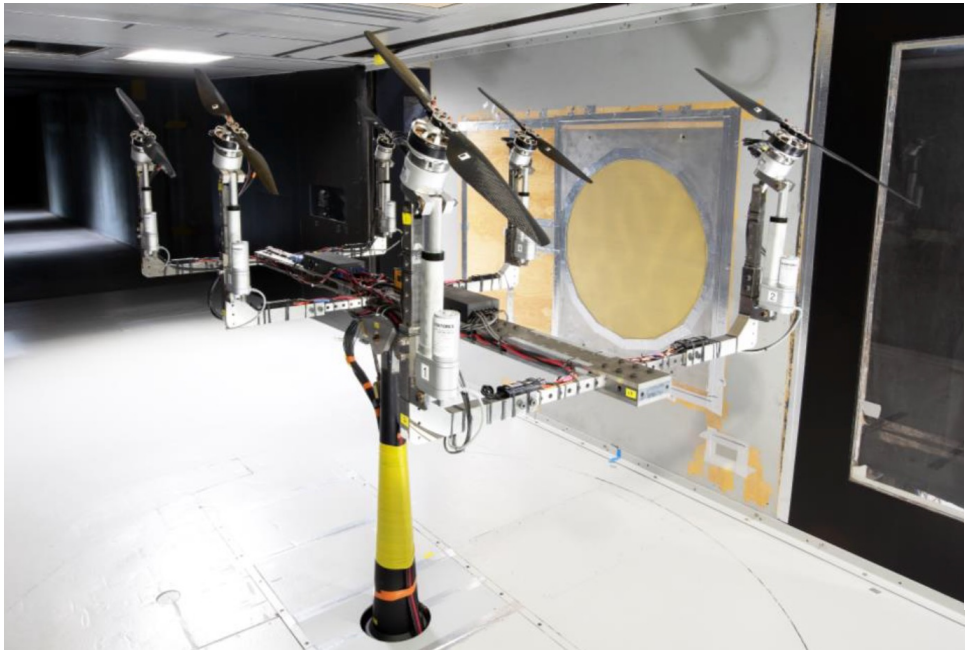
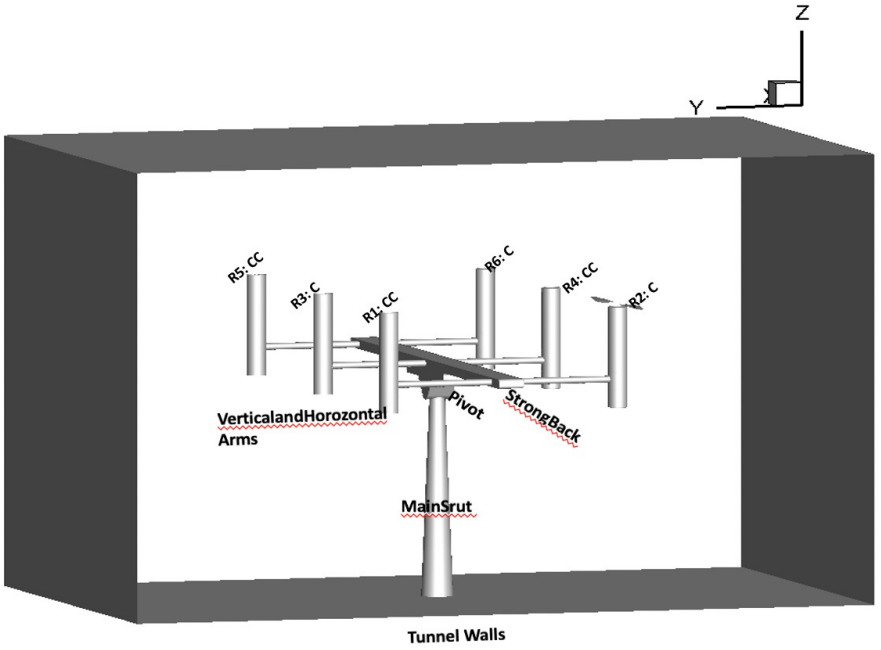
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# Multirotor Test Bed CFD and Flow Visualization

**Jasim Ahmad**
**TNP, NASA Ames Research Center**






**16th Symposium on Overset Composite Grids and Solution Technology**
**Dayton, OH**
**October 7-10, 2024**



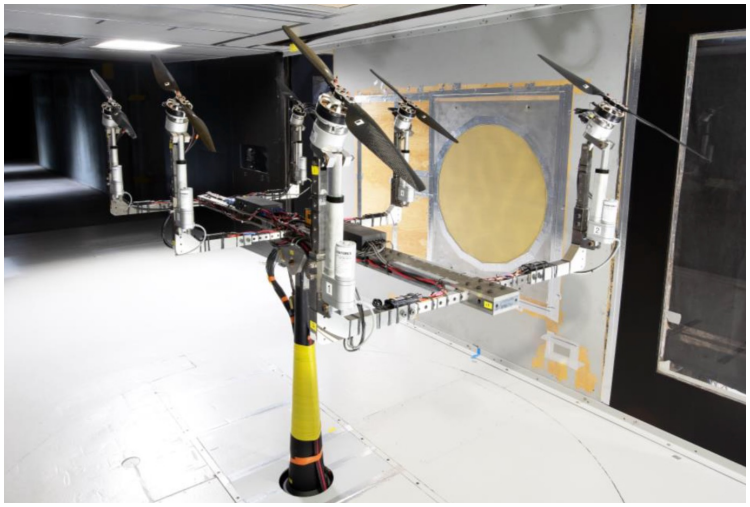
# Outline

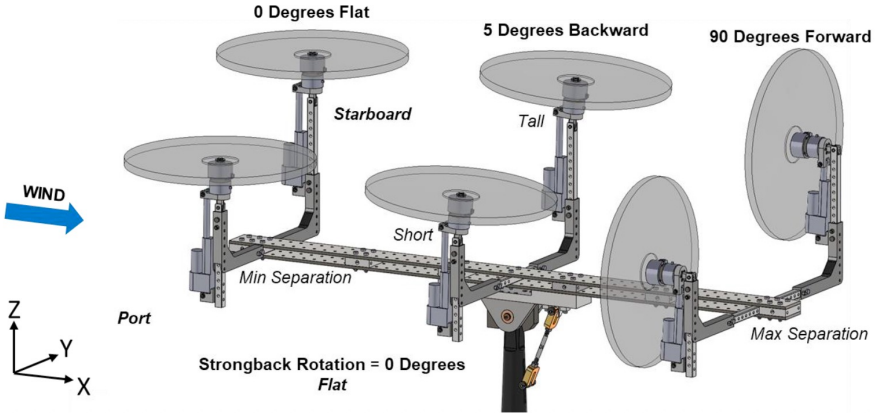



- **Multirotor Test Bed (MTB) Experiments**
- **Computational Approach: High-Fidelity and Reduced-Order CFD Methods: OVERFLOW**
- **CFD/CSD Coupling: CAMRAD II and OVERFLOW**
- **Grid Generation: Rotor, Tunnel, and Support structures**
- **Flow Visualization**
- **Validation and Comparative Analysis**
- **Future MTB Experiments and CFD**

# MTB Experiment

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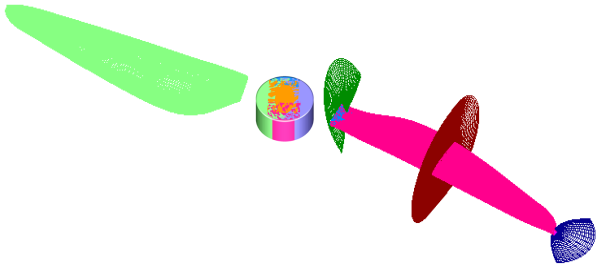


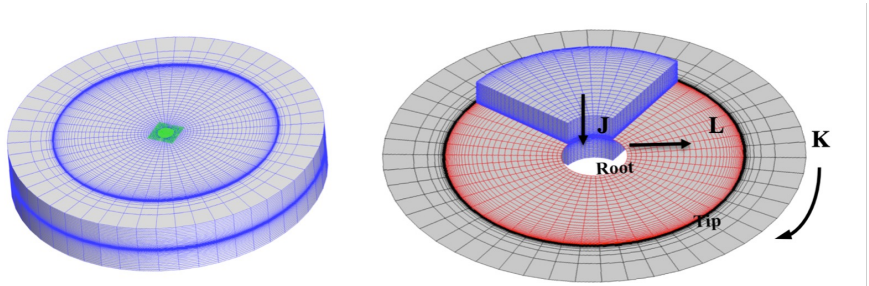

- **NASA's Multirotor Test Bed developed under RVLT Project for wind tunnel testing of multirotor aircraft configurations focused on Urban Air Mobility (UAM).**
- **The MTB tested up to six rotors with adjustable vertical, lateral, and longitudinal placement, including rotor tilt and assembly pitch.**
- **The data gathered aids in understanding the real-world performance of multirotor configurations under diverse conditions.**
- **Improvements are being made to enhance data quality measurements for future MTB testing. Insights will benefit Urban Air Mobility (UAM) simulations.**

# Computational Approach in Flowsolver: OVERFLOW

- **High-fidelity method uses unsteady flow analysis for discrete rotating blades capturing detailed rotor blade aerodynamics and performance.**
  - **Full unsteady flow.**
  - **Moving grids.**

- **Reduced-order method employs rotor-disk model in OVERFLOW CFD code for efficient yet detailed aerodynamic and rotor performance analysis.**
  - **Series of approximations.**
  - **Steady state assumption where disk is filled with infinite number of blades,**
  - **Source term is added to the equation for steady-state. Source term is computed with Blade Element Theory (BET).**
  - **Average flow properties are computed from the recent Navier-Stokes solution of all the flowfield.**






