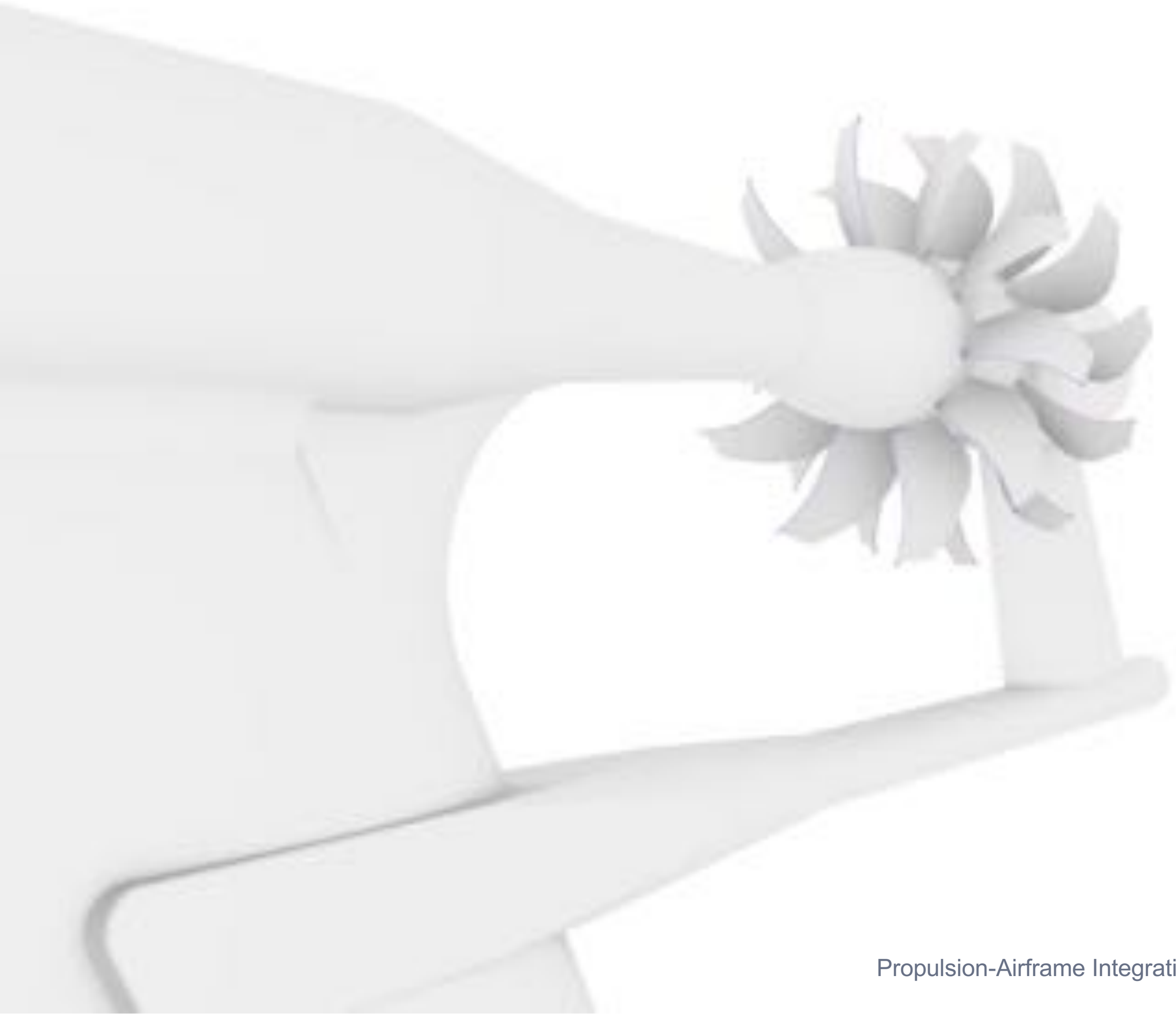
Experimental Validation of Open Rotor Noise

Fundamental Tones

Higher-Order Interactions



Investigating Installation Effects

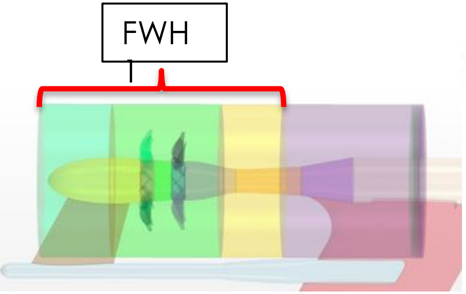


Seed colors:

