



Coupled CFD Analysis of Propulsion-Airframe Integration

Shishir Pandya, Wai-Ming To

Boundary Layer Ingesting Tailcone System (BLITS)

Novel Propulsion Airframe Integration (NPAI)

Advanced Air Transport Technology (AATT)

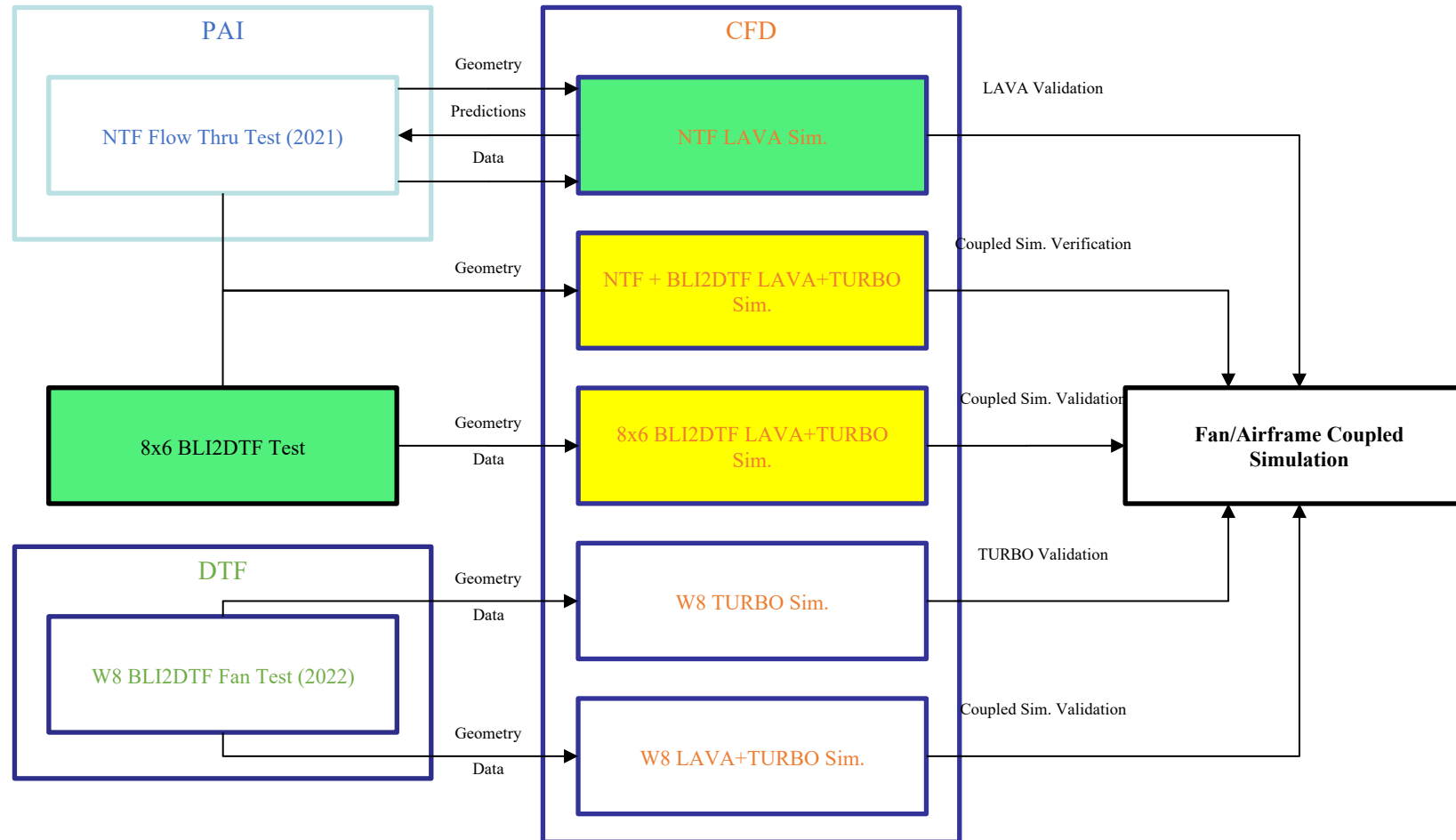
Motivation



- In use today:
 - Airframe CFD with fan models
 - Can obtain proper flow rate and thrust through the nacelle.
 - Can not get any details for propulsor (e.g. efficiency).
 - Propulsor influence on airframe is not modeled.
 - Propulsor CFD
 - Airframe is modeled as inlet boundary condition.
 - Propulsor influence on airframe is not modeled.
- Need:
 - Coupled capability to model airframe and propulsor together.

- Couple state-of-the-art airframe and propulsor solvers.
 - Myriad solvers are available.
- Chose to go with LAVA and Turbo.
 - LAVA has multiple options, but overset structured solver is best suited for this work.
 - Turbo is the obvious choice for propulsor solver.
- Need to verify that we can put an airframe and a propulsor together and run it.
 - Do enough testing to get a feel for
 - Problem complexity,
 - Resource requirements.
- Need to validate solvers against test data.
 - LAVA to be validated against CRM/TCT test in NTF (2021)
 - Turbo has already been validated.
 - LAVA+Turbo coupled capability to be validated using BLI2DTF tests (8x6, W8).

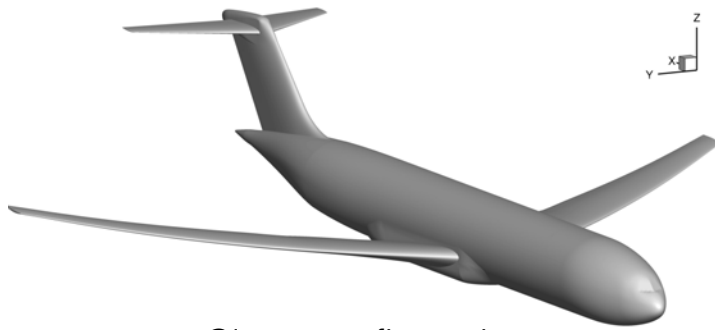
Overview of BLITS



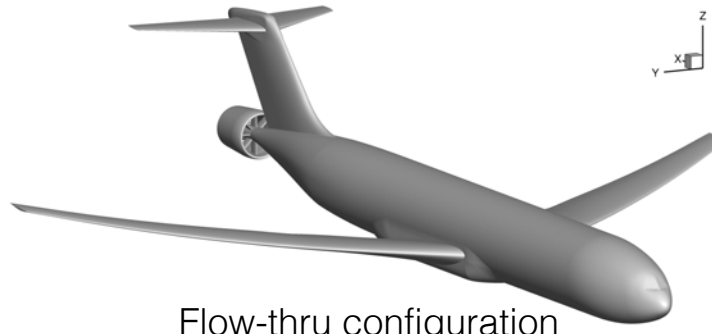
NTF Flow-through Test



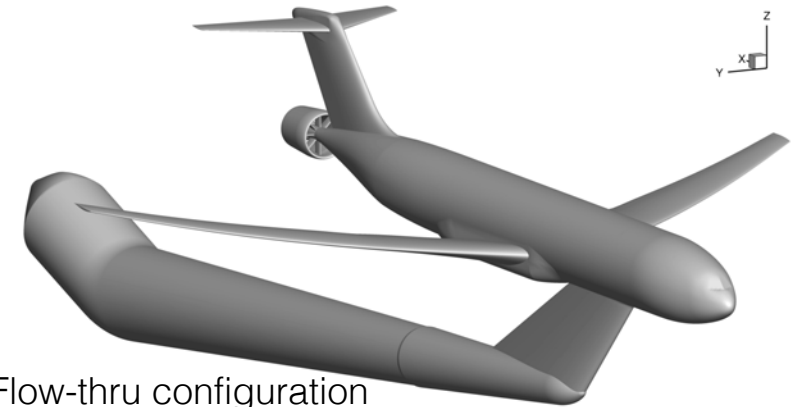
- Test article design is complete.
 - Model manufacturing has begun.
 - Test is delayed due to CoVID19.