(a). Disk with block grid at singular axis

(b). Grid indices used in source term





# Computational Approach in Flowsolver: OVERFLOW

- **Rotor Unsteady Flow Analysis**
  - **Unsteady flow analysis focuses on full discrete rotating blades offering detailed insights into blade aerodynamics and rotor performance.**
  - **High-fidelity simulations provide an in-depth look into rotor unsteady flow and its implications on the overall multirotor performance.**
  - **Such detailed simulations are key for developing advanced multirotor configurations suited for diverse Urban Air Mobility (UAM) applications.**
- **Reduced-order Disk Model**
  - **Computational efficiency.**
  - **This method is particularly useful for initial testing and design iterations where rapid feedback is crucial.**
  - **Despite being a reduced-order model, it effectively captures key aerodynamic features essential for performance assessments.**
  - **The model is validated against high-fidelity methods ensuring its reliability and accuracy in various scenarios.**
  - **Known Issues: Application of turbulence model.**



# Computational Approach in Flowsolver: OVERFLOW Options Used

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- **Higher-order spatial differences for convective fluxes with 5$^{th}$ order accuracy on uniform Cartesian grids.**

- **The results presented here were obtained using one of the HLL family of upwind approximate Riemann flux algorithms, namely, the contact preserving HLLC variant, with nominally 5th order WENO reconstruction for the inviscid fluxes.**

- **To advance the solution in time, an implicit, second-order backward difference scheme is used in which the nonlinear system of equations is linearized at each time step. In this study, the resulting system of linear equations is solved using symmetric successive overrelaxation (SSOR).**

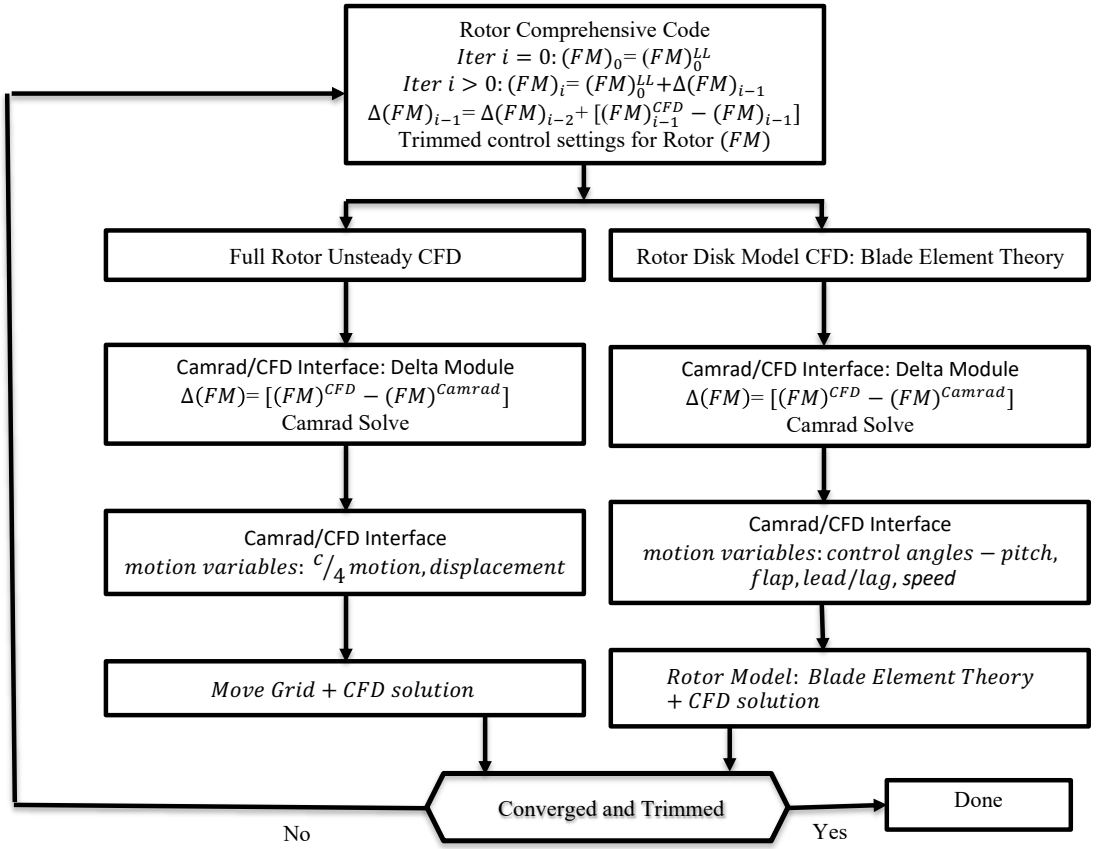
- **Several time-stepping schemes are available, including dual-time schemes .**

- **Several turbulence models in OVERFLOW. The standard one-equation model of Spalart-Allmaras with Delayed Detached Eddy Simulation (DDES) length scale model.**

# CFD/CSD Coupling: CAMRAD II and OVERFLOW

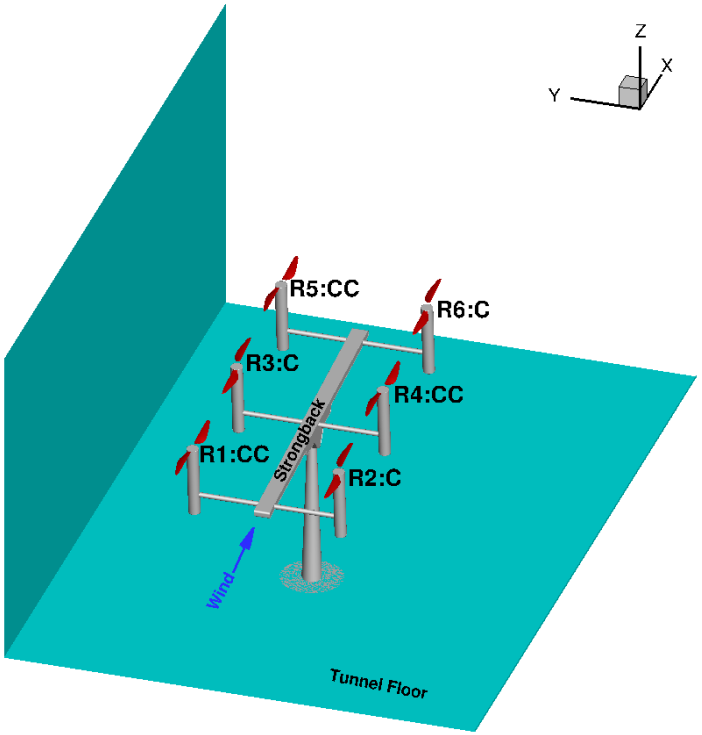
Ames Research Center

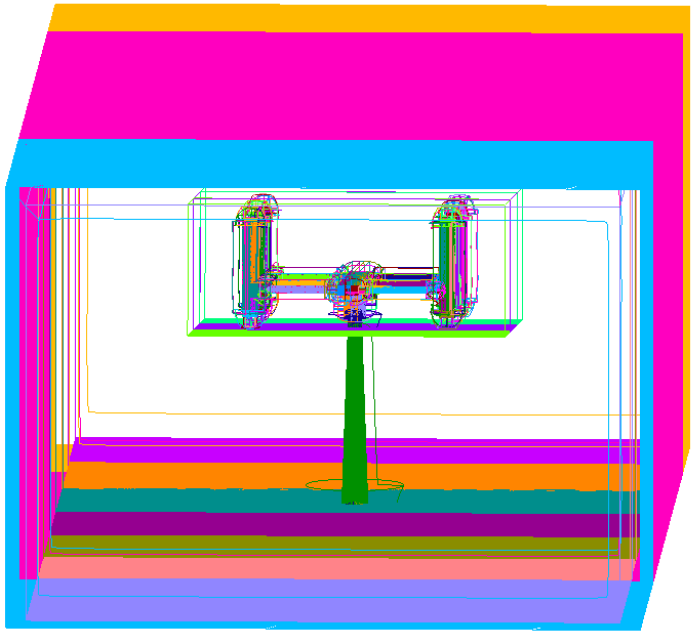
- **OVERFLOW is coupled with rotor comprehensive code CAMRAD II.**
- **The coupling accurately captures essential aspects of rotor blade aerodynamics, blade and rotor performance, rotor-body interactions.**
- **The coupling facilitates the appropriate rotor trim.**



# OVERSET Grid System: Grid-Generation

- **Overset grid system is generated using the Chimera Grid Tools (CGT) software.**
  - **CGT contains a very efficient and modular grid scripting library grid manipulation, generation, reorganization, overset hole cutting surface creation, and generation of OVERFLOW input files.**
  - **Near body grid.**
  - **Intermediate or Cartesian box grid.**
- **Recent Grid Automation tools.**

