



Computational Study of a Small Ducted Propeller

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What is RVLT?

- **RVLT = Revolutionary Vertical Lift Technology Project**

- **Goals**

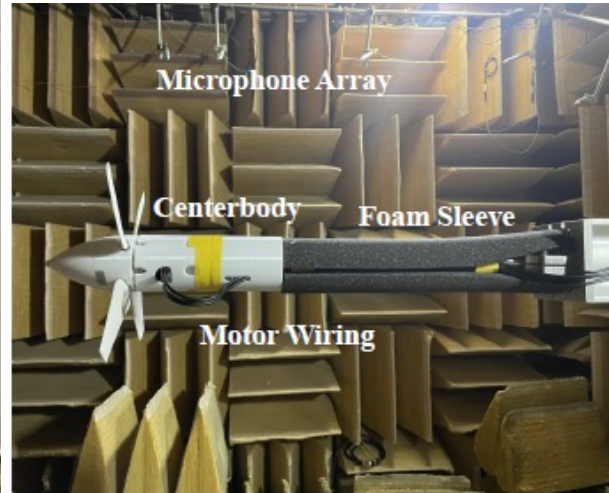
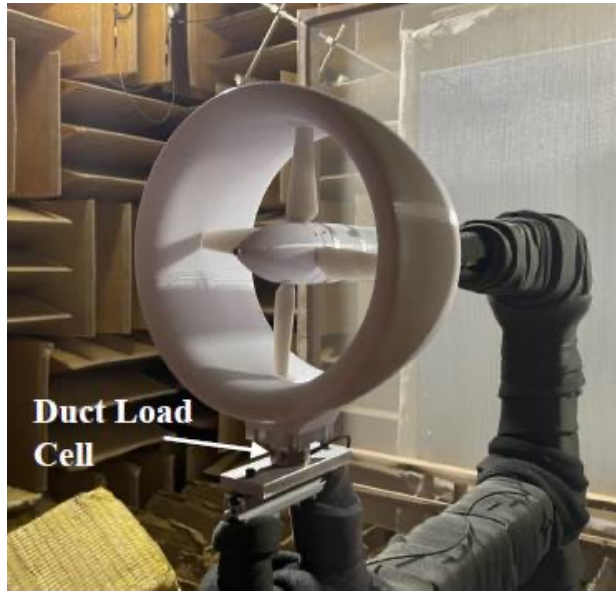
- Enable current and future vertical lift vehicles to operate safely and reliably
- Reduce environmental impacts and minimize intrusion – especially by noise – when in close proximity to people and property
- Increase access to sustainable transportation and services



What is the Small Ducted Propeller?



- Small scale representative of a nominal ducted propeller design Wind tunnel test at NASA Glenn to gather a variety of performance data
- Main goal was to examine the difference between a rotor with and without a duct, feeding into the first and second objectives of RVLТ



Images from: Zawodny, N. S. et al., "Aerodynamic and Acoustic Characterization of a Ducted Propeller in a Small Hover Anechoic Chamber," Tech. Rep. NASA-TM-2023-0006669, 2023.

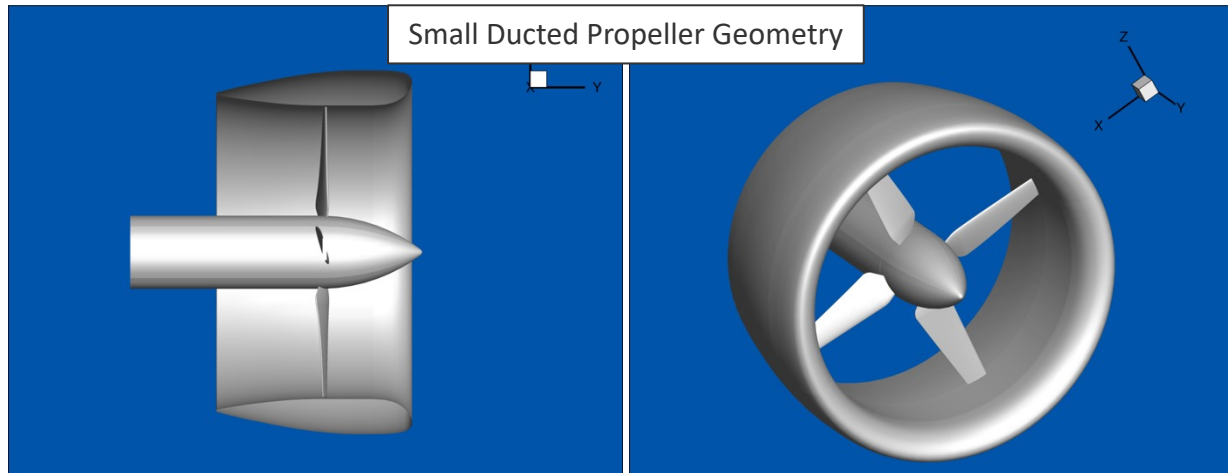
Goal of the Computational Fluid Dynamics Simulations



- **Determine the best practices for accurate simulation of the Small Ducted Propeller**
 - The most efficient amount of mesh needed for the rotor
 - The best numerical scheme to capture the flow physics
- **Apply these best practices to full vehicles using multiple ducted propellers**



Forward Flight



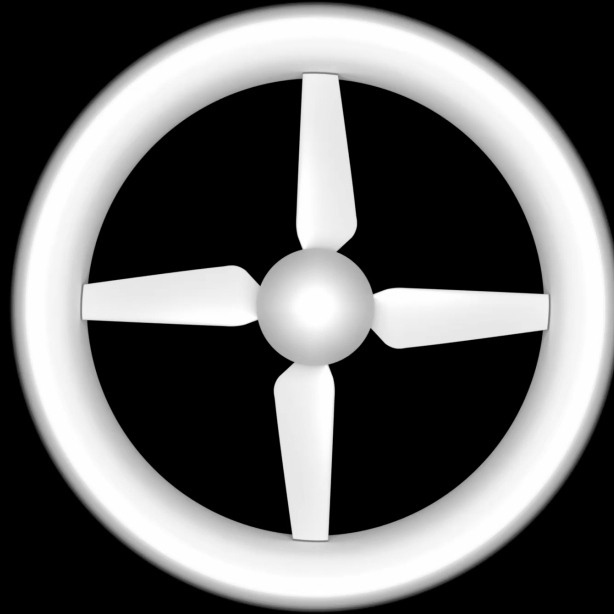
Hover

CFD Methodology / Run Conditions



- **Chimera Grid Tools (CGT)** is used to generate the overset structured meshes
- **Overflow 2.4c** is used as the flow solver
 - Studied the use of unsteady RANS and DDES
 - The physical timestep corresponds to a quarter-degree rotation of the propeller
 - Used the SA turbulence model with the RC and QCR2000 terms
 - Studied the difference between the HLLC and HLLE+ schemes with the Koran limiter and SSOR
 - Made use of Overflow's automated mesh adaption features (based on 2nd derivative of the flow variables)
- **Run Conditions**
 - RPM = 8167
 - Hover condition (zero free stream velocity)
 - Atmospheric conditions matched to what was measured in the experiment