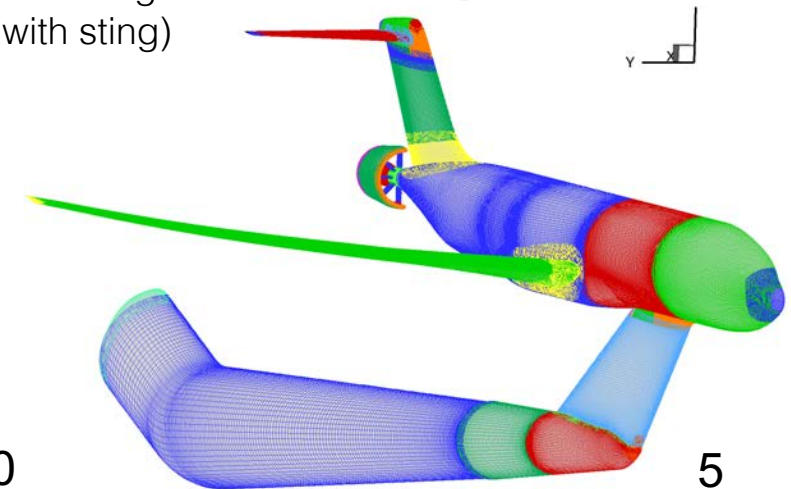
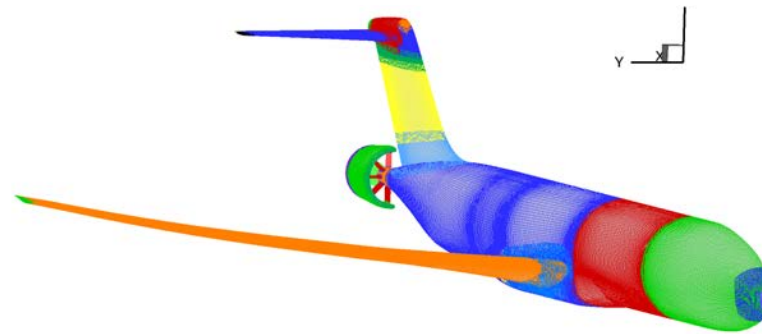
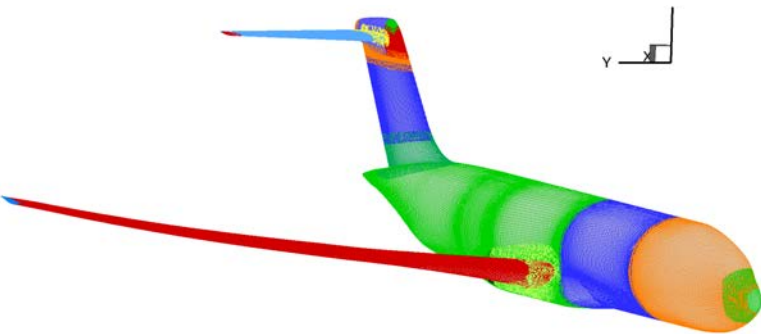
Clean configuration
(no sting)



Flow-thru configuration
(no sting)



Flow-thru configuration
(with sting)



LAVA Curvilinear Solver



- LAVA Curvilinear is a multi-block/overset CFD solver
- It is used for steady RANS, URANS, (Z)DDES, LES and WMLES
- Extremely high computational performance on CPU architectures (MPI + OpenMP Hybrid)
- Various discretizations including central schemes, upwind schemes and HWCNS schemes
- Primitive are used in the code
- Strong non-linear and linear solvers (Inexact Newton's Method + GMRES + ILU(p))
- SA turbulence model + variants
- General equation of state
- Sutherland's Law for viscosity



Scale resolving simulation of the NASA Juncture Flow Model computed using LAVA Curvilinear. Passive particles colored by stream-wise velocity

USM3D Mixed Element Solver



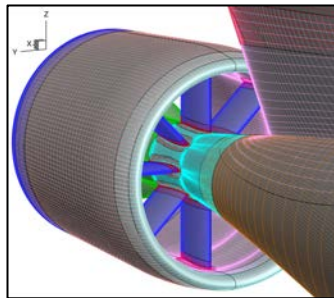
- Solver Details
 - Cell-centered RANS/Euler solver
 - Mixed element version of USM3D allows for variety of cell types including tets, prisms, hexes, and pyramids
 - Variety of inviscid flux schemes and flux limiters
 - Only SA-Neg-QCR implemented for turbulence at this time
 - Offers both time-accurate and steady-state solution strategies
 - Features HANIM solver to drastically improve convergence rate
- Solution Strategy
 - Steady-state
 - Roe scheme for inviscid fluxes with no limiter
 - SA-Neg-QCR for turbulence model
 - HANIM to accelerate convergence

NTF Flow-through Test: Mesh Refinement

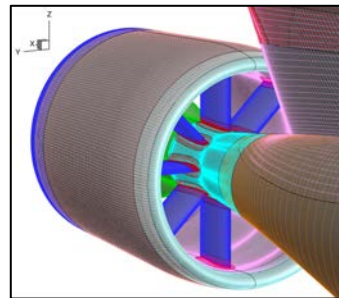
- NTF conditions precomputed using **LAVA** and **USM3D**.
 - Mesh refinement study performed with both solvers.

	Clean			Flow-thru cruise		
	Coarse	Medium	Fine	Coarse	Medium	Fine
# Grid Points (million)	21 / 15	59 / 45	156 / 135	30 / 20	84 / 60	224 / 180

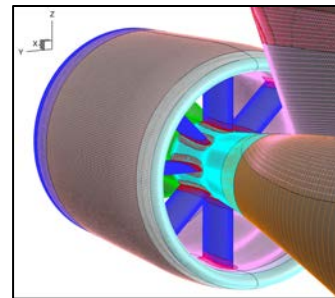
LAVA



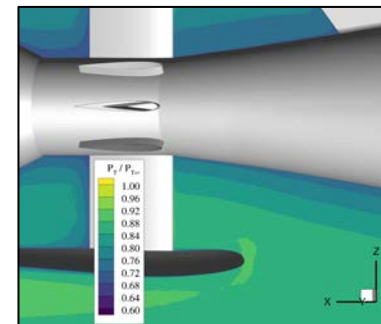
Coarse



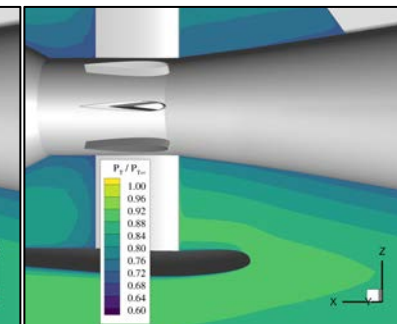
Medium



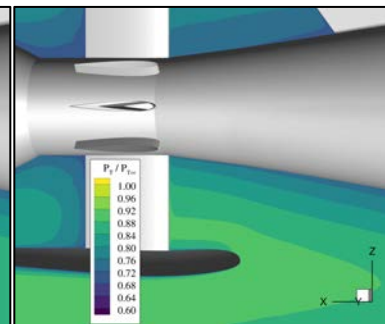
Fine



Coarse

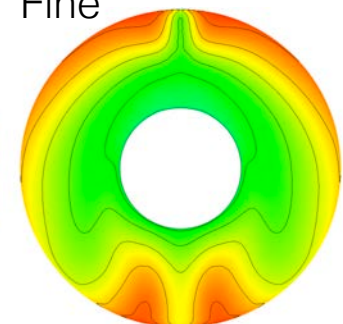
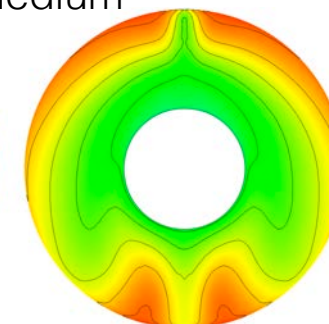
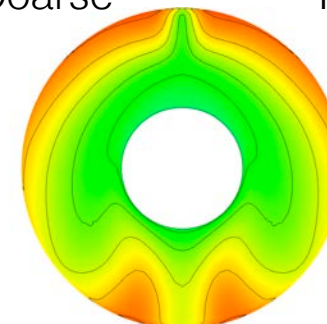
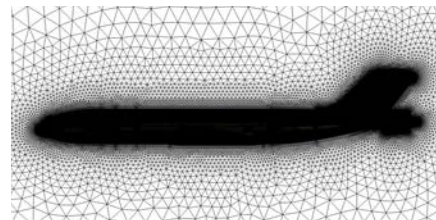
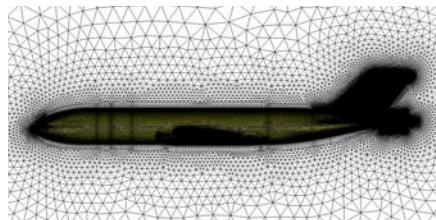
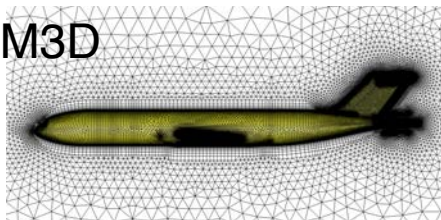