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

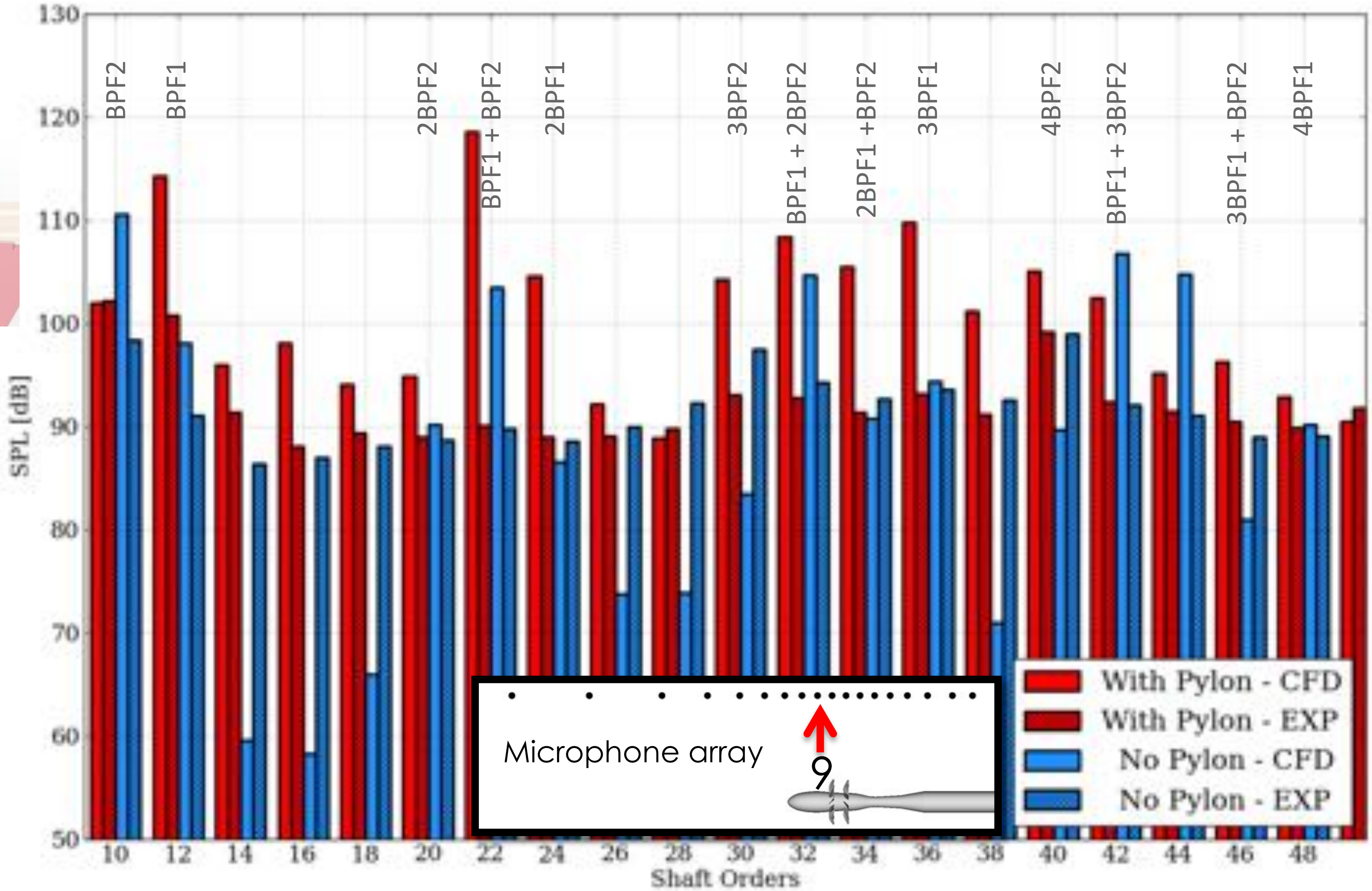
Investigating Installation Effects

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

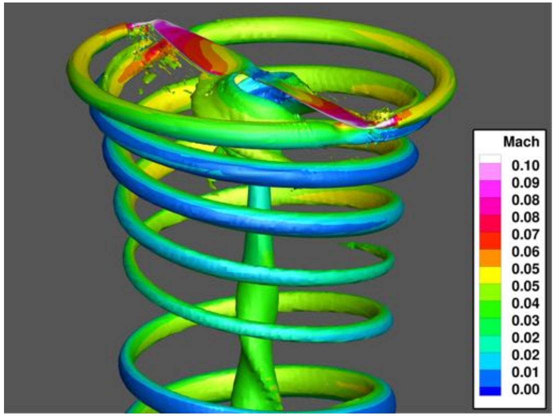
- **Build-up approach**
  - Single rotor first
  - Add other rotors
  - Add fuselage