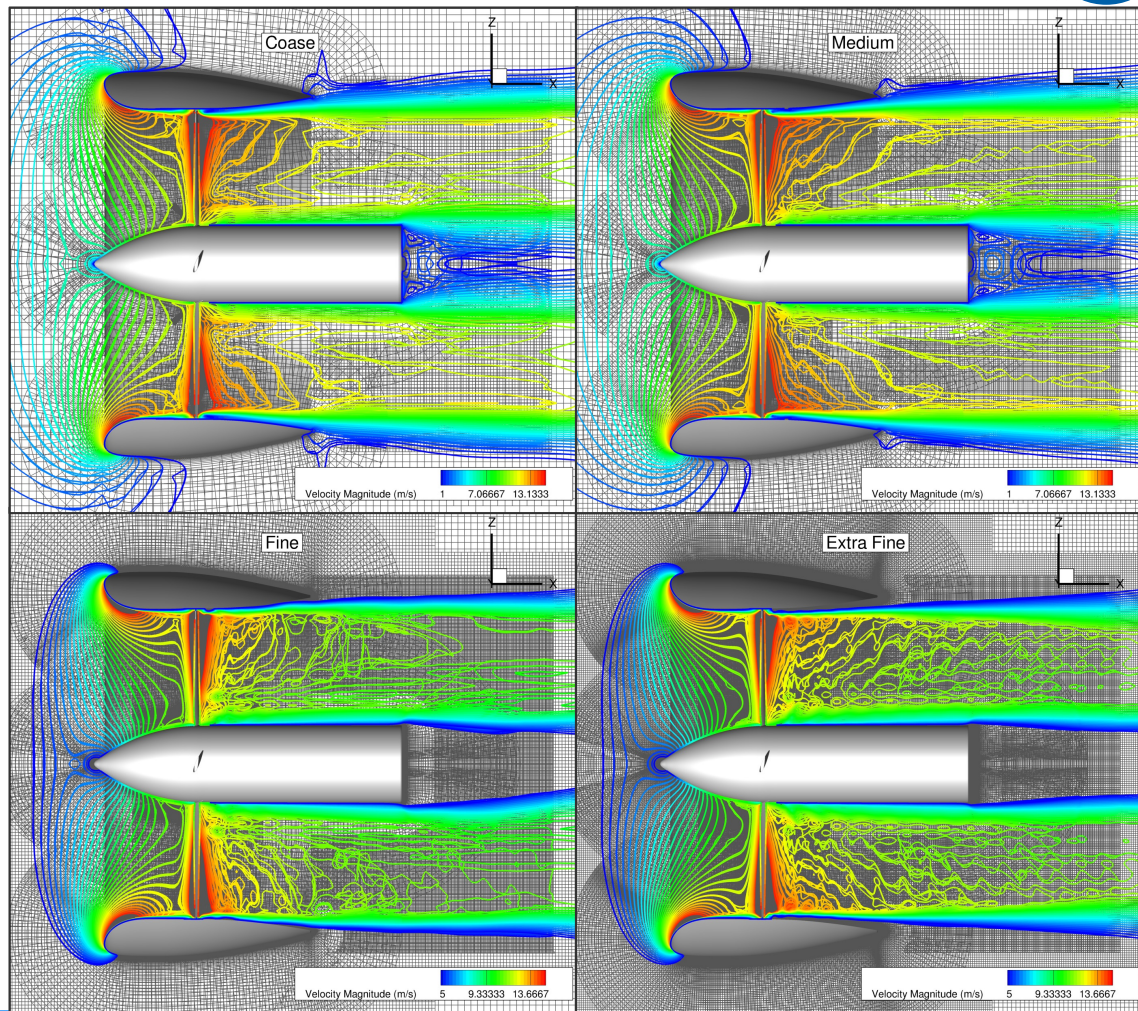
CFD Visualization of the Tip Vortices



Mesh Refinement Study: Meshes

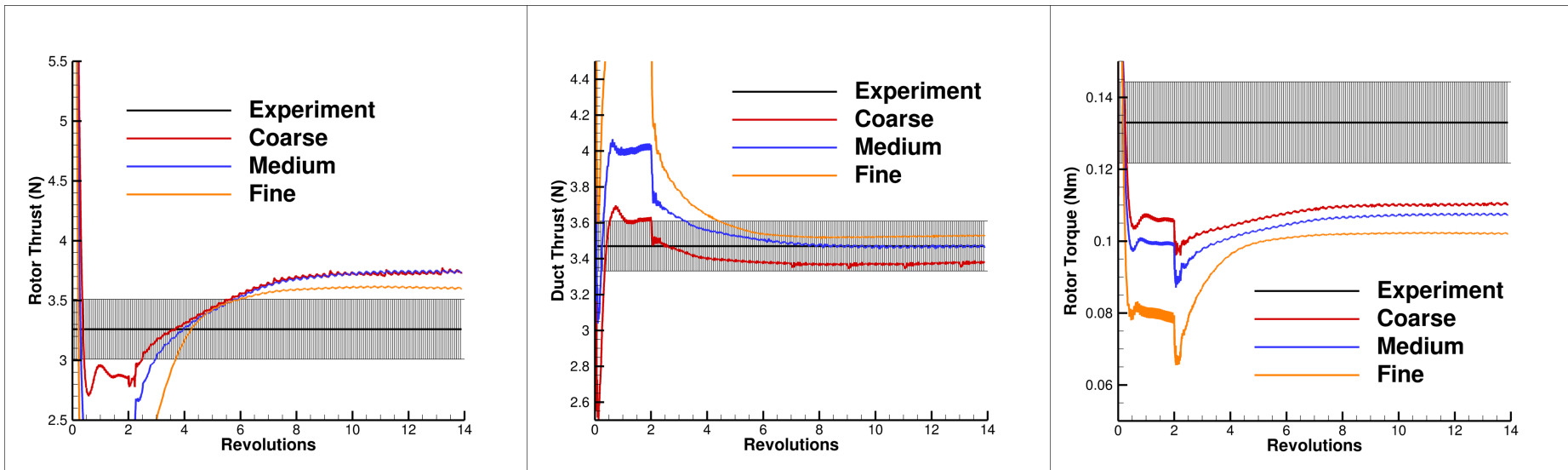
- Goal was to find the best compromise between mesh size and solution accuracy
- Used CGT to generate a family of four mesh levels