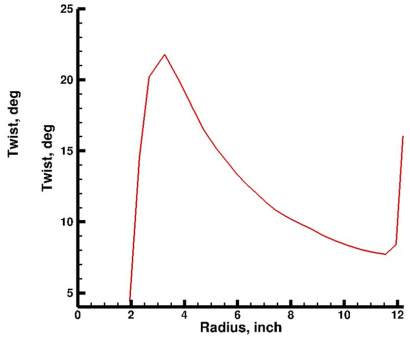


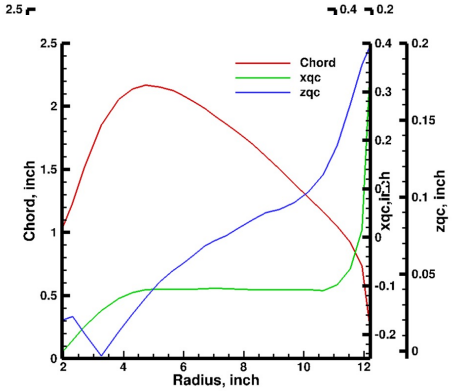



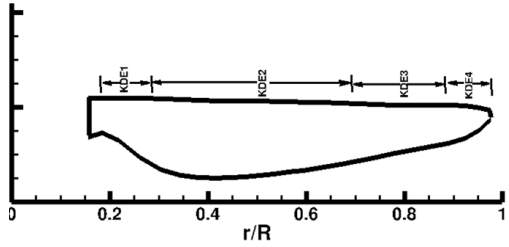
# OVERSET Grid System: Rotor Geometry

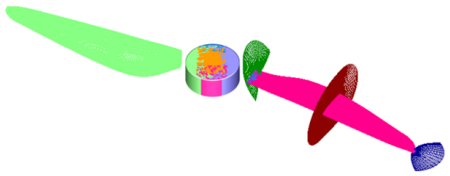
| r/R | Airfoils | KDE-CF245-DP Airfoil Sections |
|---|---|---|
| 0.1891 | KDE1 | MTB_roR_1891.c81 |
| 0.2662 | KDE2 | MTB_roR_2662.c81 |
| 0.7515 | KDE3 | MTB_roR_7515.c81 |
| 0.9435 | KDE4 | MTB_roR_9435.c81 |

**Table 1.** Radial locations of KDE-CF245-DP Airfoil Sections







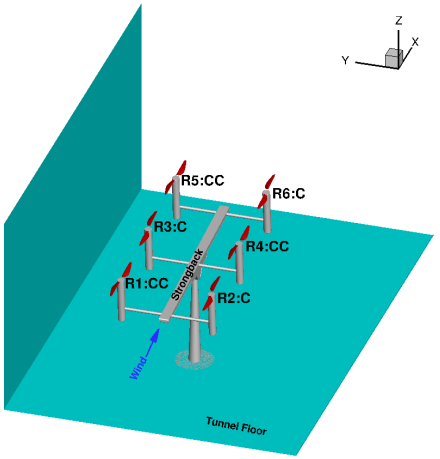
# Flow Visualization: Intricate Details of the Flowfield

- **NASA Advanced Supercomputing Division**
  - **Cutting edge tools**
  - **Detailed flow structures**
- **Flowfield represented by**
  - **Q-criteria iso-surfaces**
  - **Particle traces**
- **Particles are seeded near the surface geometry**
  - **Advected through the domain using Runge-Kutta-Fehlberg method**
  - **Final visualizations are created with open-source tool OSPREY**

# Solution Sensitivity

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- **An optimum choice of parameters for computation*: h, Δt, S, LC, Tr***
  **- *h* is the grid spacing, $h = 1/(Total\ grid\ points)^{1/3}$.**
  **- Δ*t* is the time step, S is the subiterations,**
  **- LC is the loose coupling step, *Tr* is the trim strategy.**




- **Trim strategy, Tr:**
  **1: no trim only fixed collective used in the measurement**
  **2: only one front rotor**
  **3. all 6 rotors**
  **4. longitudinal line rotors, rotor 1, 3, 5 or 2, 4, 6**
  **5: counterclockwise and clockwise rotors: 1, 4, 5 and 2, 3, 6**

- **Subiterations S: 10-20**

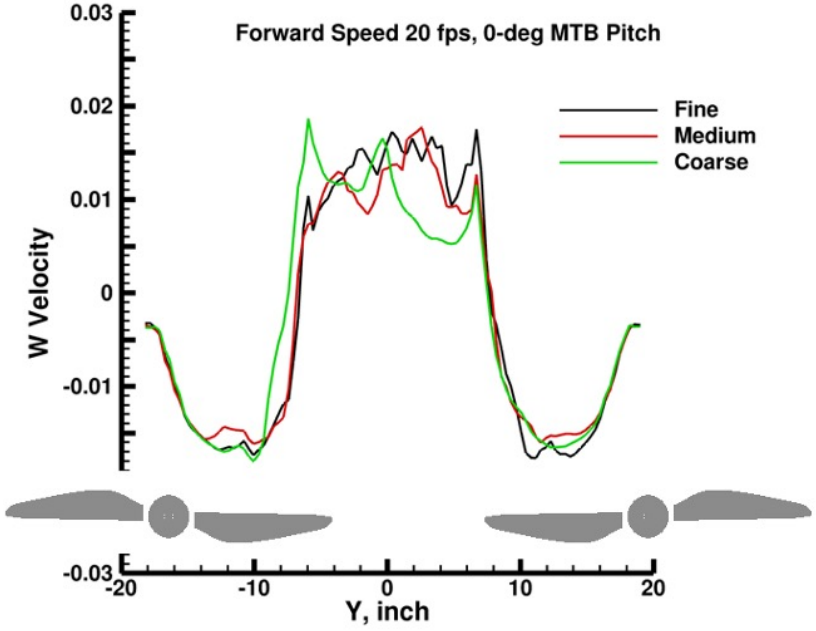
- **Time step: Δt is equivalent to an incremental azimuthal advance in degrees per physical time step. Δψ of 0.25 deg**

- **Loose Coupling (LC) step: Periodic fraction based on number of blades in a rotor for full rotor simulation, 100 to 200 steps for steady state rotor disk simulation.**

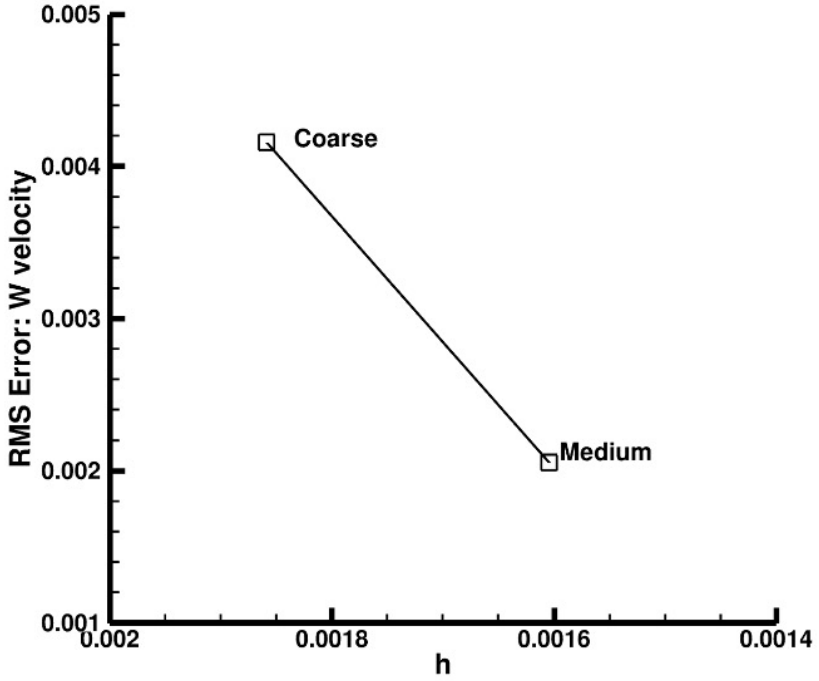
# Solution Sensitivity: Spatial

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| Grid | Total number of grids | Total points in NB grids in millions | Total points in NB Support grids in millions | Total points in transition grids inside the tunnel in millions | Total Points in Tunnel Wall Grids in millions | Total Points in millions | Average Grid Spacing, h | Refinement Ratio |
|---|---|---|---|---|---|---|---|---|
| Fine | 236 | 40 | 27 | 557 | 27 | 584 | $h_1$= 0.00119 | |
| Medium | 236 | 40 | 27 | 215 | 27 | 242 | $h_2$= 0.00160 | $r_{21}=\frac{h_2}{h_1}=1.34$ |
| Coarse | 236 | 40 | 27 | 126 | 27 | 156 | $h_3$= 0.00186 | $r_{32}=\frac{h_3}{h_2}=1.16$ |



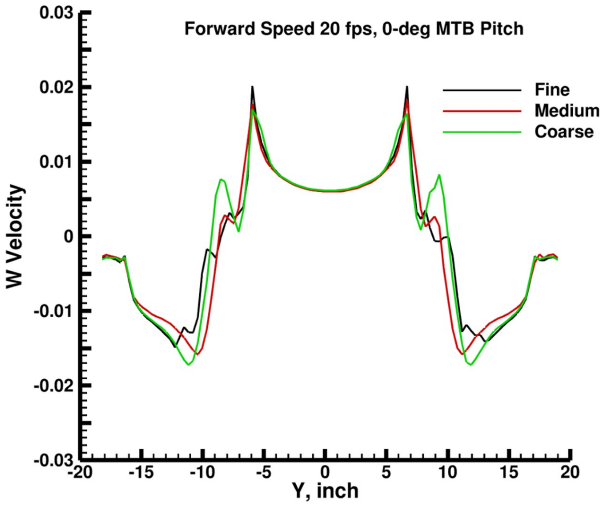

(a) Line between R5 - R6



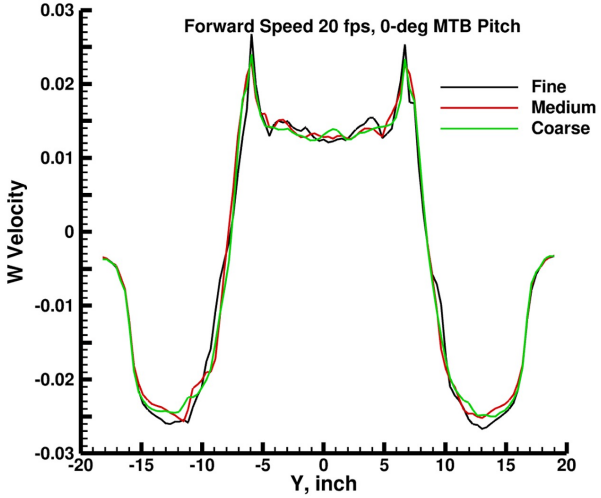

(b) Differences (Fine, Medium), and (Fine, Coarse)