Medium



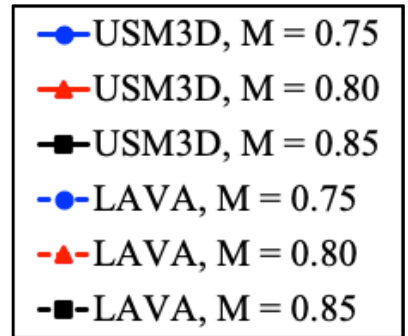
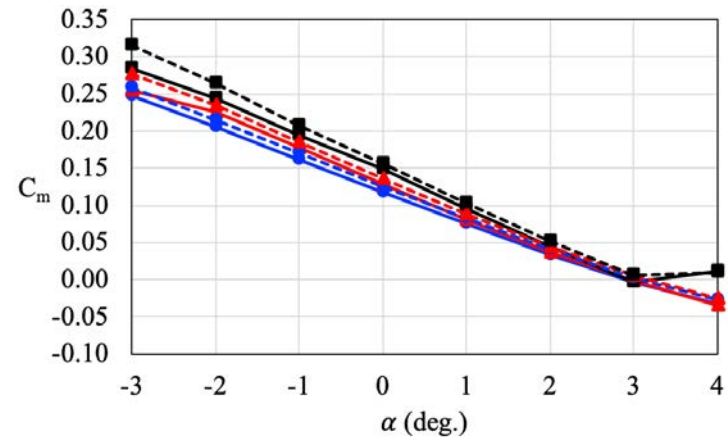
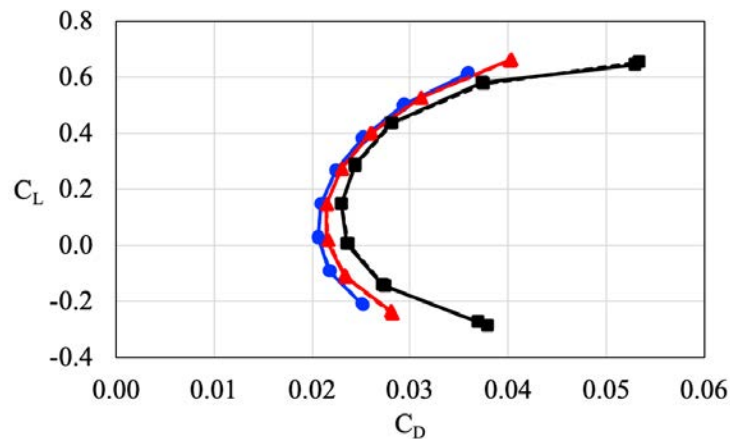
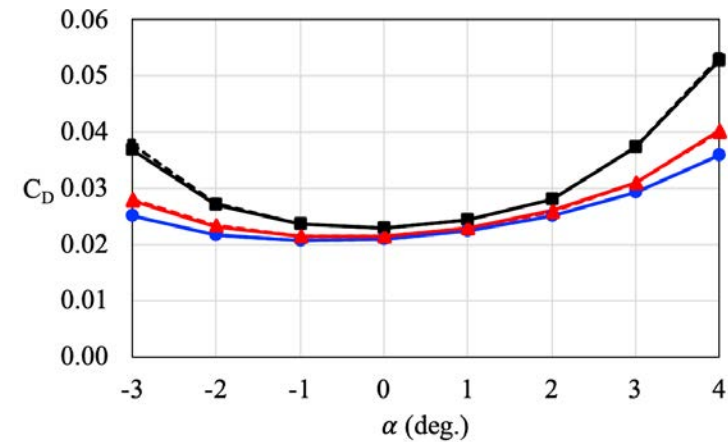
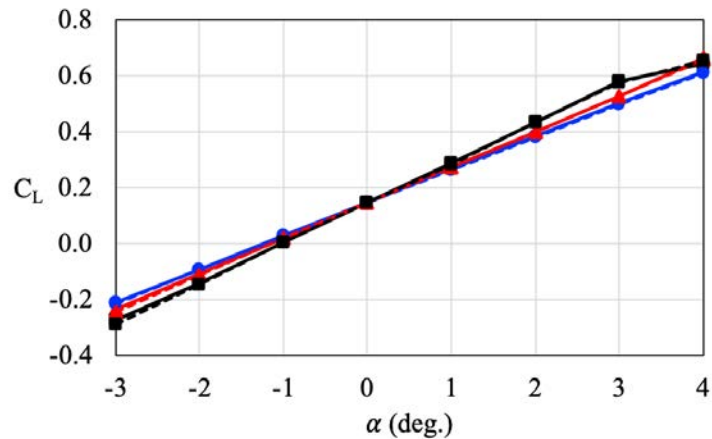
Fine

USM3D



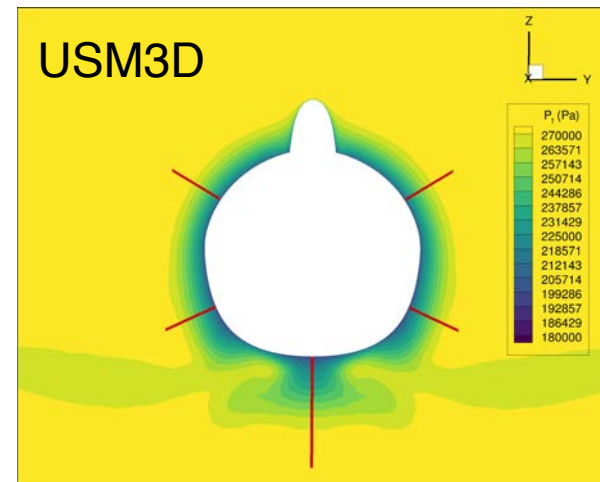
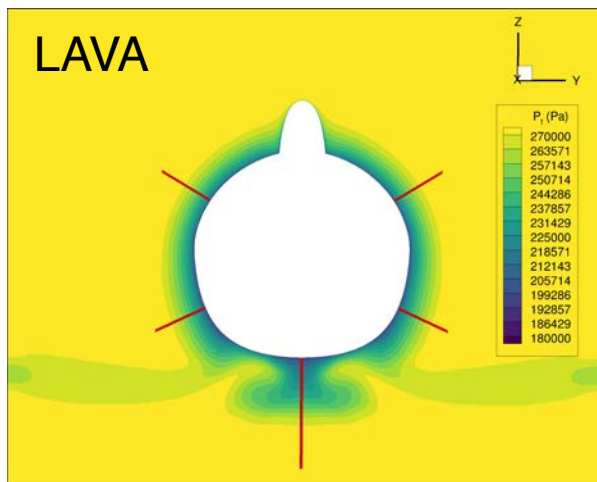
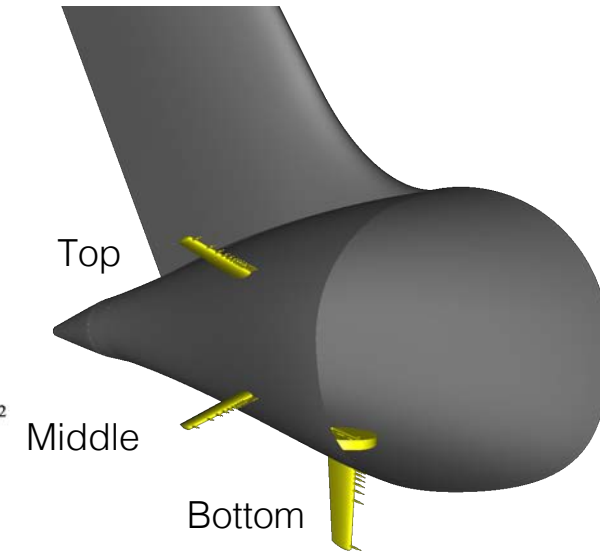
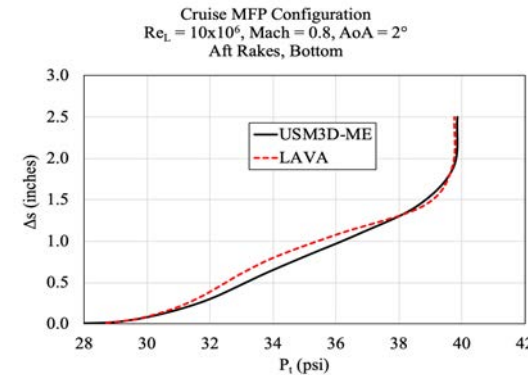
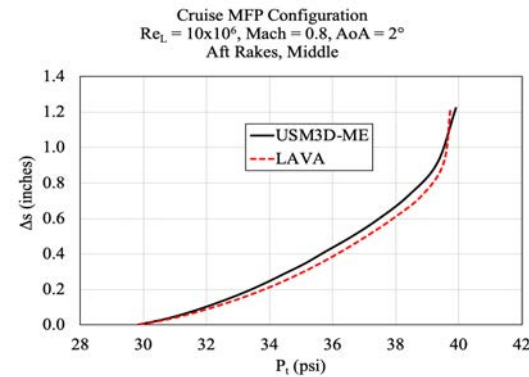
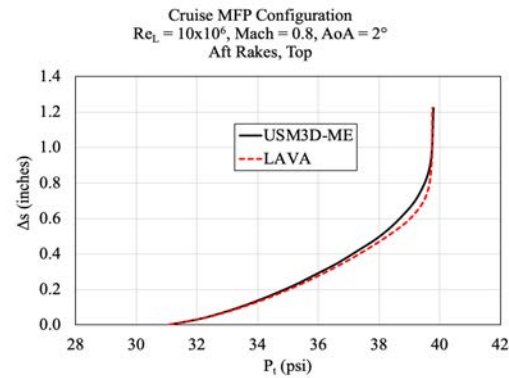
NTF Flow-through Test: Loads