- **Computational Methodology**
  - Overset Structured Grid/Solver
  - Cartesian AMR

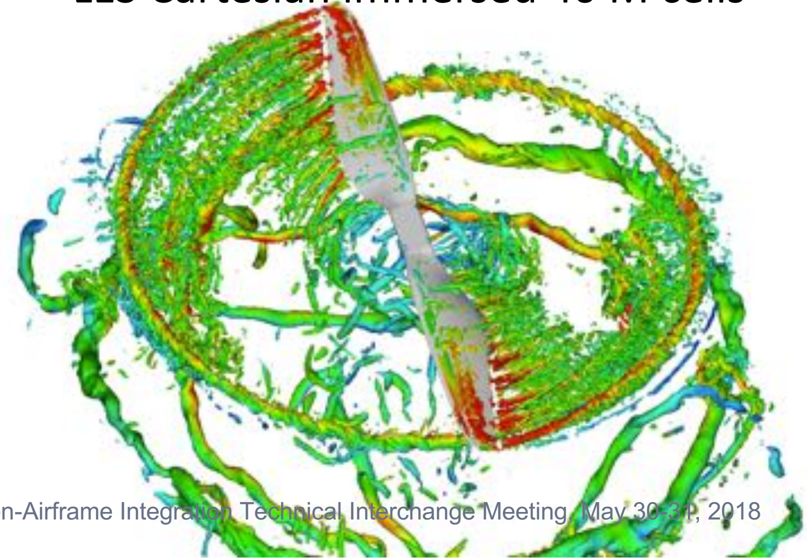
- **Validation Comparison**
  - Integrated Loads
  - Far-field Acoustics