# Solution Sensitivity: Spatial

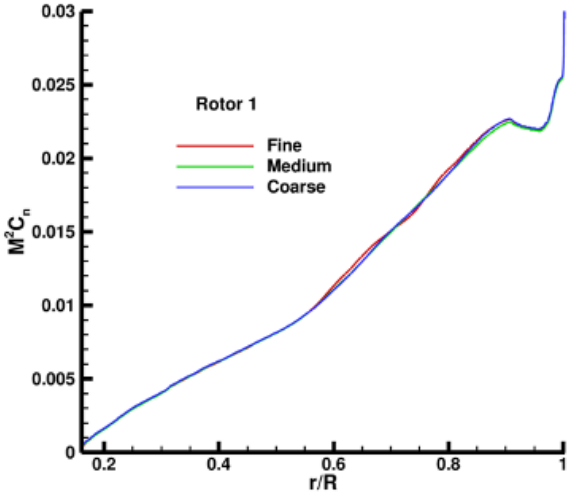
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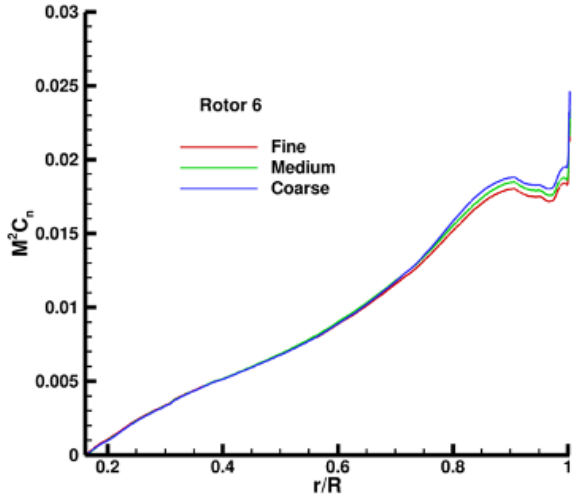



(a) Line between R1 - R2




(b) Line between R3 - R4



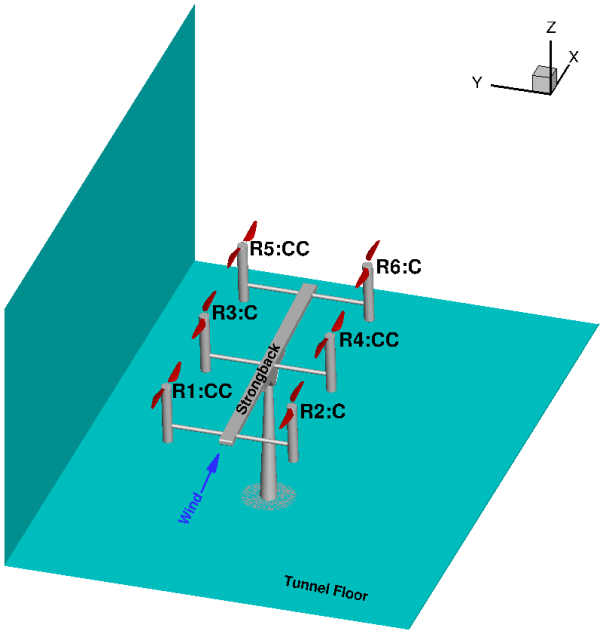
# Results

- Computations for low-Reynolds number flows with varying setups of in-plane and out-of-plane rotors to simulate various operating conditions.

- Both methods undergo detailed comparison and validation for accuracy in rotor-rotor and rotor-structure interactions.

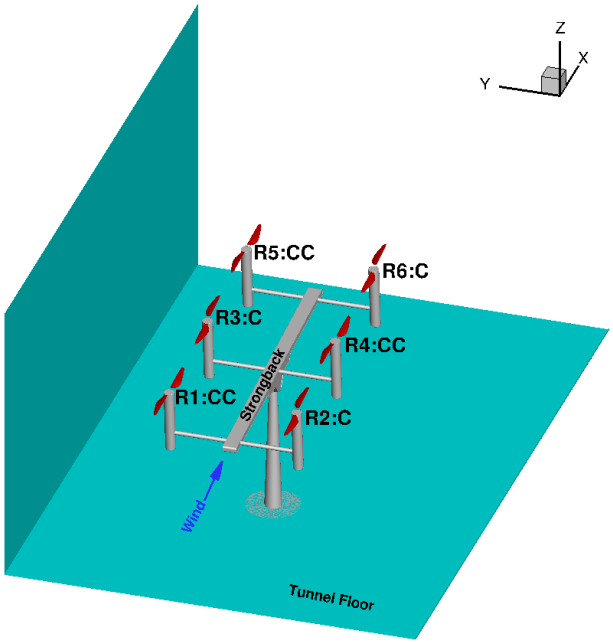
- For Helicopter Interactions are numerous
  - Main Rotor with Hub, Pylon, Engine, Fuselage, Landing gear
  - Tail Rotor, Empennage, Fin, Vertical stabilizer
  - Ground

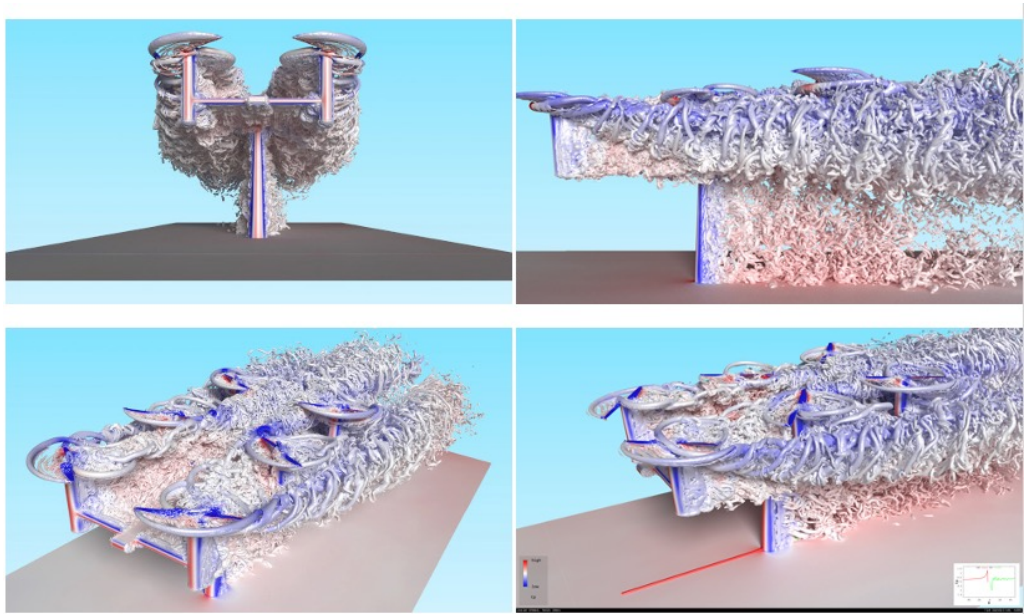
- For Multirotor
  - Rotor-Rotor
  - Rotor-structure
  - Tunnel



# Results

- **Testing in the tunnel with different numbers of rotors 6, 4, 2, 1**
- **Rotor rpm 2000**
- **Tunnel speed of 20fps, 40fps**
- **Convergence**
- **Flow visualizations**
- **Showing some of the validations**