- Ran α sweeps for $Re=5, 10$, and 20 million at mass flow rates of cruise $\pm 10\%$.
- Good agreement between codes for forces. Pitching moment is more sensitive.



NTF Flow-through Test: Boundary Layer Profiles

- Minor disagreements in boundary layer profiles due to mesh density.

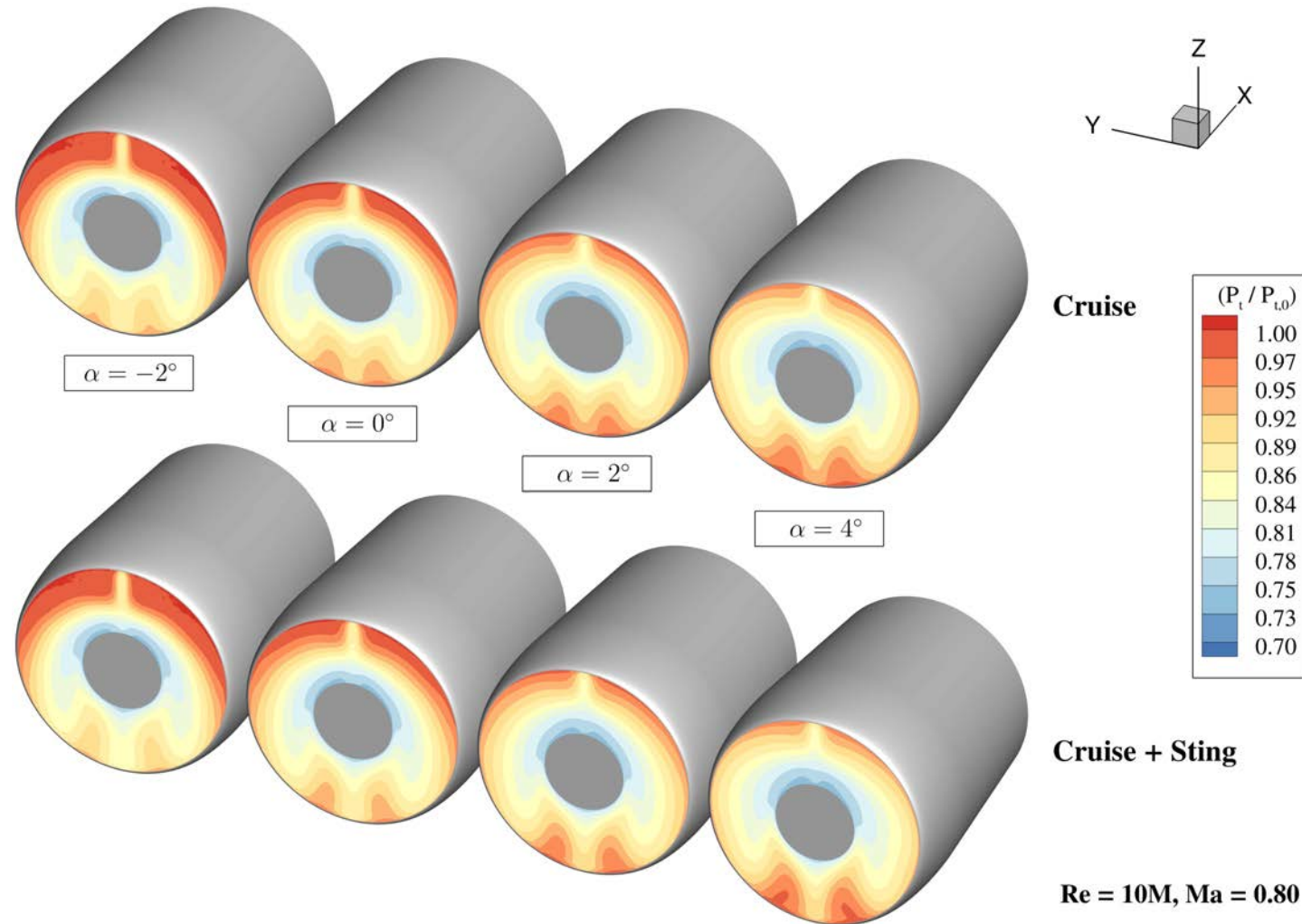


NTF Flow-through Test: Total Pressure vs. Angle of Attack



Re = 10M, Ma = 0.80

- At lower angles of attack, the **nacelle** partially **ingests flow unaffected by remaining aircraft structures**, between $\theta \approx 10^\circ$ and $\theta \approx 90^\circ$
- **Higher total pressure losses on top half of hub** as angle of attack increases
- **Total pressure losses increase** around $\theta = 180^\circ$ when **sting** is included
- **Mixing** of near-freestream flow with boundary layer flow due to fuselage upswEEP eddies is **enhanced by the presence of the sting**, leading to an increase in the maximum total pressure ratio measured at all ARP1420 locations, around $\theta = 175^\circ$