	# of Surface Points (Thousands)	# of Volume Points (Millions)
Coarse	160	8.6
Medium	301	22.2
Fine	676	68.2
Extra Fine	1,534	264.4



Mesh Refinement Study: Loads

- CFD predictions for the rotor thrust, rotor torque and nacelle thrust against measured values from the experiment



	Rotor Thrust (N) Corrected	Duct Thrust (N) Corrected	Rotor Torque (Nm) Corrected
Experiment	3.26	3.47	0.133
Coarse	3.74	3.38	0.111
Medium	3.74	3.47	0.107
Fine	3.37	3.61	0.102

Mesh Refinement Study: Conclusion



- **The best compromise between cost and accuracy is the fine mesh level**
 - There is no clear “best” option, while the Fine mesh level has the smallest error in Rotor Thrust, it has higher error in the Duct Thrust and the Rotor Torque.
 - Rotor Torque is the most sensitive to the mesh level
 - All levels show good agreement with the Duct Thrust

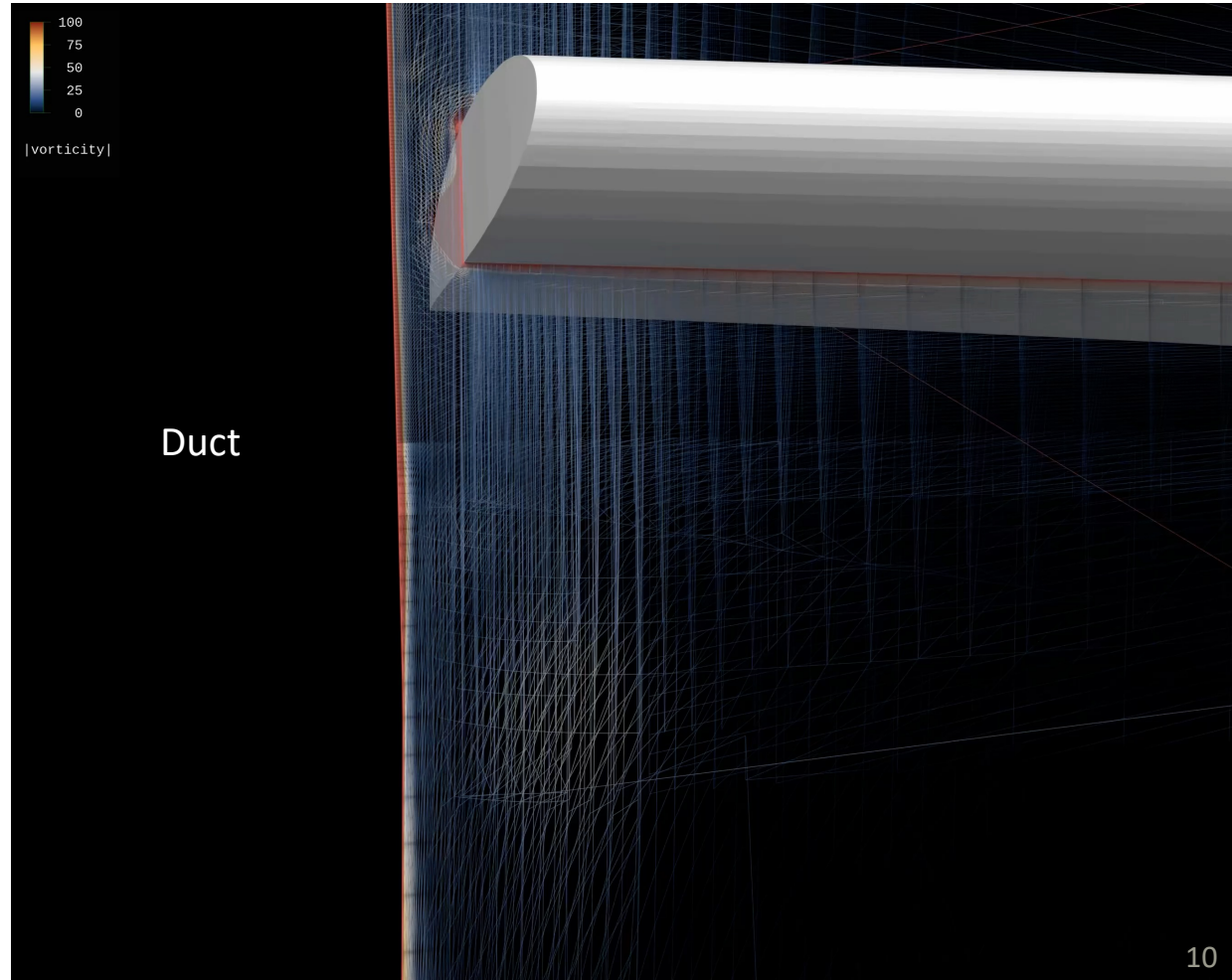
	Rotor Thrust (N) Corrected	% Error	Duct Thrust (N) Corrected	% Error	Rotor Torque (Nm) Corrected	% Error
Experiment	3.26	-	3.47	-	0.133	-
Coarse	3.74	14.7	3.38	2.6	0.111	16.5
Medium	3.74	14.7	3.47	0.0	0.107	19.5
Fine	3.37	3.4	3.61	4.0	0.102	23.3