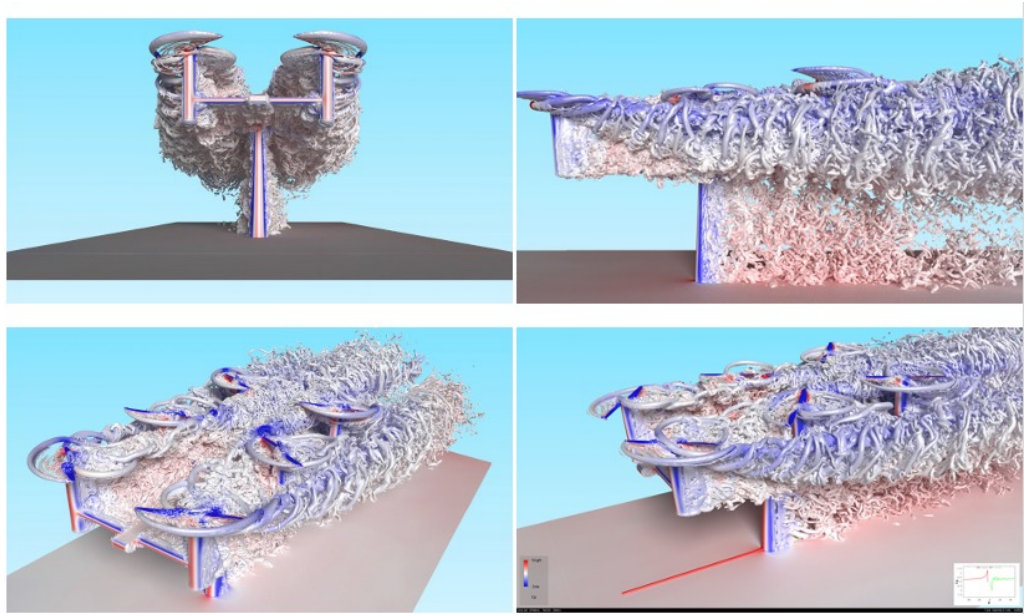


# Flow Visualization

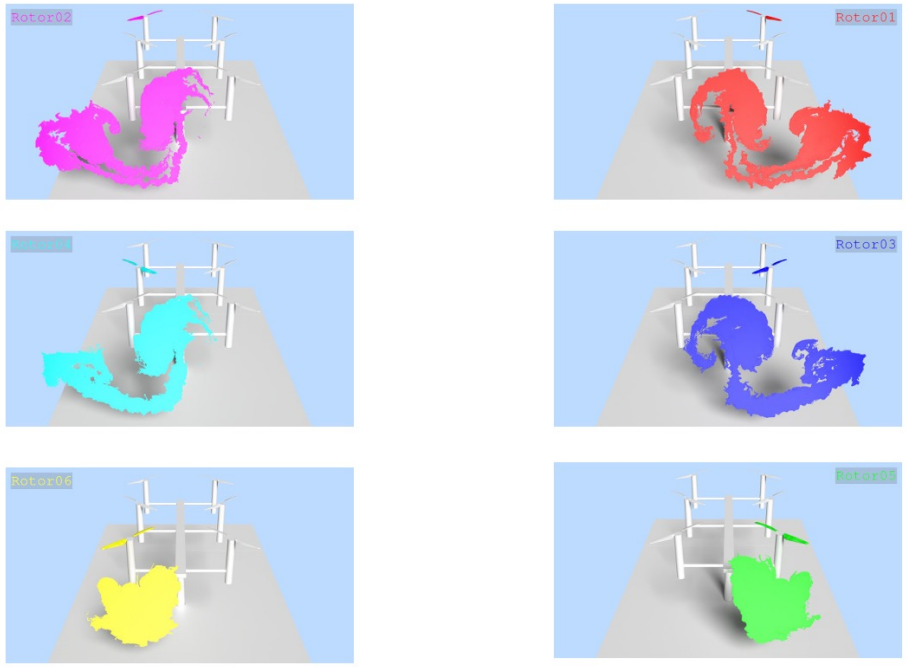
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- **Flow visualization plays a significant role in understanding the aerodynamic performance and interactions in multirotor setups.**
- **Techniques like particle traces help in visualizing flow patterns, shedding light on critical aerodynamics**
- **These visual tools are invaluable for validating CFD results for accuracy and correctness,**
- **Emphasis on flow visualization helps in multirotor designs for better performance and efficiency.**

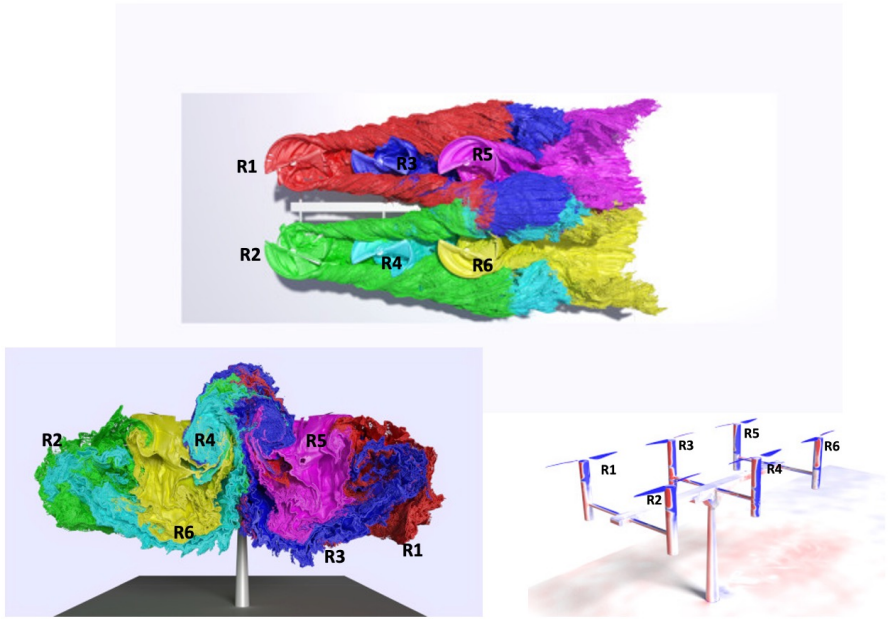


# Flow Visualization
## Footprints from each rotors

**MTB 6 rotors: Forward Flight, 20 fps, 0-deg Pitch Assembly**
**Interference Footprint at an Aft Plane: X = 55 ft**

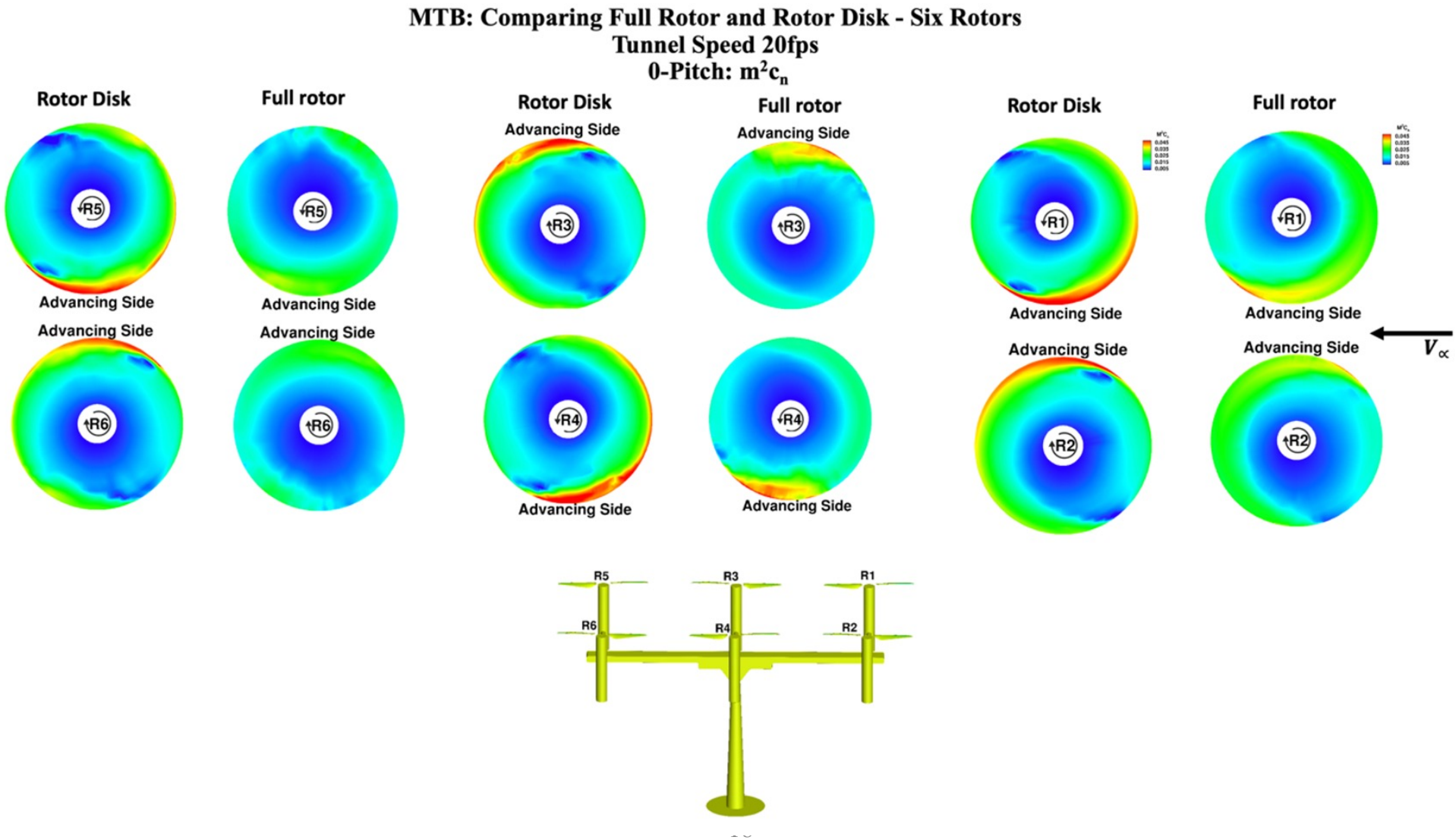



**MTB 6 rotors: Forward Flight, 20 fps, 0-deg Pitch Assembly**
**Each rotors colored differently showing the interactions**