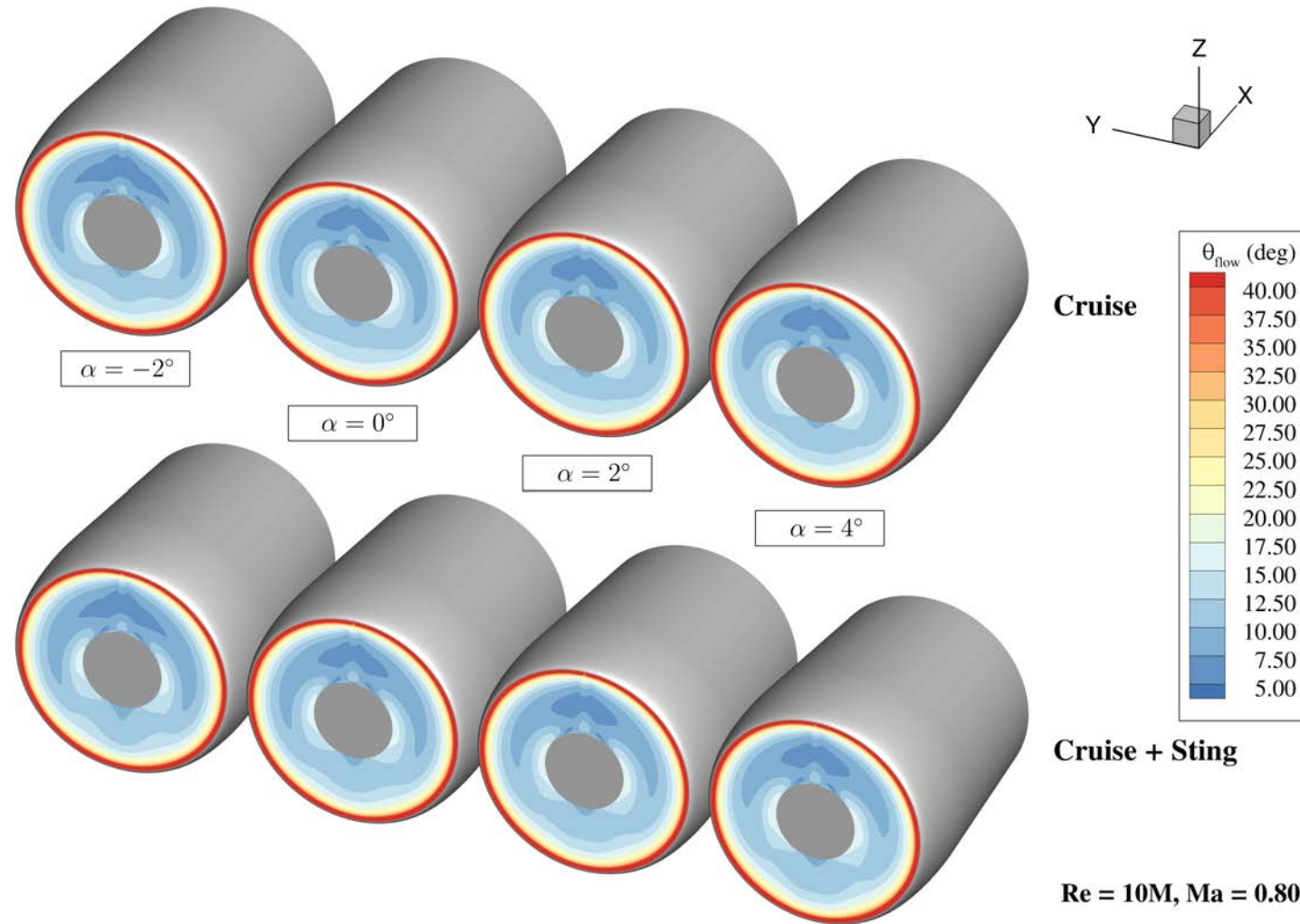


NTF Flow-through Test: Flow Angularity vs. Angle of Attack



Re = 10M, Ma = 0.80

- Lowest flow angularity region always located around $\theta = 0^\circ$, regardless of angle of attack
- Ring of high flow angularity around nacelle shroud lip due to high streamline curvature
- Effect of sting negligible except around $\theta = 180^\circ$, where a lower flow angularity is most noticeable for $\alpha = -2^\circ$
- **Validation**
 - After the test occurs, these results will be compared to test data for validation.

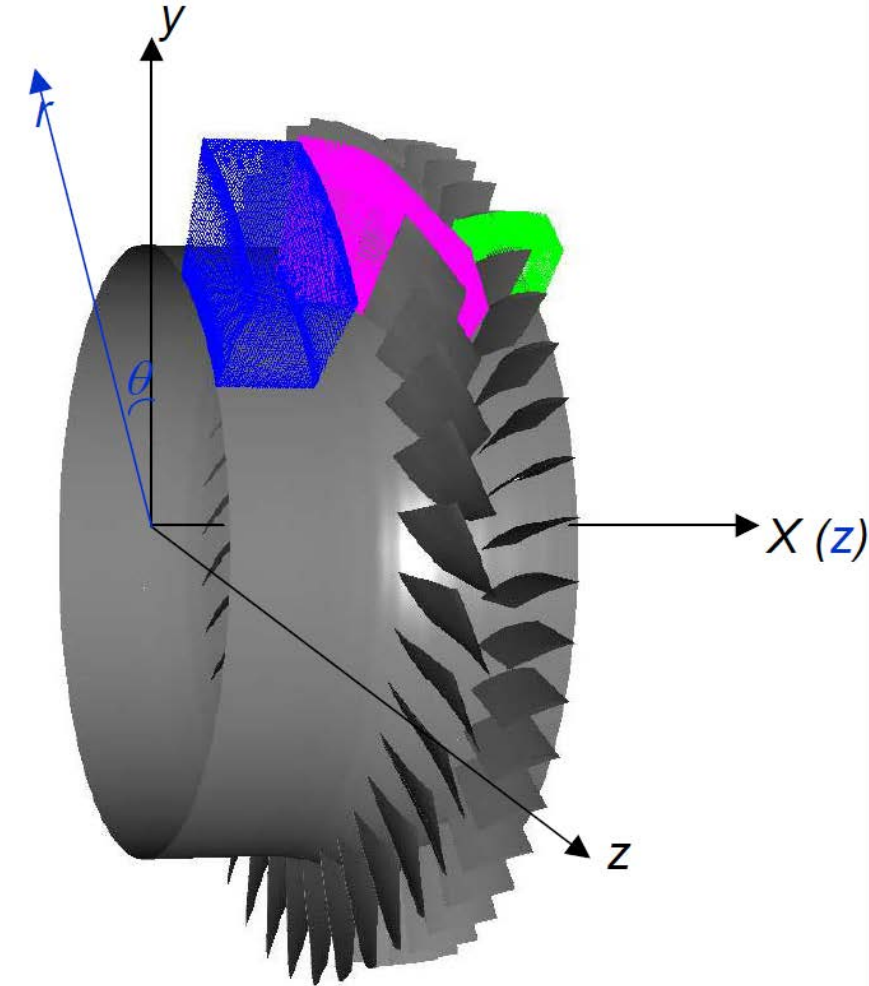


Nacelle highlight contours of flow angularity for different cases

TURBO Code



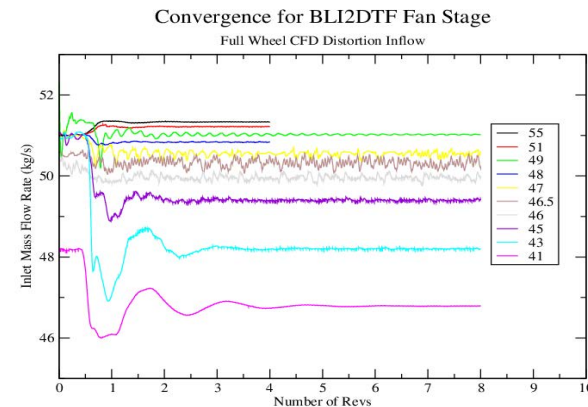
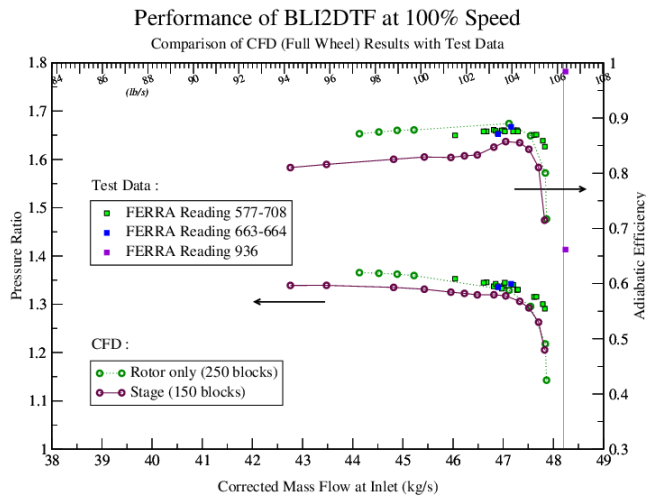
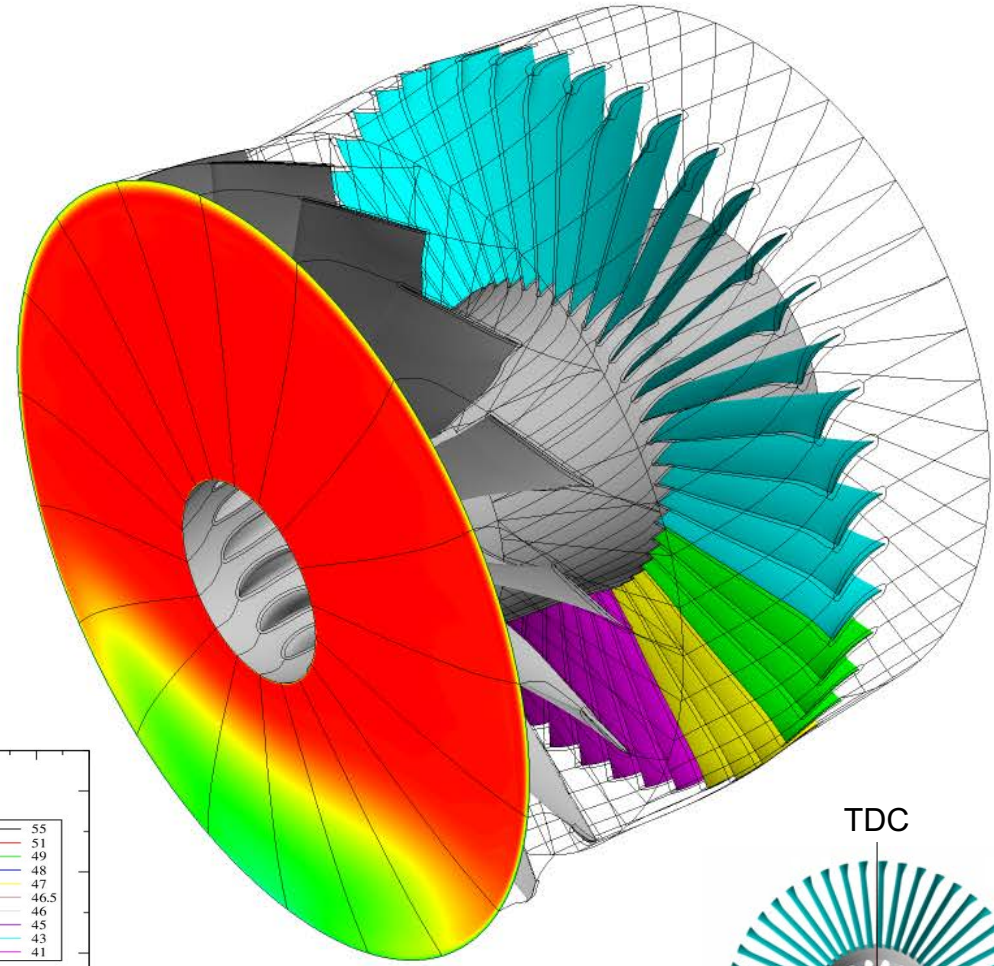
- The main function of TURBO is to perform high fidelity CFD simulations of rotating turbomachinery
 - Multistage capability allows rotating and stationary blade rows
- TURBO is a URANS based CFD solver
 - Equations formulated in the relative frame
- Numerical features
 - Structured multi-block grid capability
 - Finite volume discretization utilizing conservative variables
 - Constructed with non-dimensional variables
 - Fluxes based on a Roe scheme
 - Implicit time marching
 - Newton and Gauss-Seidel relaxation
 - k- ϵ turbulence model