	N Cores	Wall Time for 1 Rev (Hours)	Total CPU Time for 1 Rev (Hours)	Total Wall Time for Simulation (Days)
Coarse	48	13.5	648	6.75
Medium	120	12	1440	6
Fine	336	11	3696	5.5

Mesh Refinement Study: Adapted Mesh Introduction



- General idea is that adaption will be able to add points where they are most needed
- For this problem, the majority of adapted grid points are being placed around the tips of the blades

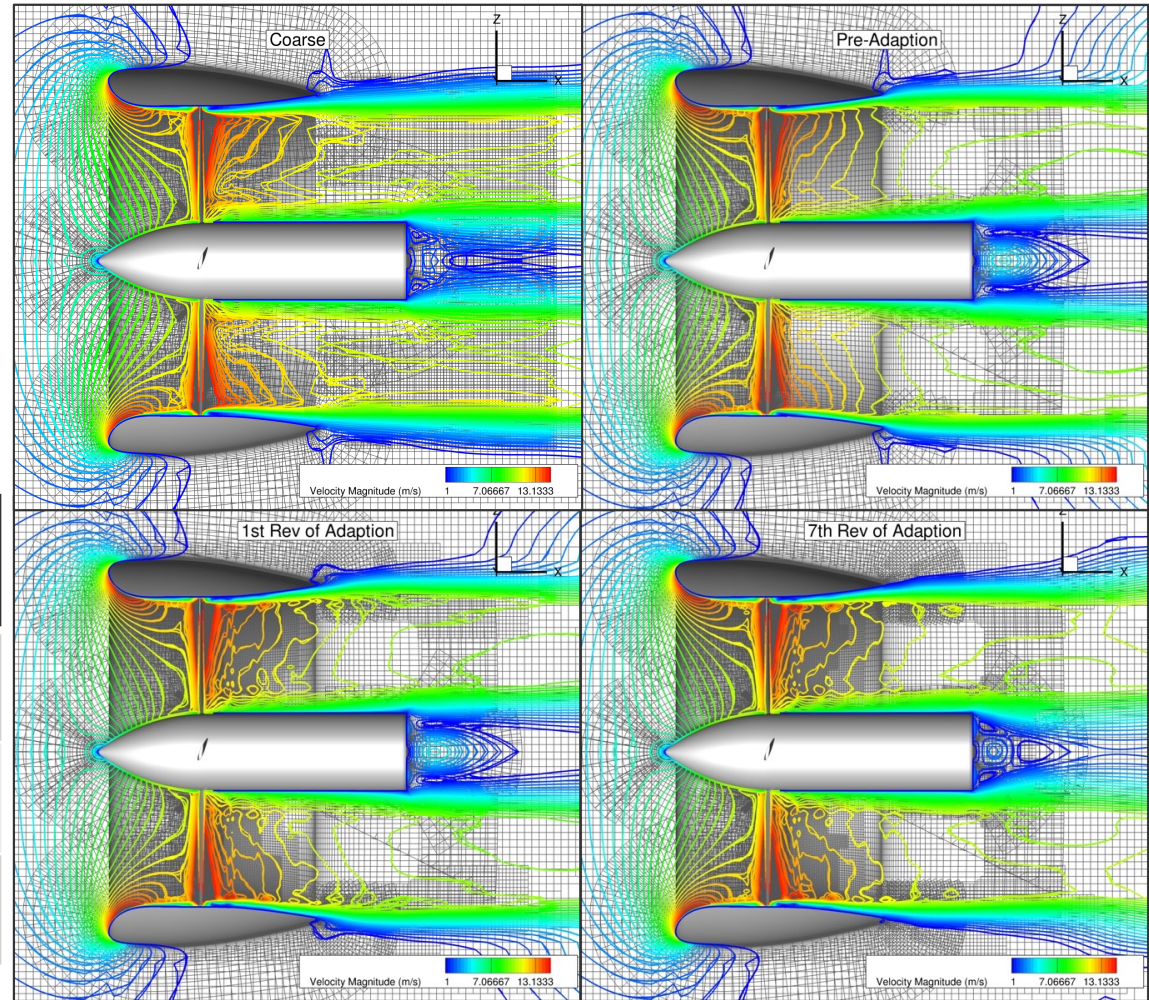


Mesh Refinement Study: Adapted Mesh Solutions

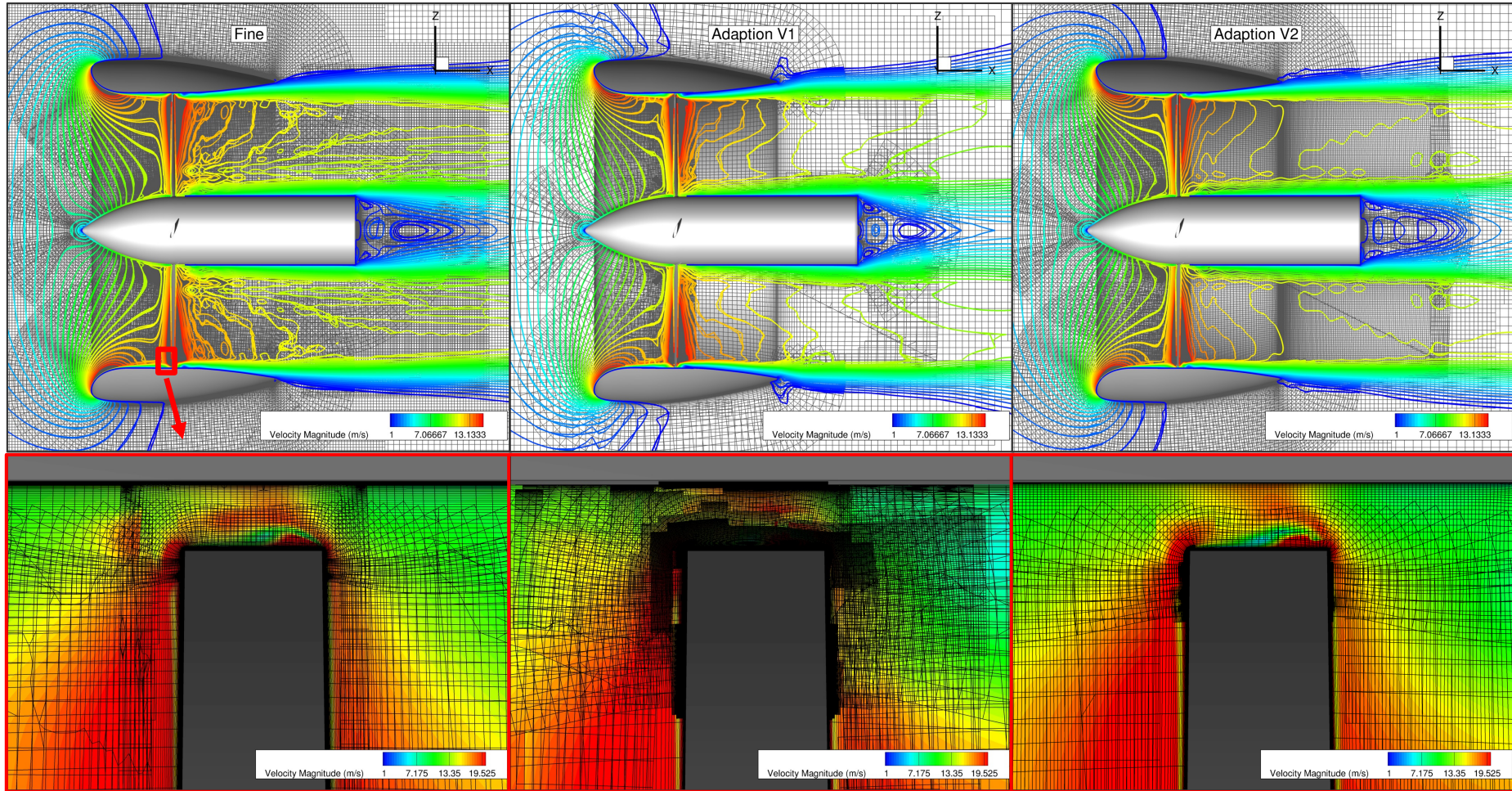


- Goal was to see if using mesh adaption within Overflow would lead to a more accurate solution
- Ran using two different adaption schemes

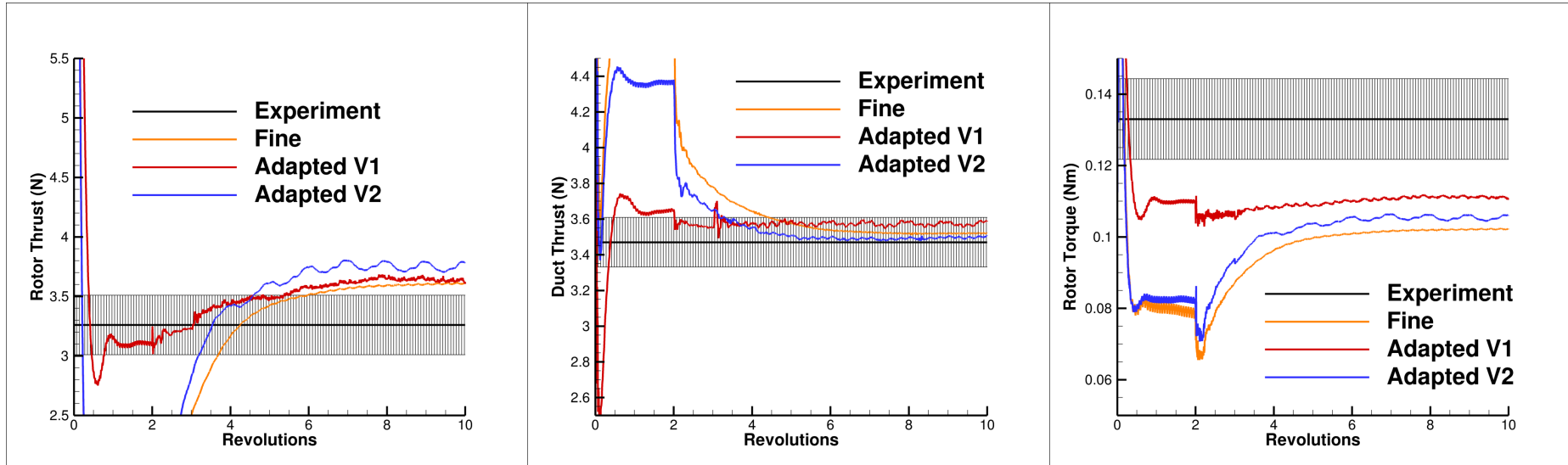
	# of Surface Points (Thousands)	# of Volume Points (Millions)
Fine	520	57.9
Adapted V1	141	151
Adapted V2	372	97.1