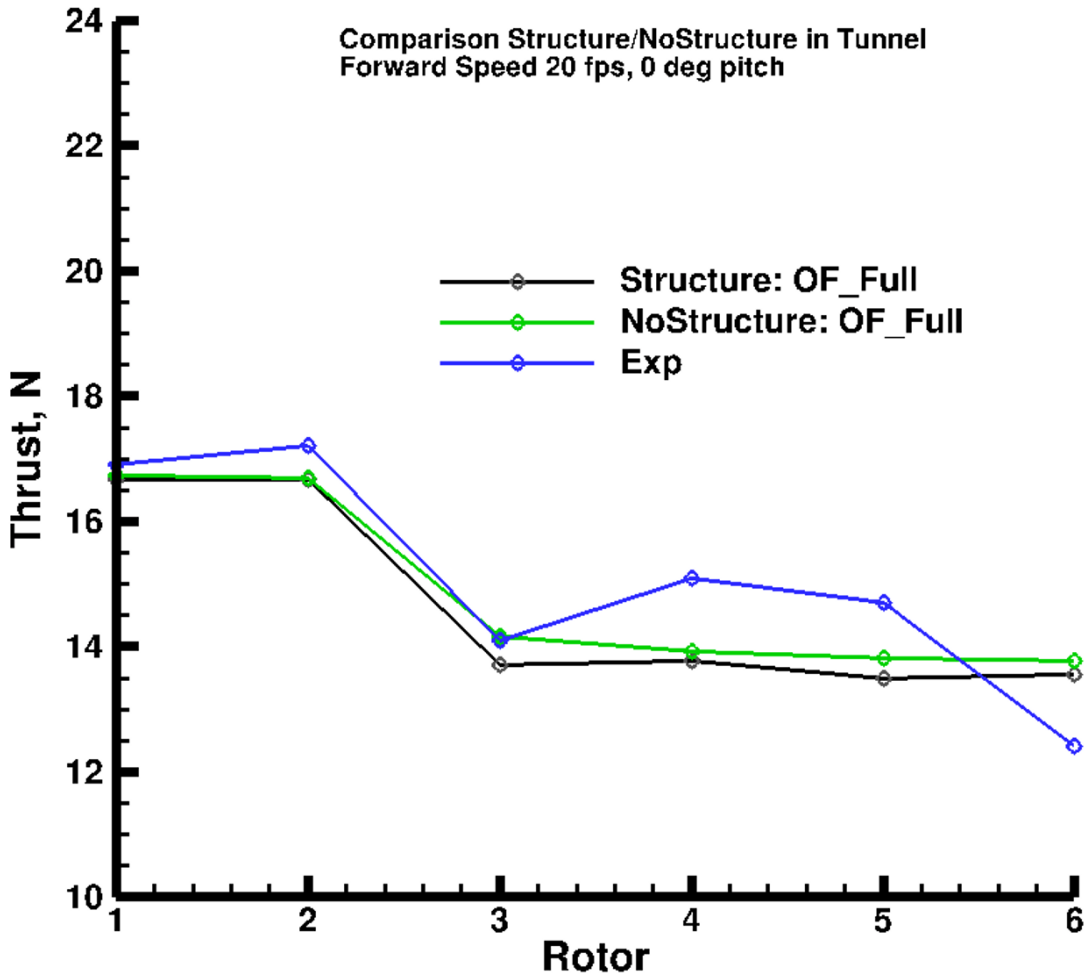



**Crossflow lateral plane at the back of R5 and R6: at location x > 35**

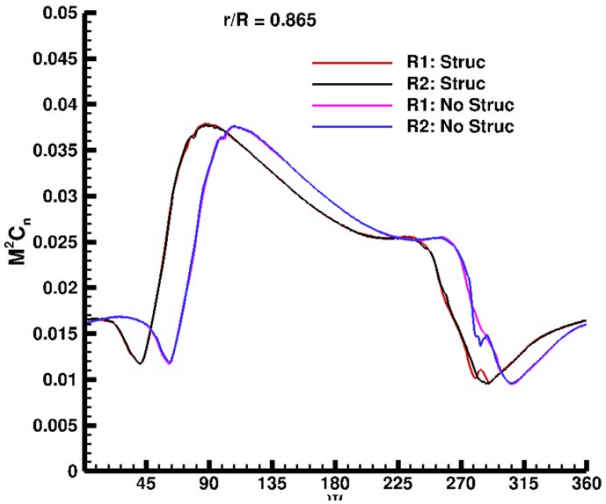
# Comparing Rotor Unsteady versus Rotor-Disk