Data From Zawodny and Haskin AIAA-2017-3709

URANS curvilinear overset 6 M cells

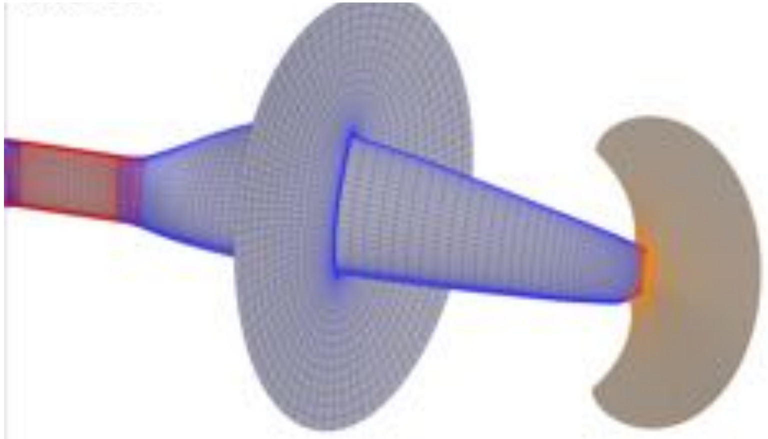


LES Cartesian immersed 40 M cells

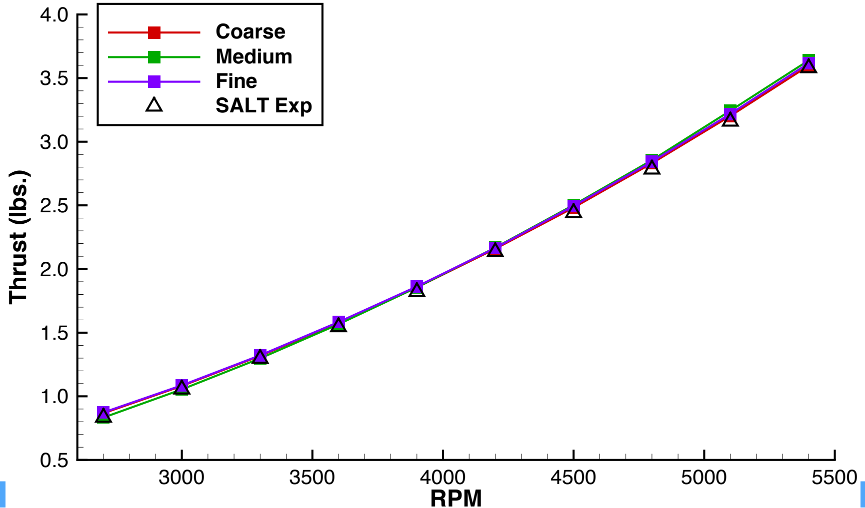


Experimental Validation of SUI Rotor Noise Predictions

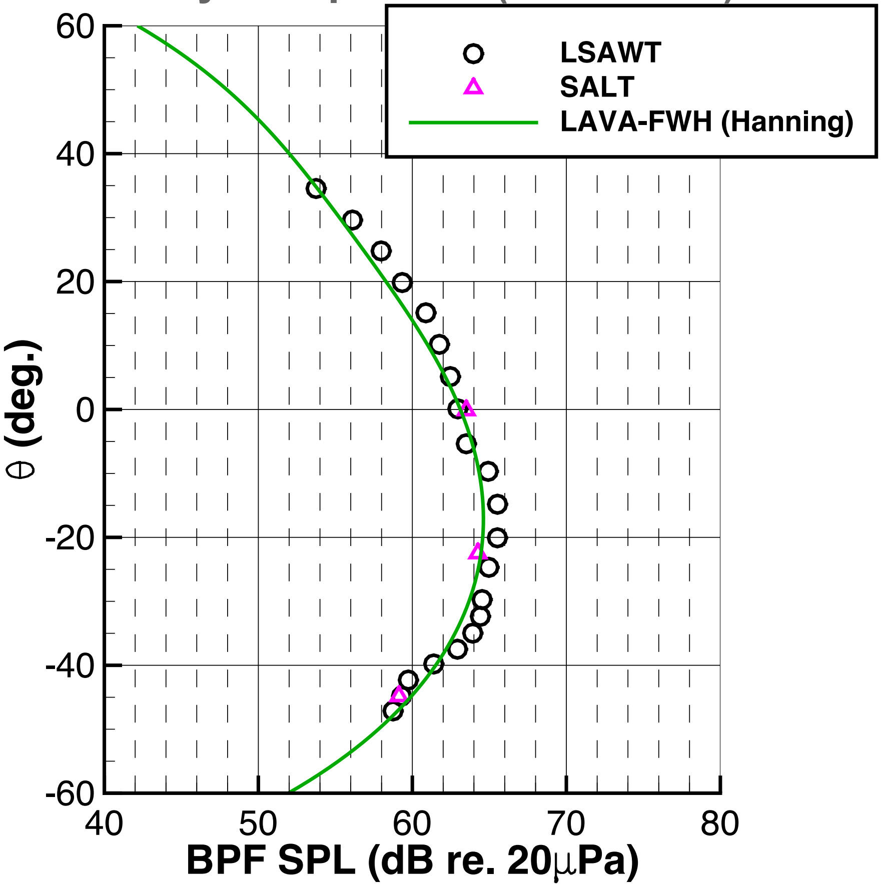
Structured Overset Grid



Integrated Loads: Thrust versus RPM



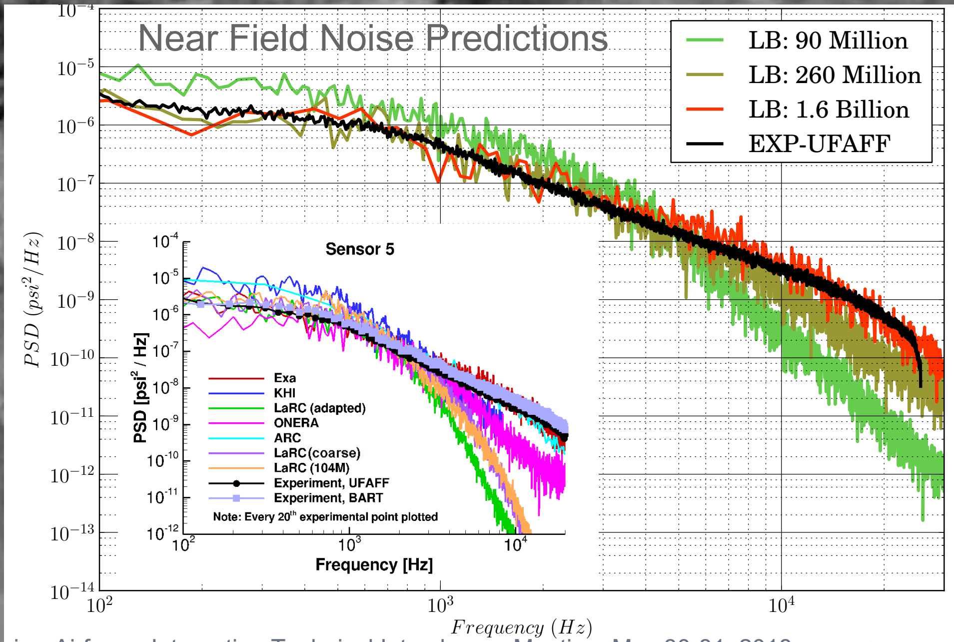
BPF Directivity Comparison (RPM=5400)