Mesh Refinement Study: Adapted Mesh Differences



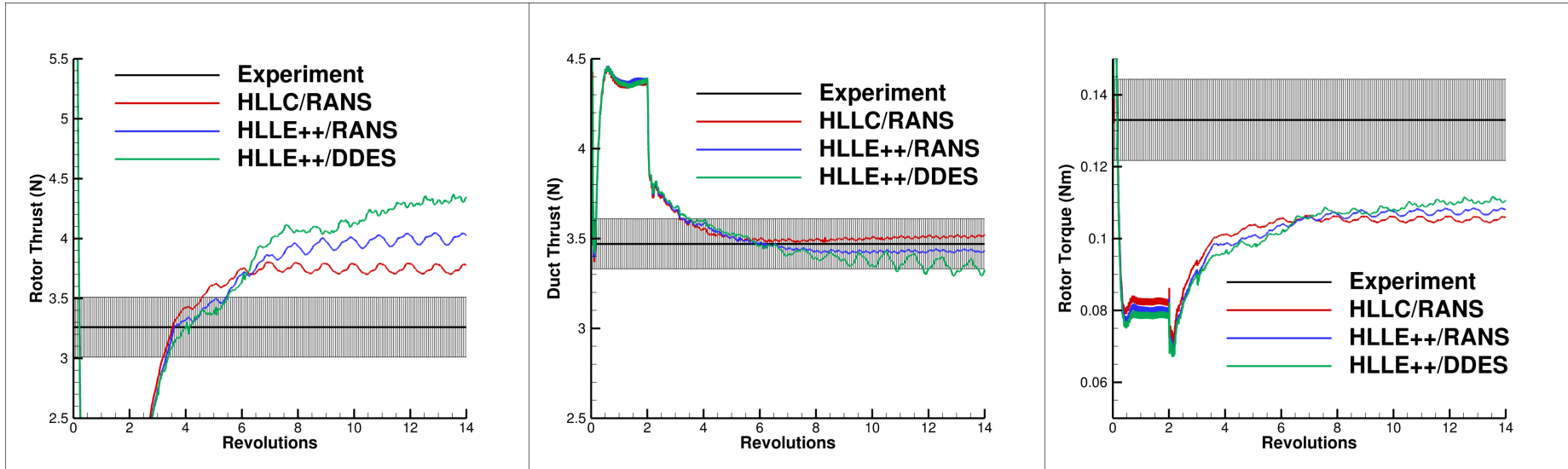
Mesh Refinement Study: Adaption Loads



	Rotor Thrust (N) Corrected	% Error	Duct Thrust (N) Corrected	% Error	Rotor Torque (Nm) Corrected	% Error
Experiment	3.26	-	3.47	-	0.133	-
Fine	3.37	3.4	3.61	4.0	0.102	23.3
Adaption V1	3.64	11.7	3.67	5.8	0.111	16.5
Adaption V2	3.75	15.0	3.50	0.9	0.105	21.1

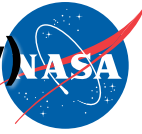
Numerical Study

- HLLC and RANS are the most stable and cheapest to run
- HLLC++ is a scheme that has less numerical dissipation than HLLC
- DDES does a better job of predicting eddy viscosity and the tip vortex behavior

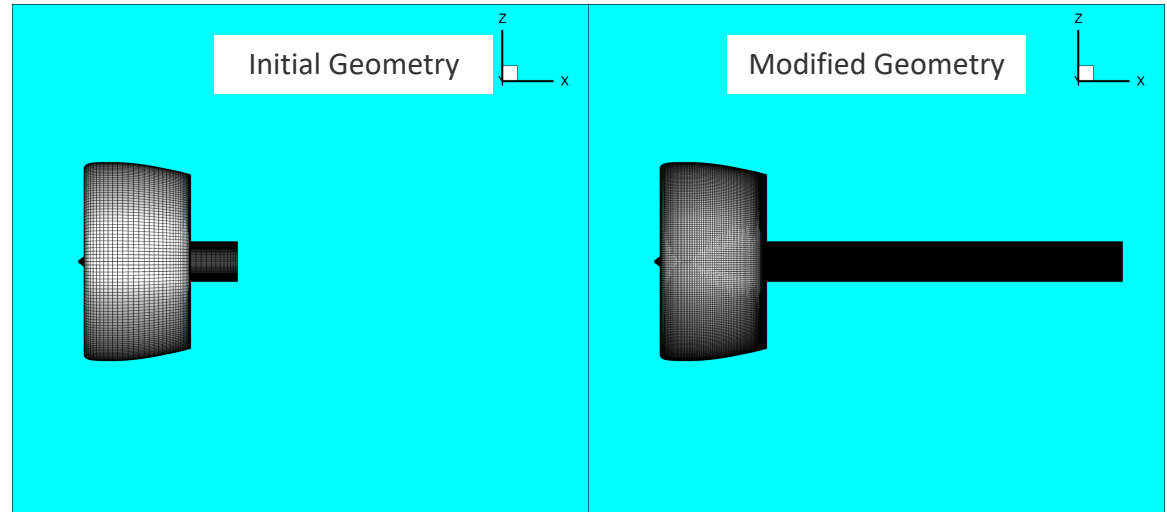


	Rotor Thrust (N) Corrected	% Error	Duct Thrust (N) Corrected	% Error	Rotor Torque (Nm) Corrected	% Error
Experiment	3.26	-	3.47	-	0.133	-
HLLC/RANS	3.75	15.0	3.50	0.9	0.105	21.1
HLLC++/RANS	4.00	22.7	3.43	1.2	0.108	18.8
HLLC++/DDES	4.31	32.2	3.35	3.5	0.110	17.3

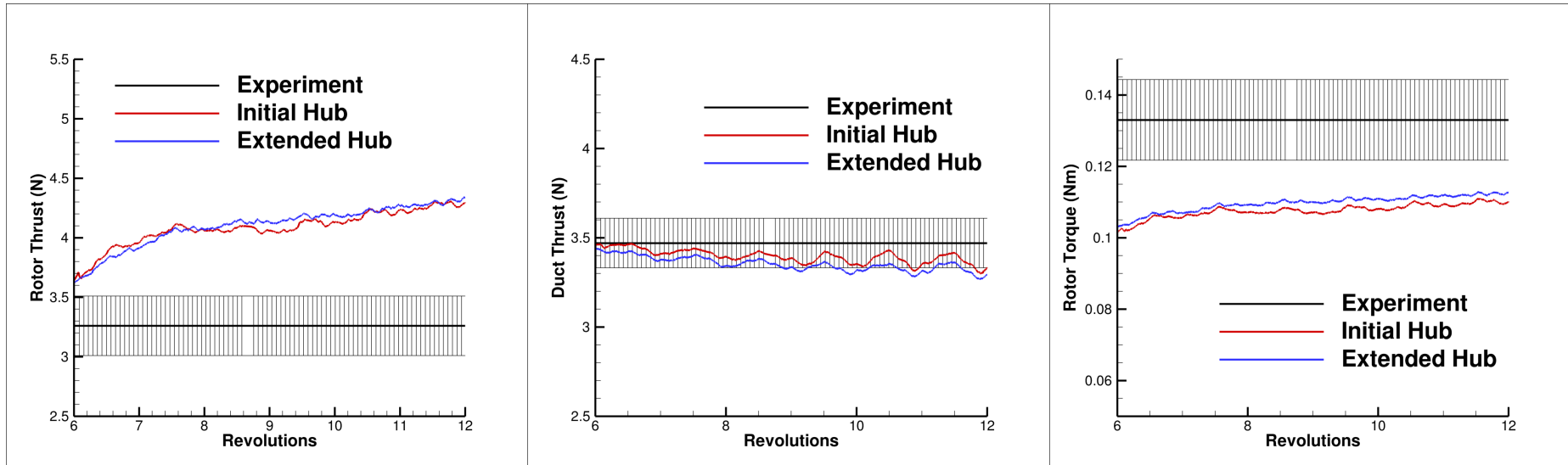
Improved Modeling of Experiment: Mounting Hardware (Geometry)