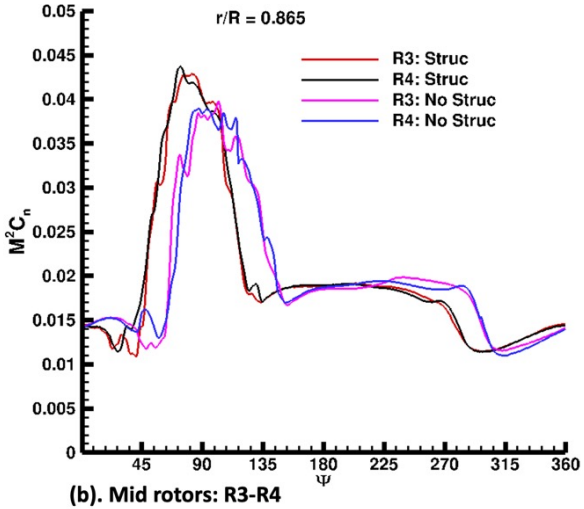
# Effect of Structure: Fixed collective



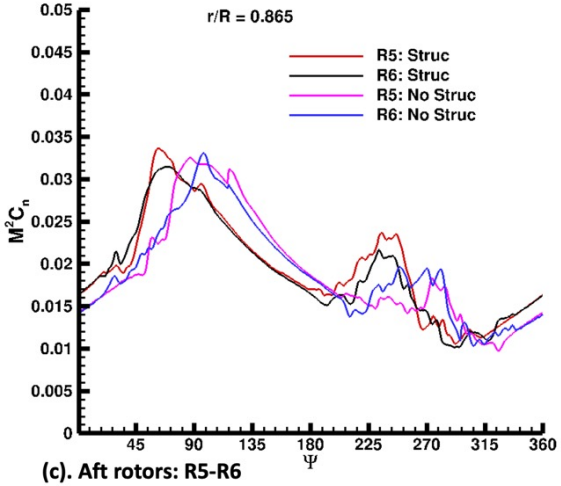
# Effect of Structure: Fixed collective



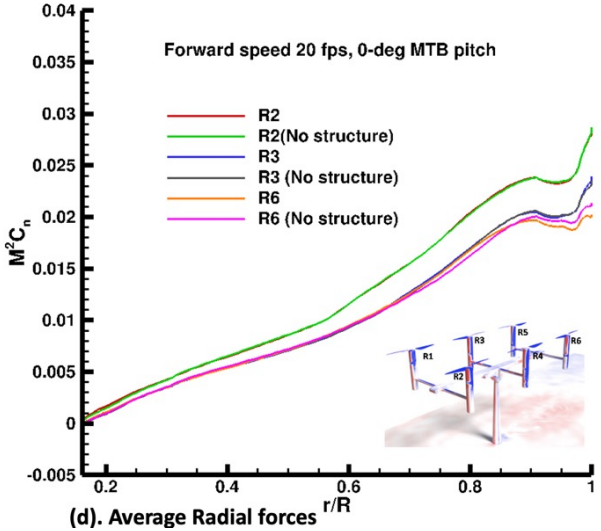
(a). Front rotors: R1-R2



(b). Mid rotors: R3-R4

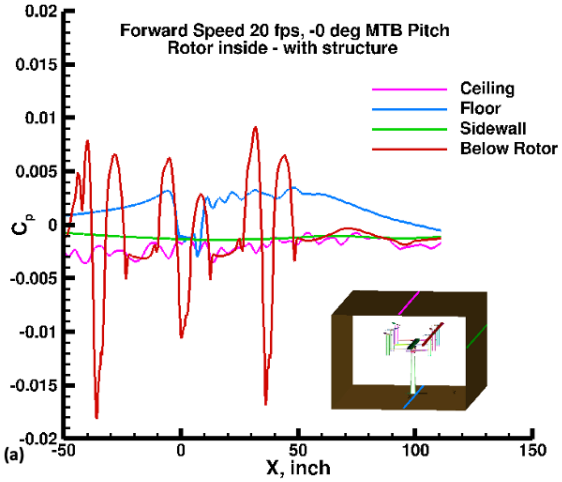


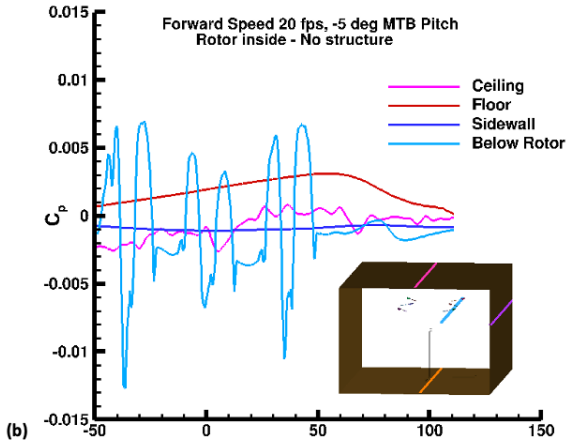
(c). Aft rotors: R5-R6

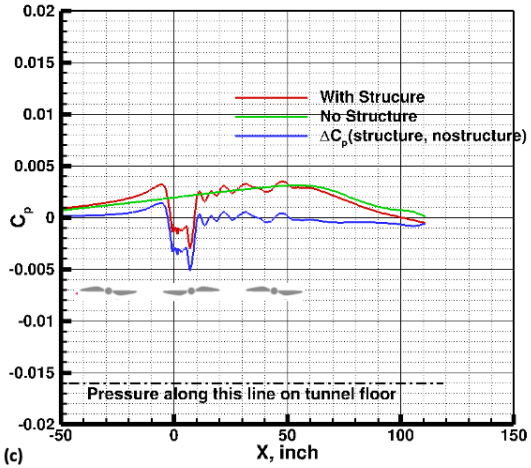


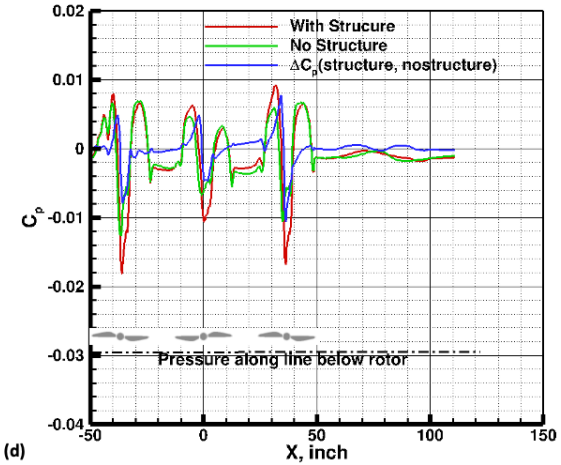
(d). Average Radial forces

# Four In-plane Rotors

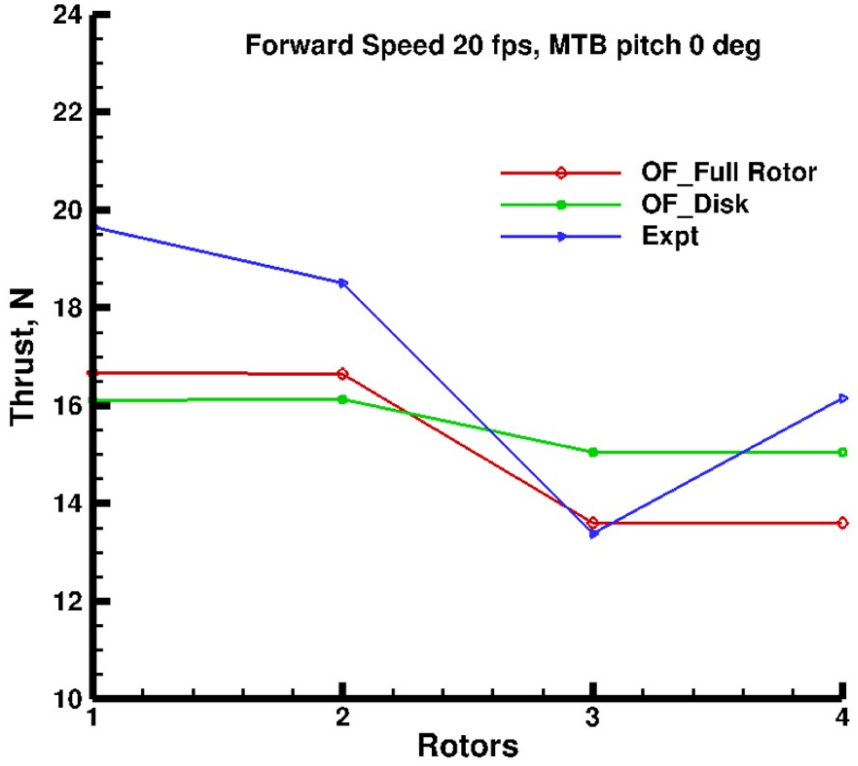


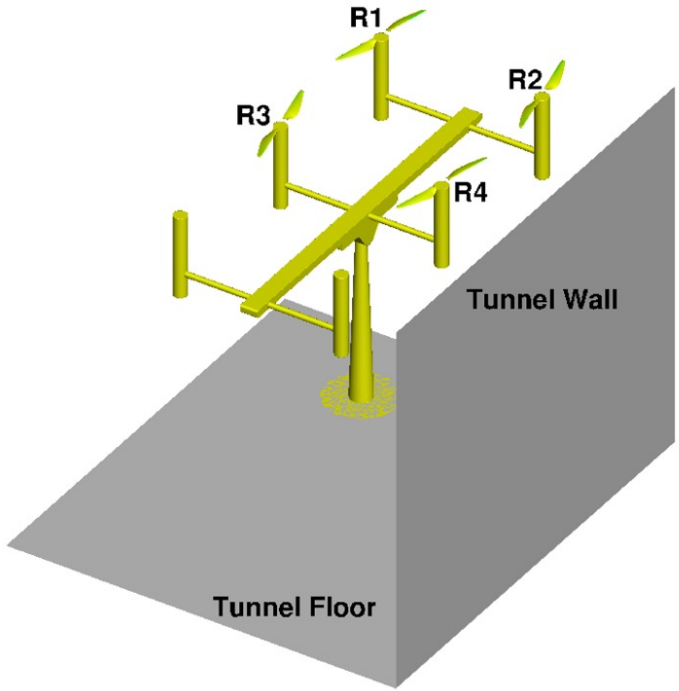



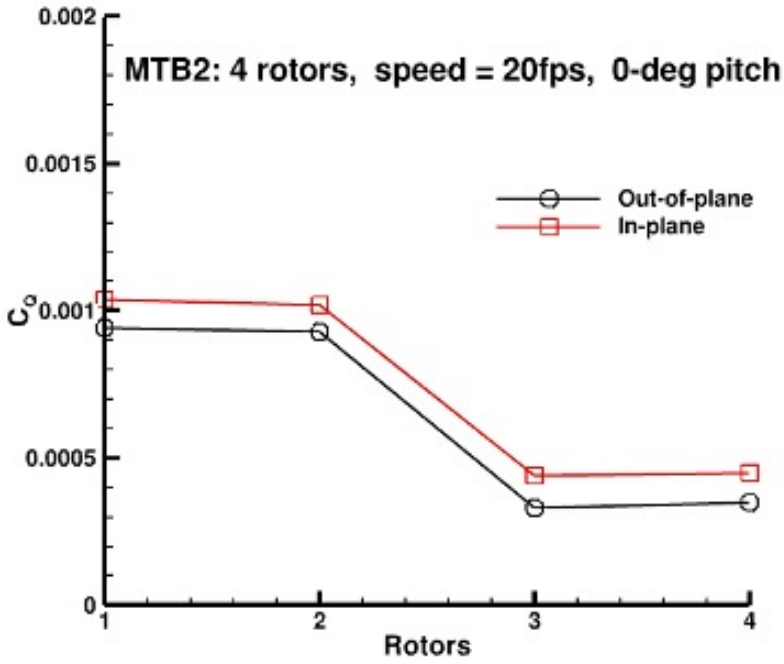



# Four In-plane Rotors

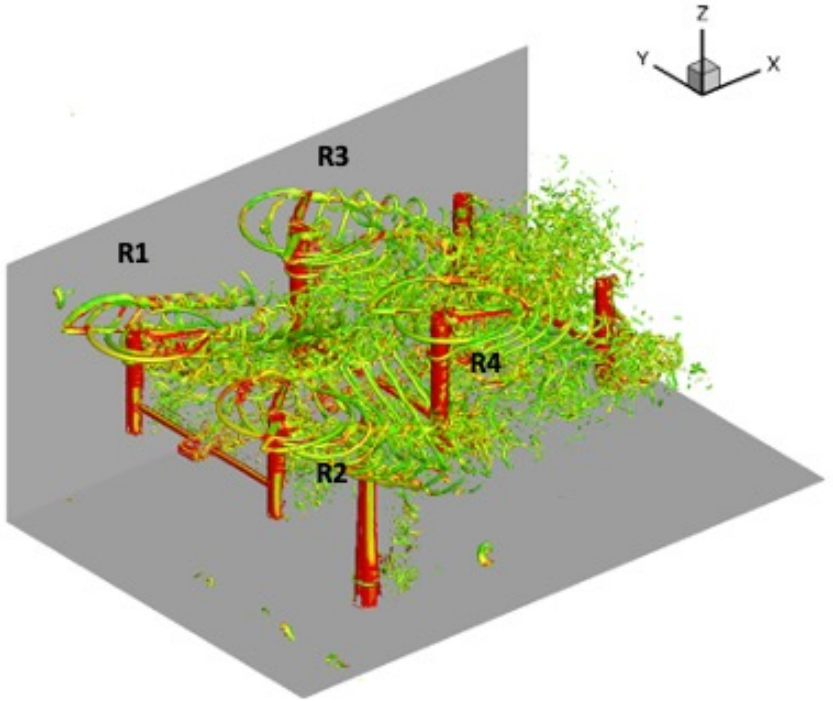


# Four Out-of-plane Rotors in Quad configuration



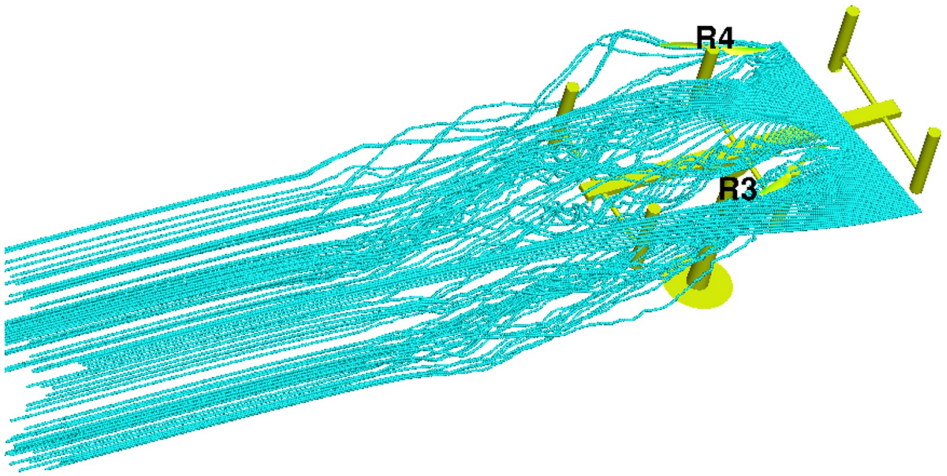

(a) Torque




(b) Q-criteria colored by vorticity magnitude

# Two Side by Side rotors

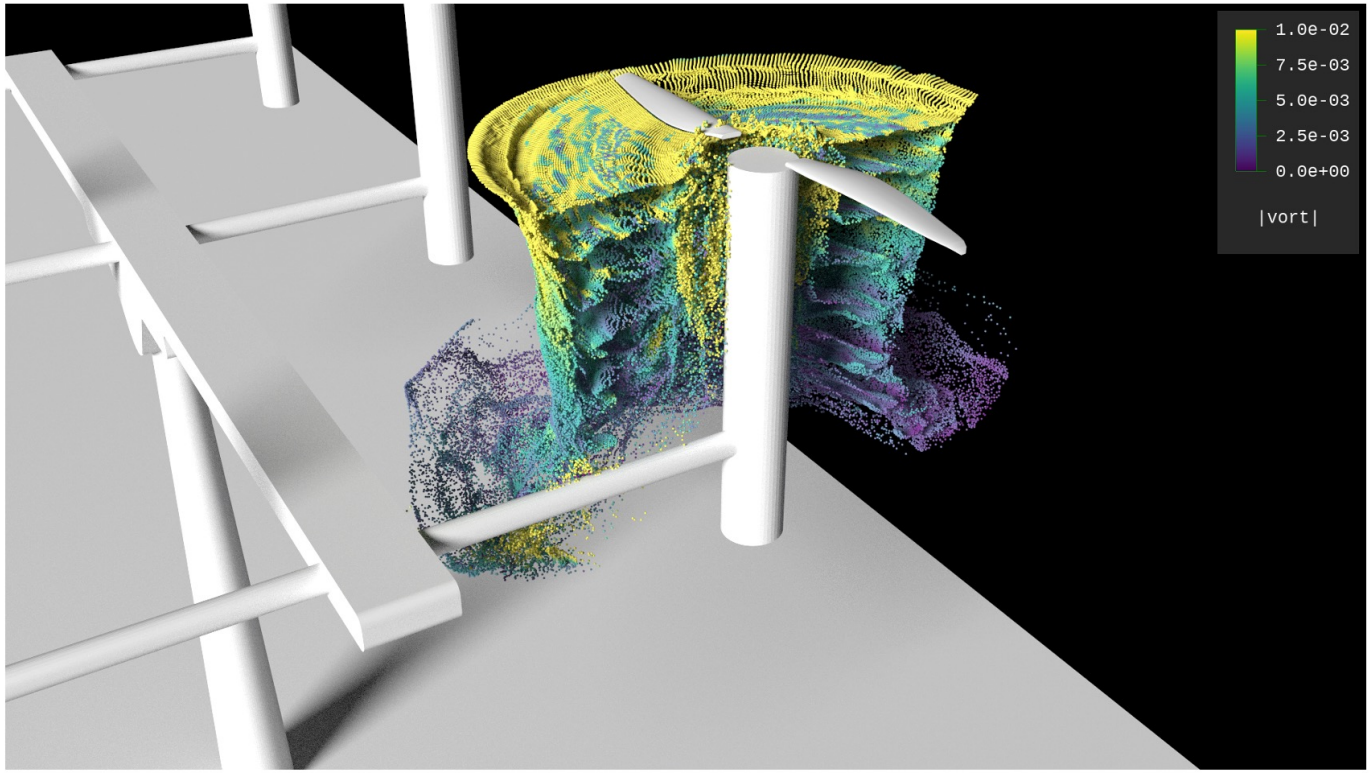
| Rotors | OF_Full Thrust, N | OF_Disk Thrust, N | Expt. Thrust, N |
|---|---|---|---|
| 3 | 16.20 | 18.90 | 16.9 |
| 4 | 16.17 | 18.90 | 17.8 |



# Single Rotor in Hover

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| Cases | FM |
|---|---|
| FM: Full Rotor | 0.710 |
| FM: Disk | 0.713 |
| FM: Expt | 0.714 |





# Summary and Conclusions

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- **The analyses and experimental setup are briefly discussed.**
- **The grid generation was based on an initial CAD model of the various support structures inside the tunnel. The tunnel geometry was not part of the CAD model.**
- **A limited verification procedure was performed to assess solution sensitivity to spatial resolution, and different trim strategies for multirotor configurations.**
- **The rotor disk results were presented for a loosely coupled comprehensive code.**
- **Both qualitative and quantitative comparisons of the computed and measured flow field reveal that the simulation captures the key features of the complex rotor wake, rotor-structures interactions, and rotor-rotor interactions. However, in the case of fixed collective setting of the experiment, the computed thrusts agree with the measured trends within a reasonable bound except for the lateral symmetry. Computation maintains lateral symmetry for all the configurations as opposed to the measured thrust.**



# Summary and Conclusions

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- **Most of the qualitative comparisons are done with fixed rotor collectives. For different collective settings, some aspects of the rotor trimming were performed with the rotor-disk algorithm**

- **Overall, the disk model results are encouraging.**