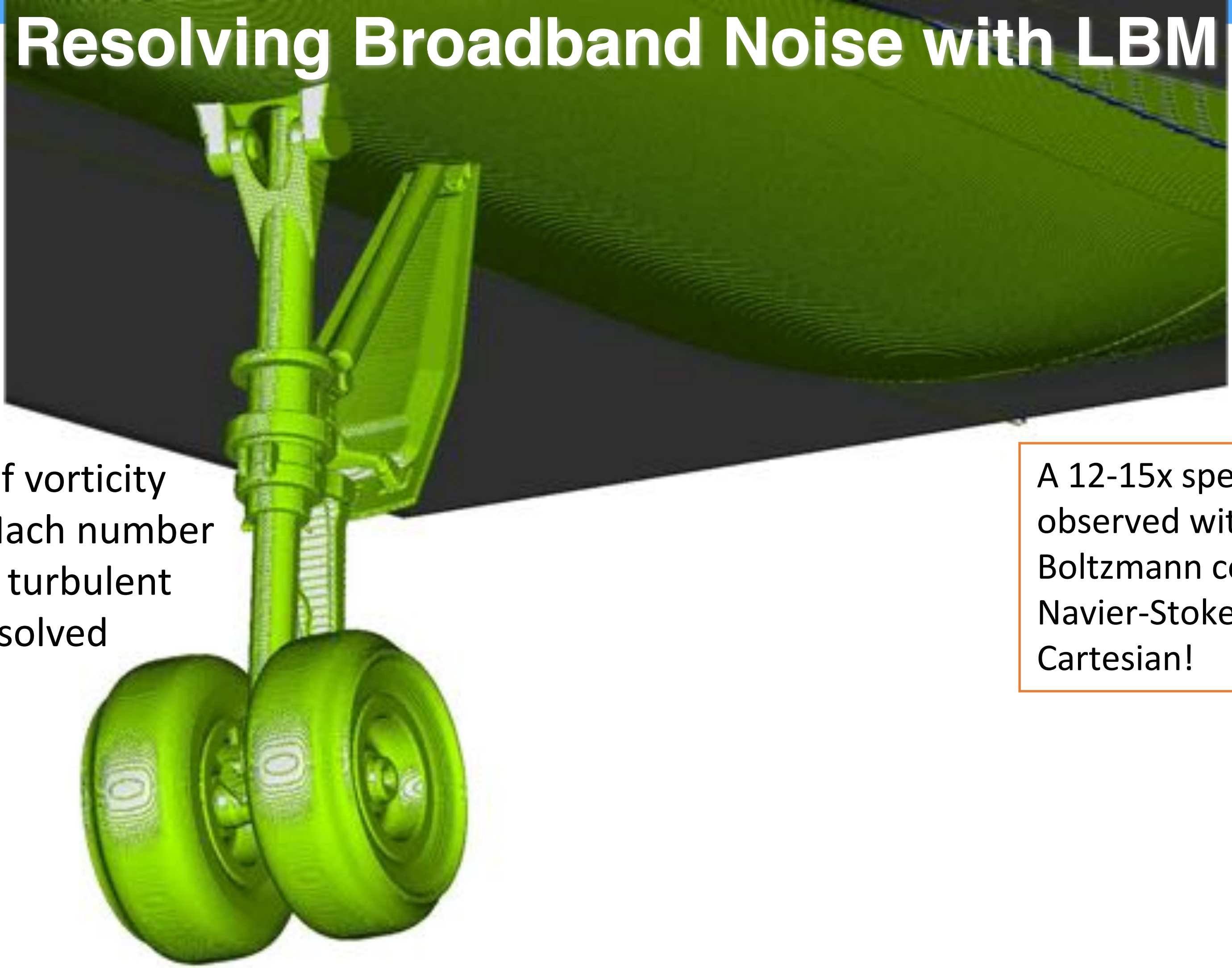
Predicting Landing Gear Broadband Noise

LBM @ 1.6 billion – Velocity Magnitude at Centerline

"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

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

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- Transformational Tools and Technologies (T^3)
- 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