- CFD was only modeling the geometry highlighted in red
- To better model the mounting system from the experiment, the CFD geometry was changed to have a center body that extended to the same length as the experimental hardware



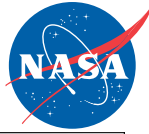
Improved Modeling of Experiment: Mounting Hardware (Loads)



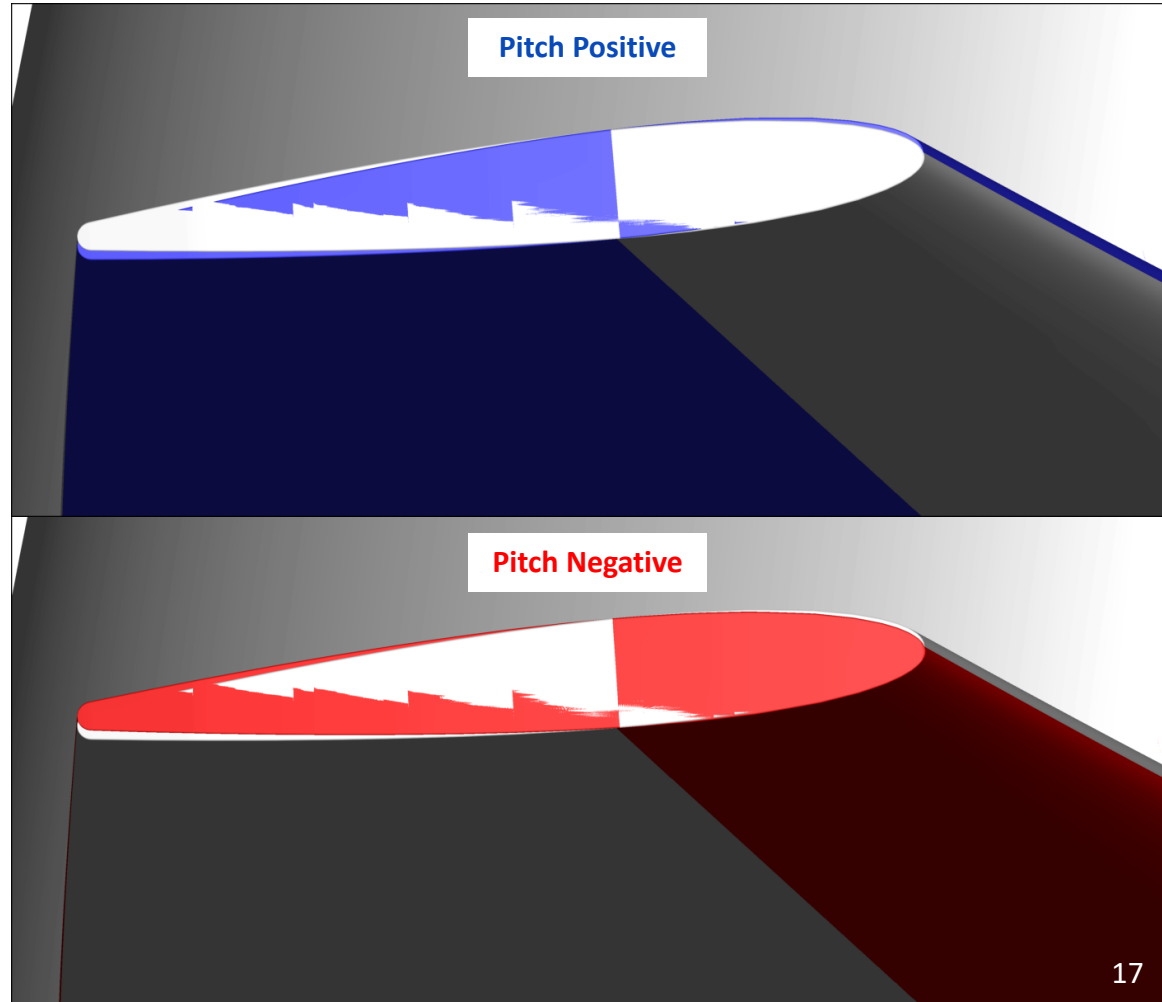
	Rotor Thrust (N) Corrected	% Error	Duct Thrust (N) Corrected	% Error	Rotor Torque (Nm) Corrected	% Error
Experiment	3.26	-	3.47	-	0.133	-
Initial Hub	4.31	32.2	3.35	3.5	0.110	17.3
Extended Hub	4.26	30.7	3.32	4.3	0.112	15.8

- Simulations were run using the HLLC++/DDDES scheme
- Change to the hub did not have significant effect on comparison to experiment