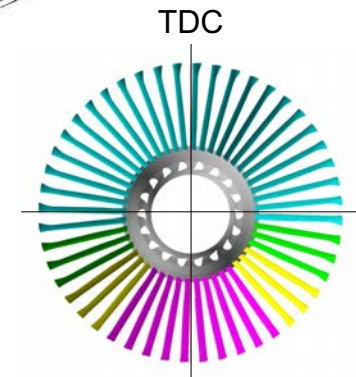
NASA BLI2DTF Fan Stage Test



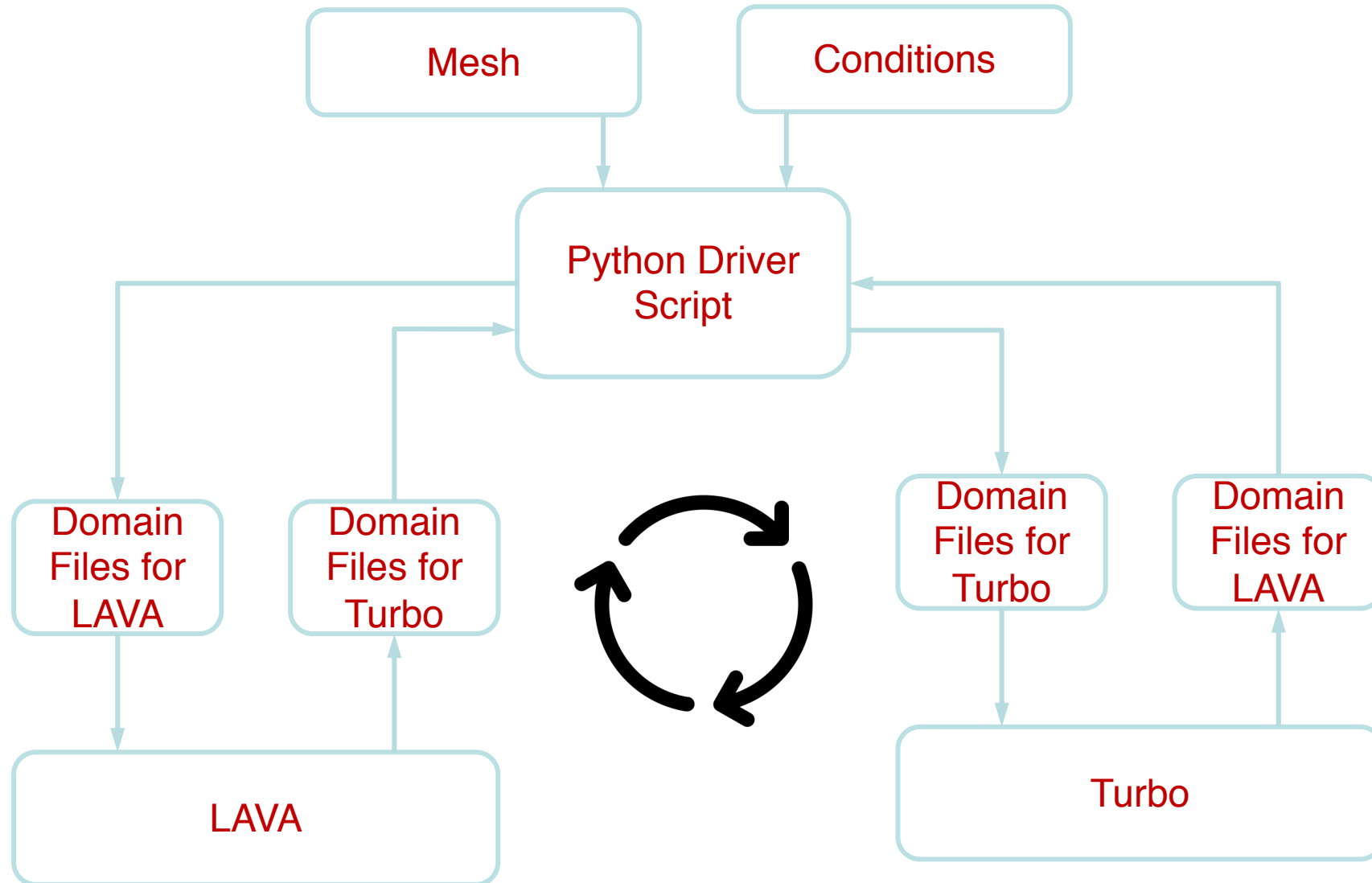
- 2D flow distortion profiles extracted from UT CFD imposed statically at the inflow boundary
- Blade counts: 18/48
- Rotor span = 7.37" (0.187 m)
- $\Omega = 11863.5$ RPM (~ 0.005 s/rev)
- Rotor tip speed = 345 m/s
- Tip gap, $d = 0.01$ " (0.000254 m), $Re_d = 5150$
- Average inlet speed = 255.5 m/s
- Diameter, $D = 22$ " (0.5588 m), $Re_D = 9.7 \times 10^6$
- Rotor midspan cord, $c = 0.078$ m, $Re_c = 1.36 \times 10^6$
- 85 million cells in 150 blocks
- Mesh file size ≈ 1 G, q vector file size ≈ 1.7 G
- 1800 time steps per rev
- 8 revs in 94 hours wallclock time