- **The ability of the disk representation to predict the mean characteristics of the rotor flowfield was demonstrated.**

- **Improved representation of separated flow behind the rotor mount would require full Navier-Stokes equations.**

- **The thrust predictions for the untrimmed rotor are underestimated by both the rotor-disk and full rotor solutions. The rotor-disk solution deviated by approximately 10% from the full rotor simulation. Despite this difference, the rotor-disk simulation requires significantly less computational resources. In the hover case examined in this study, there is a notable 60% reduction in computational expenses.**





# Future Directions and Improvements

- **MTB3 and LMTB**
- **Future directions involve enhancing the MTB capabilities and improving the fidelity of both CFD methods and experimental setups.**
- **Ongoing improvements focus on better data collection techniques and more precise simulation models for comprehensive analyses.**
- **These advancements aim to bridge the gap between experimental data and simulation accuracy for more reliable multirotor designs.**
- **The goal is to support the development of advanced multirotor configurations that meet the Urban Air Mobility challenges effectively.**



# Acknowledgements

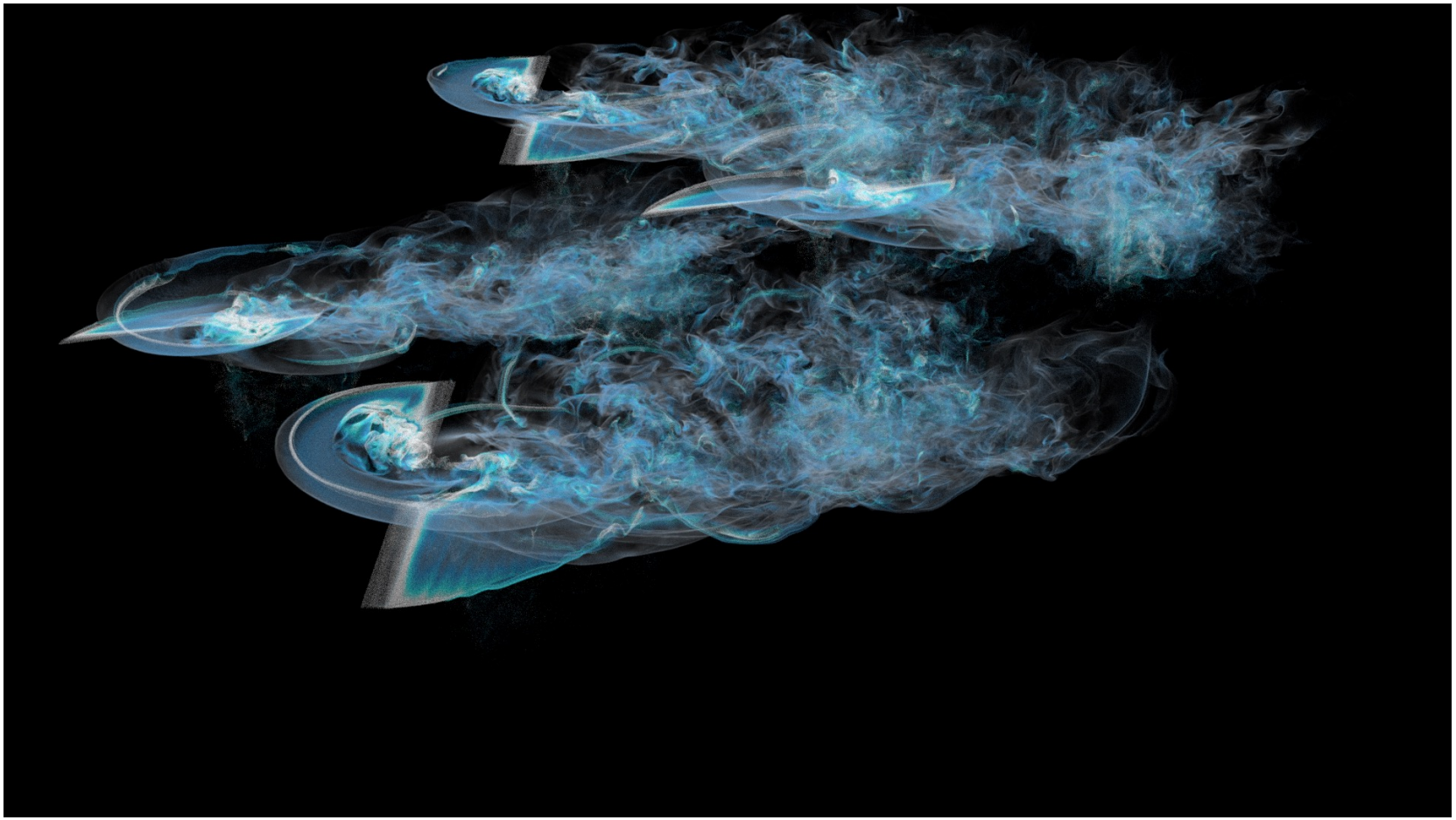
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- **Revolutionary Vertical Lift Technology (RVLT)**
- **Flow Visualization: Tim Sandstrom**
- **Experiment: Carl Russell, Sarah Conley**
- **Comprehensive analysis, CAMRAD II and many discussions: Wayne Johnson**
- **Grid Generation: William Chan**
- **Flowsolver, latest release of Overflow with Disk Model: Pieter Buning and Joseph Derlaga.**
- **Computational Resources: NAS Supercomputing Facility**





# Flow Visualization: Out-of-plane rotors in Quadrotor Configuration



# Taxonomy of Multirotor Vehicles

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- AAM is the high level category, with the others falling below it.
- AAM: Advanced Air Mobility – not incredibly well-defined, but generally includes missions less than 500nmi, increased autonomy, and electrified propulsion. Not necessarily VTOL.
    - UAM: Urban Air Mobility – basically the urban air taxi category of AAM.
    - UAS: Uncrewed Aerial System – aircraft system of any size that has no passengers or crew aboard. Includes any ground support equipment necessary to operate the vehicle. Some UAS fall within AAM, and others don't. There isn't a clear dividing line, but the UAS within AAM are generally going to be stuff like package delivery.
    - UAV: Uncrewed Aerial Vehicle – just the vehicle component of a UAS.
    - RAM: Regional Air Mobility – short-hop fixed-wing aircraft. Not VTOL, but possibly ESTOL.