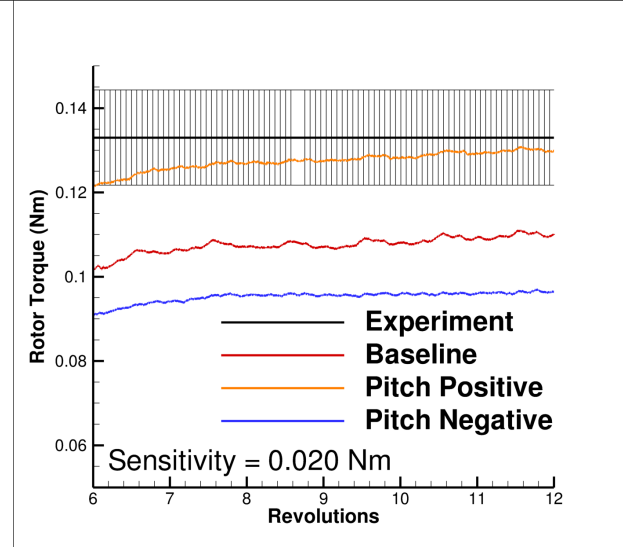
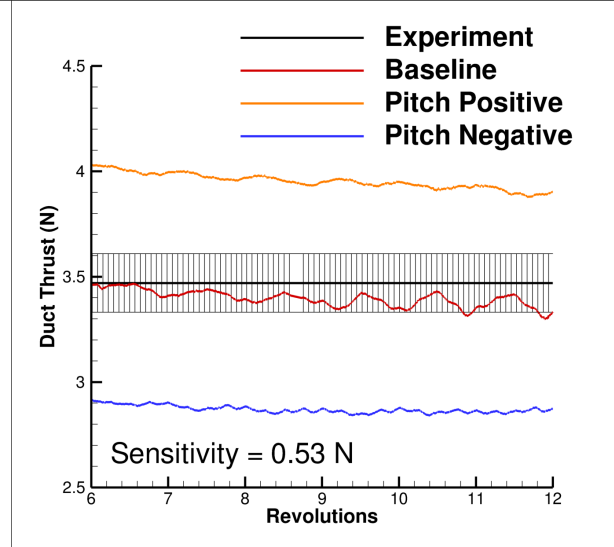
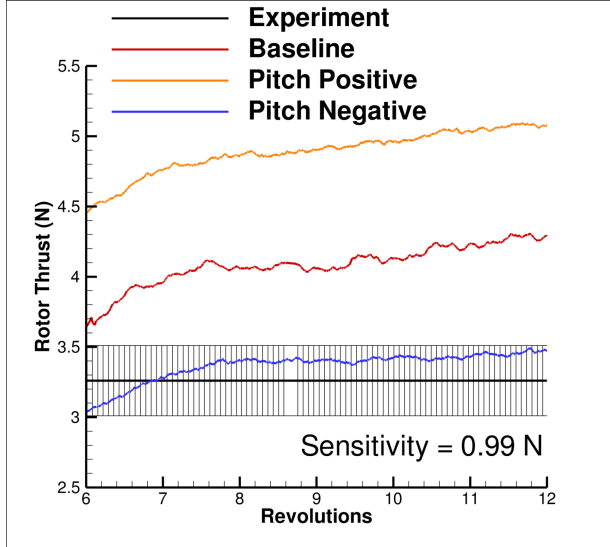
Improved Modeling of Experiment: Blade Pitch (Geometry)



- There was a one degree uncertainty in the mounting angle of the rotor blades
- Created two different CFD models, one with all four blades positively pitched, and one with all four blades negatively pitched
- This was used to quantify the sensitivity of the CFD to the blade pitch angle



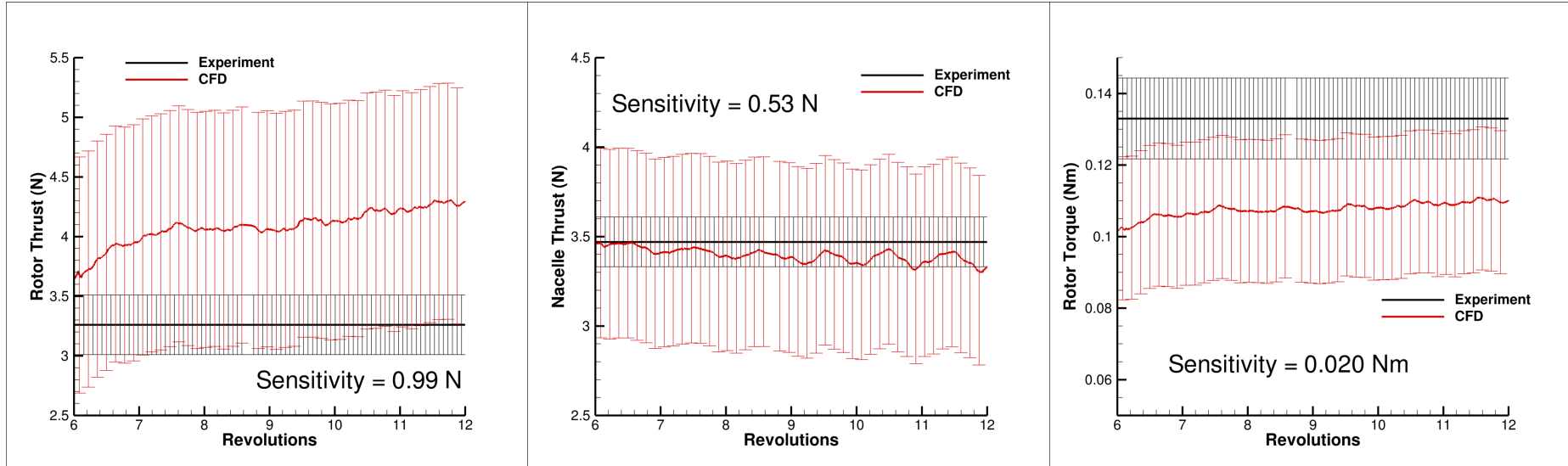
Improved Modeling of Experiment: Blade Pitch (Loads)



	Rotor Thrust (N) Corrected	% Error	Duct Thrust (N) Corrected	% Error	Rotor Torque (Nm) Corrected	% Error
Experiment	3.26	-	3.47	-	0.133	-
Baseline	4.31	32.2	3.35	3.5	0.110	17.3
Pitch Positive	5.07	55.5	3.90	12.4	0.130	2.3
Pitch Negative	3.46	6.1	2.86	17.6	0.096	50.4

- Simulations show significant sensitivity to the blade pitch angle

Improved Modeling of Experiment: Blade Pitch (Sensitivity Comparison)



- **Overlap between the experimental uncertainty bound and the CFD sensitivity bound indicates that there the CFD could more closely match the experiment with a modification of the pitch**
- **For this study, the blades were all uniformly changed, which isn't necessarily how it would be in the actual geometry. Each blade might have it's own unique pitch angle**

Conclusions



- **Determined important best practices information**
 - A fine grid was required to get better results and the best way to distribute the points was to use Overflows mesh adaption
 - The HLLE++ scheme predicts more thrust and torque on the rotor compared to the HLLC scheme
 - DDES did a better job at matching the experimental rotor torque but seemed to over-predict the thrust values compared to RANS
 - Modeling the extended center body mounting hardware didn't have a significant effect on the results
 - Changing the pitch angle of the blades has a significant effect on the CFD predictions. Using the proper pitch angles is critically important
- **Obtained rough estimates for resources needed to accurately simulate a single rotor**
 - Approximately 100 million cells to get an appropriate mesh
 - Roughly 6-7 days of wall-time to run a simulation on 500 CPUs

Acknowledgments



- **RVTL project for funding this work**
- **NAS for providing the computational facilities used in the work**
- **Tim Sandstrom for making the video of the rotating blade**
- **Tom Pulliam, Neil Chanderjian, and William Chan for their help with setting up Overflow for this problem**

Questions?