- 4 types of airfoil
- Round OGV hub
- Elliptic OGV casing



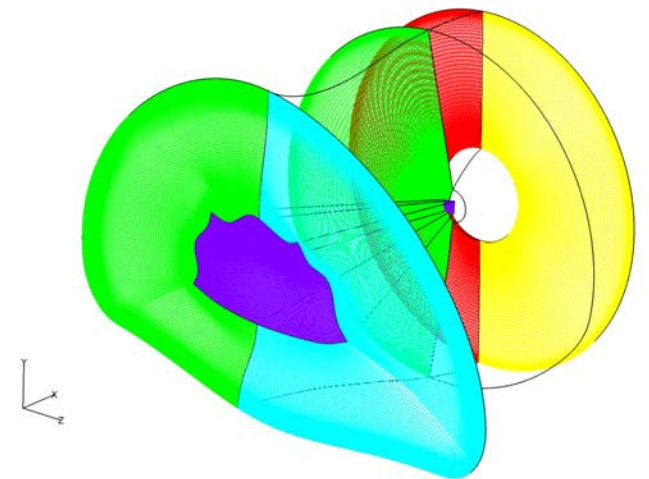
LAVA+Turbo Coupling



LAVA+Turbo Coupling: Plan



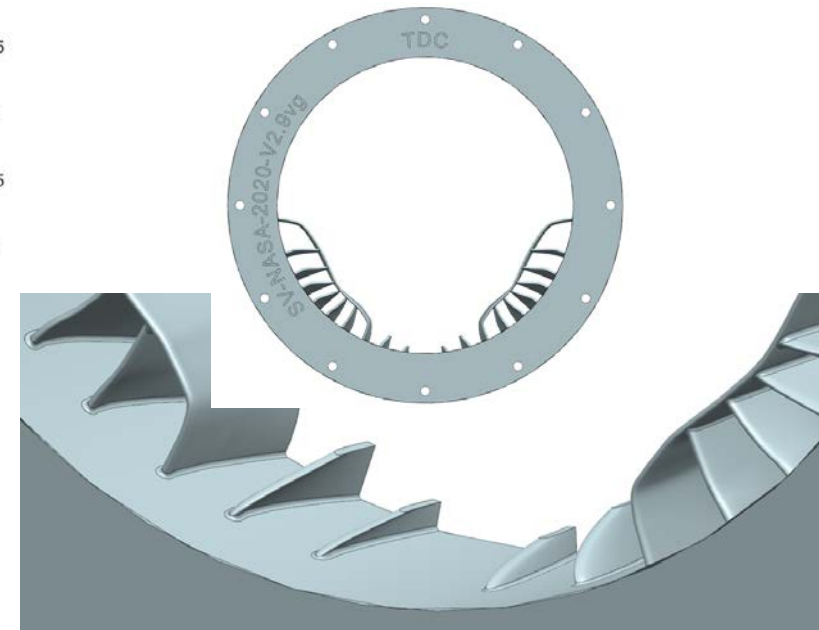
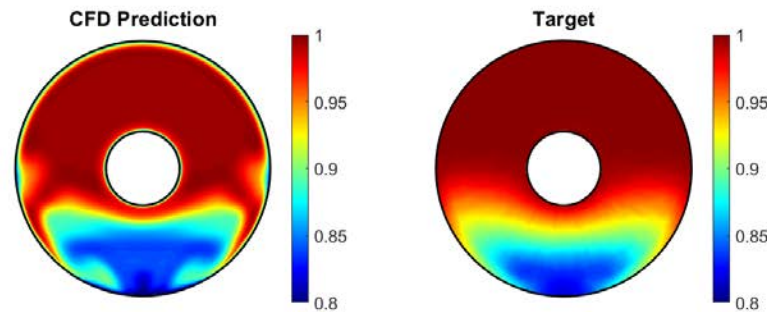
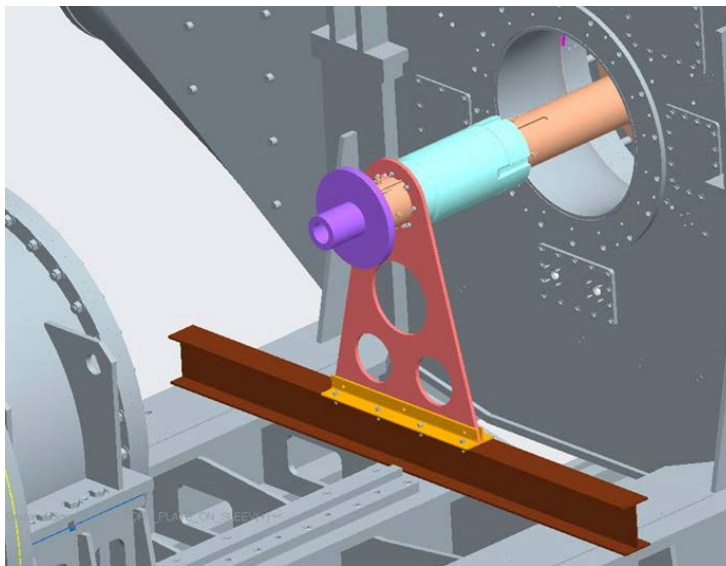
1. Coupled LAVA+TURBO tests:
 - a. Coupling mechanics tests:
 - 2-block rectangular channel – *inviscid, upstream interface*.
 - 3-block circular annular duct – *turbulence quantities, downstream interface BC*.
 - b. Bladeless propulsor tests: 8x6 BLI2DTF or NTF – *mesh disparity between LAVA and TURBO, mesh topology*.
 - 3-5 points per degree or $\mathcal{O}(10^3)$ points circumferentially, $\mathcal{O}(10^2)$ points radially.
 - c. Rotor only propulsor tests: 8x6 BLI2DTF or NTF – *data exchange frequency test*.
 - Wheel speed is $\mathcal{O}(\text{msec})$ per rev and time step size is $\mathcal{O}(\mu\text{sec})$.
 - d. Axisymmetric BLI2DTF fan stage tests.
 - e. Validation: 8x6 BLI2DTF wind tunnel test; W8 BLI2DTF wind tunnel test.
2. Fullwheel TURBO simulation of a TCT fan for the NTF:
 - Scaled axisymmetric BLI2DTF @ 2° AOA
3. Lightweight CAD model for the 8x6 BLI2DTF geometry.



W8 Testing



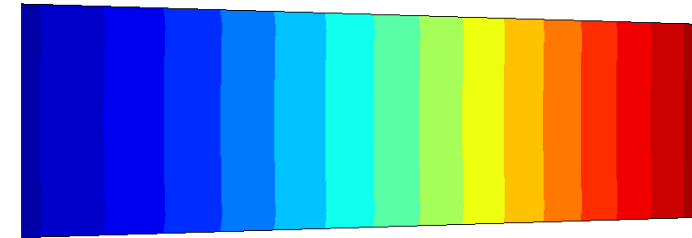
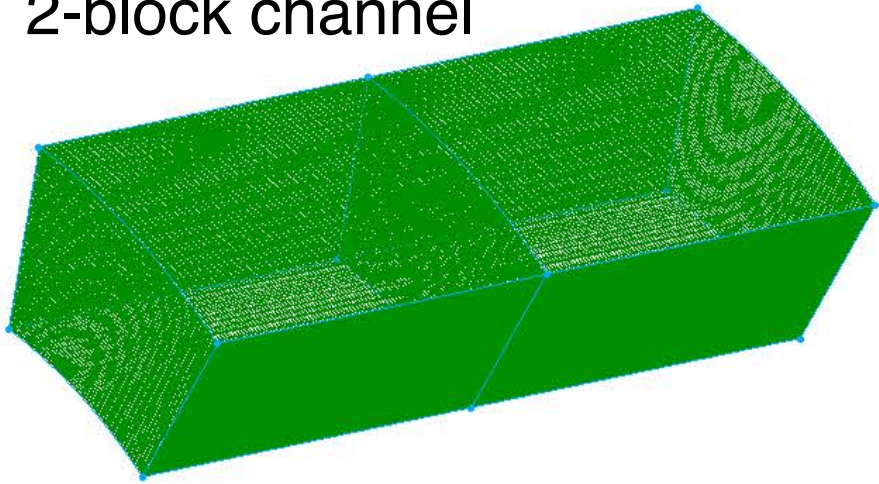
- Final W8 upgrades are progressing.
 - Expect to begin flow checkout testing in W8 soon.
- Using BLI2DTF means fan does not need to be manufactured.
- Screenvanes under development at Va. Tech. to model engine inlet conditions.



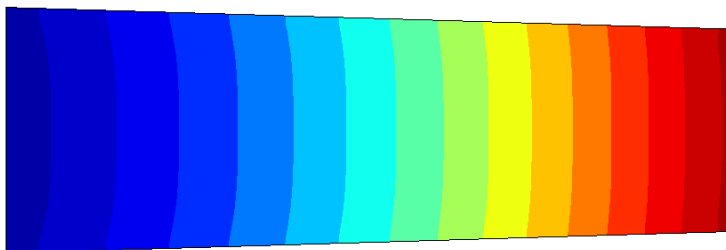
LAVA+Turbo Coupling: 1st problem



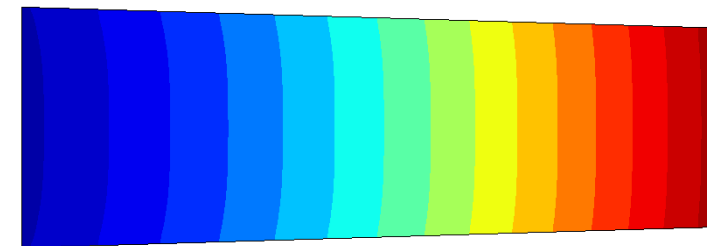
- 2-block channel



TURBO-TURBO coupling



LAVA-TURBO decoupled

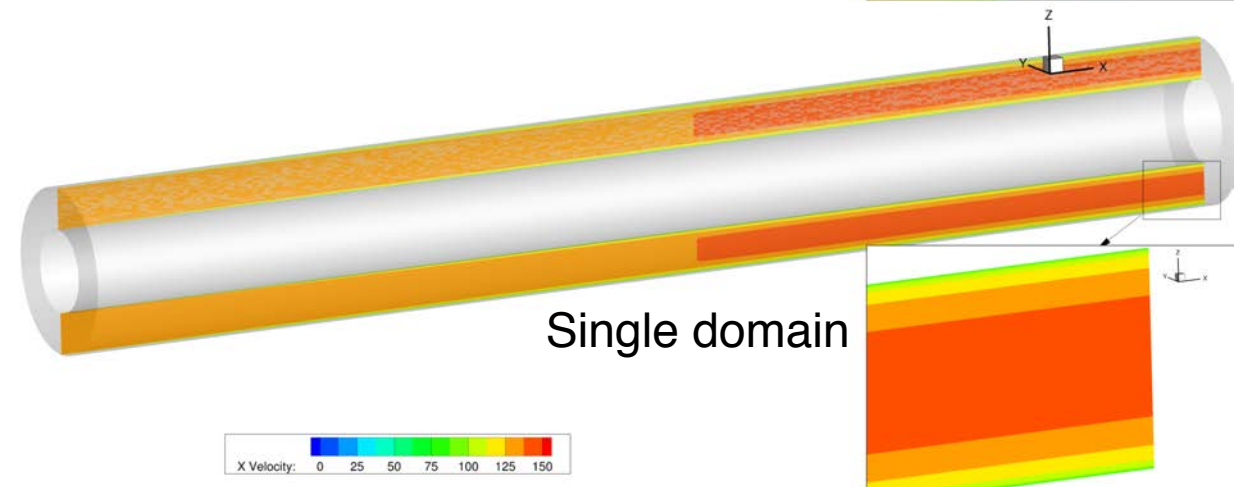
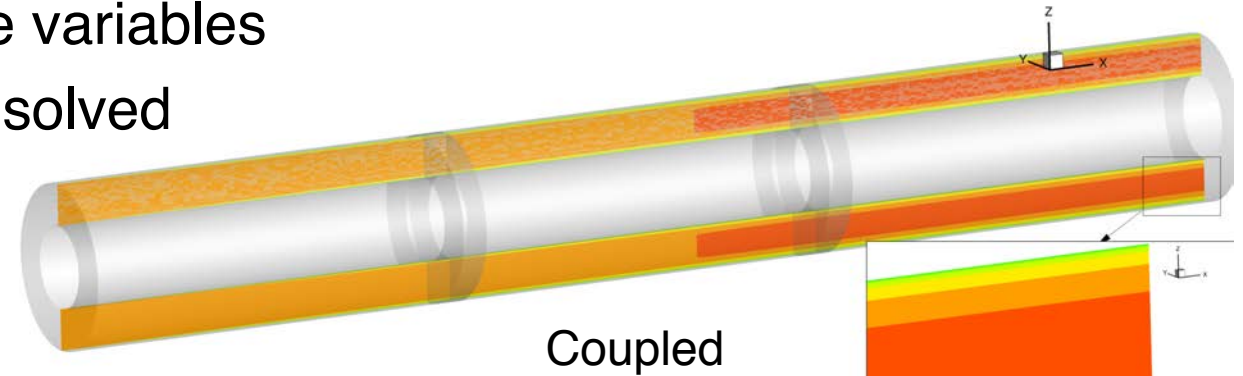
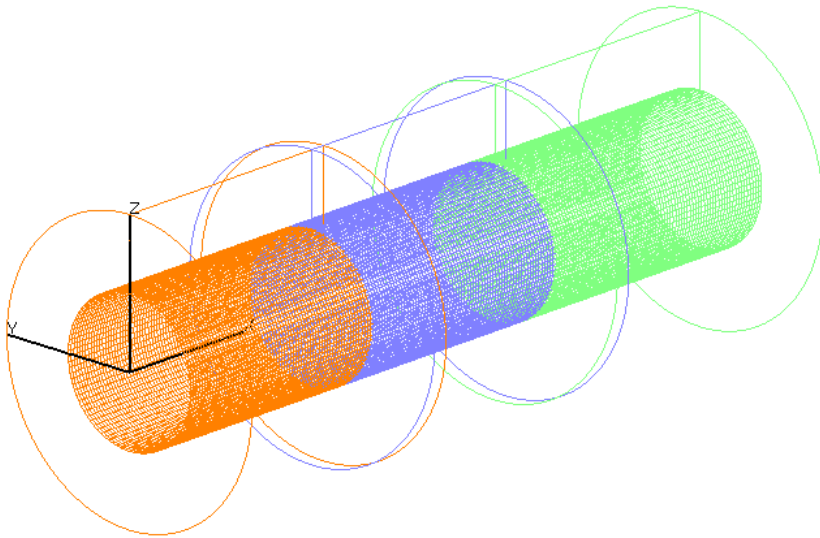


LAVA-TURBO coupling

LAVA+Turbo Coupling: 2nd problem

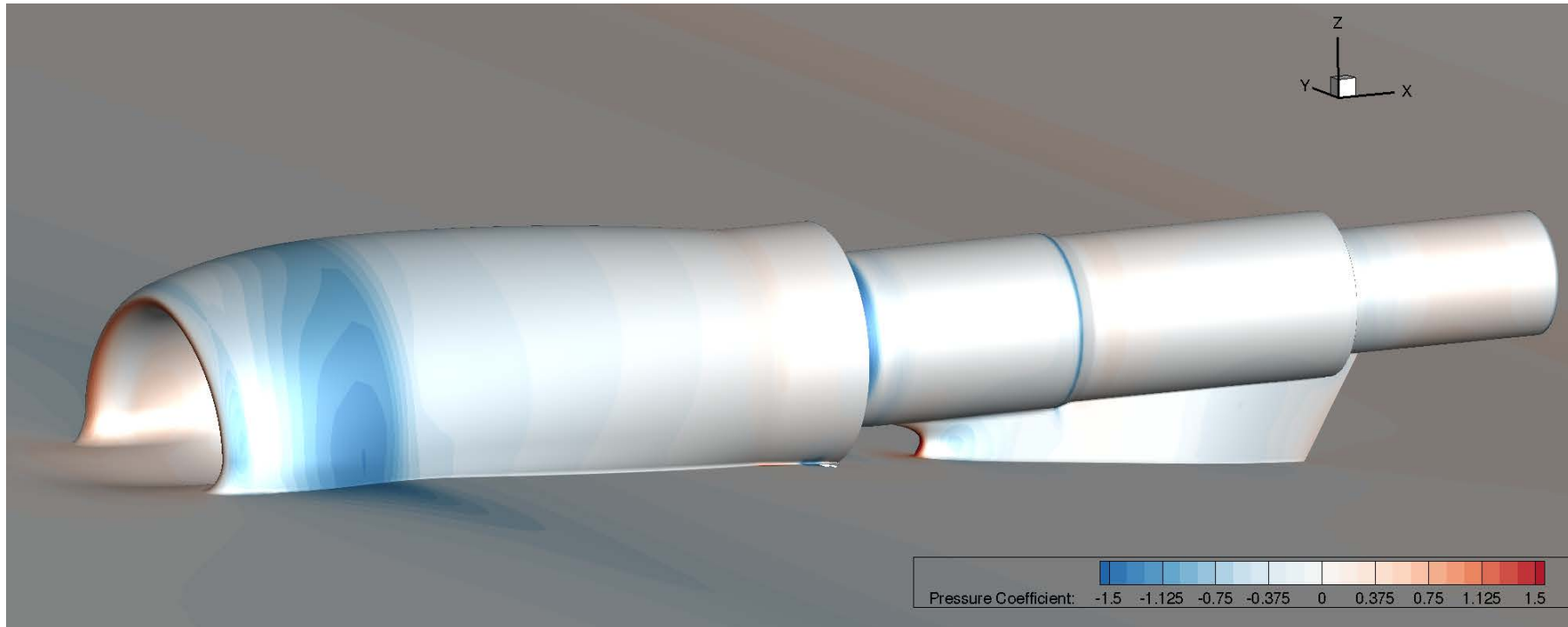


- 3-block circular duct
 - Some devils in passing the turbulence variables
 - Dirichlet boundary condition issues resolved



LAVA+Turbo Coupling: Near-term plan

- 0th Mode steady coupling
- Higher-order modes as required
- Unsteady coupling
- BLI2DTF



Acknowledgements



- Turbo team
 - Gregory Heinlein, Timothy Beach, Byung-Joon Lee, May-Fun Liou, Milind Bakhle, Mark Celestina.
- LAVA team
 - Gaetan Kenway, Jeff Houseman, James Jensen, Jared Duensing, Michael Bozeman, Leonardo Machado, Luis dos Santos Fernandez, Cetin Kiris.
- NTF experiment
 - Gregory Jones.
- BLI2DTF experiments
 - David Arend, John Wolter, Tony Shook, Jim Buckley, Julia Stevens.
- Funding
 - Advanced Air Transport Technology (AATT) Project.
- Computer resources
 - NASA Advanced Supercomputing Center.

Questions?

