High-Fidelity Simulations of NASA's Urban Air Mobility Concept Vehicles

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Urban Air Mobility

- Urban Air Mobility (UAM) is envisioned to be a safe and efficient air transportation system, where everything from small package delivery drones to passenger-carrying air taxis will operate in urban areas.

NASA is contributing to this revolution in aeronautics

NASA's RVLT UAM Concept Vehicles

Side-by-Side
(Intermeshing Rotors) [1]

Tilt-Wing
(Airplane mode for efficient cruise flight, helicopter mode for VTOL) [4]

Quadcopter
(Vertically-Separated Rotors) [2]

Quiet Single-Main Rotor (QSMR)
(NOTAR, specifically designed for quiet operations) [3]

- *Reference vehicles contain relevant UAM features and technologies*
- *6 pax VTOL; 2 x 37.5 mile mission with 10 kt headwind; 20 min cruise reserve*

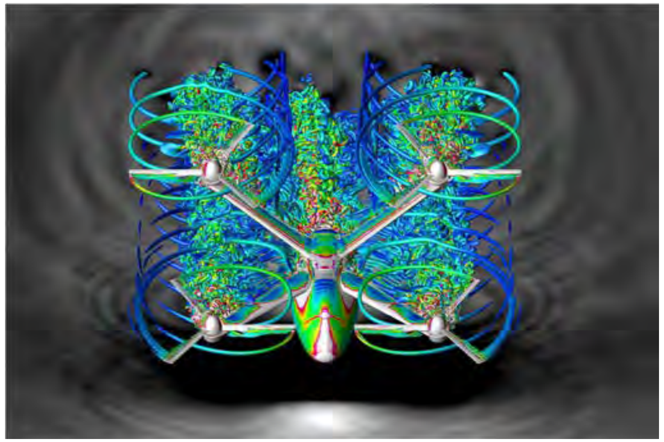
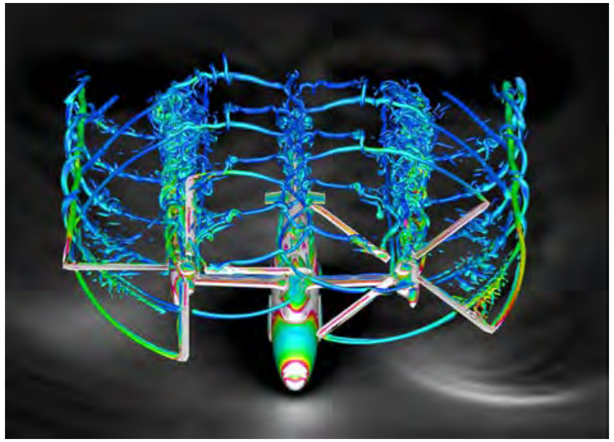
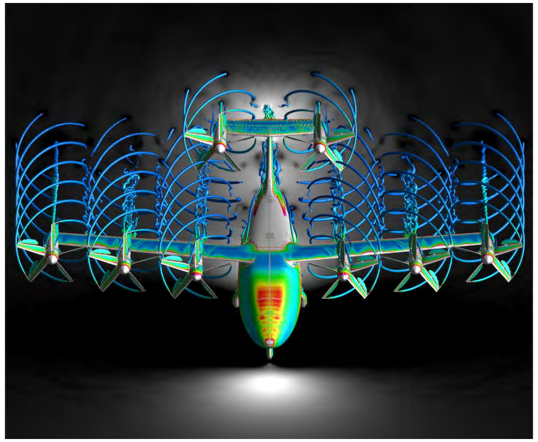
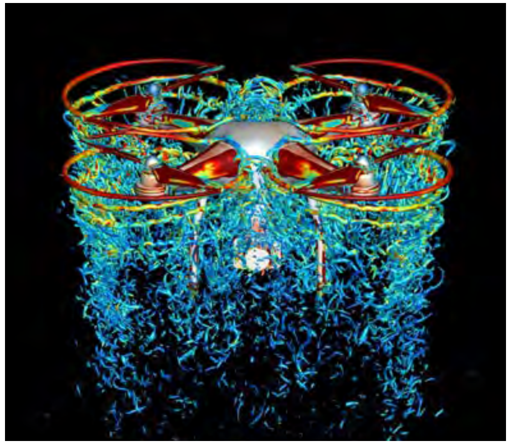
Lift+Cruise
(Hybrid-Mounted Rotors)

[1] Ventura Diaz, P., Johnson, W., Ahmad, J., and Yoon, S., "The Side-by-side Urban Air Taxi Concept," AIAA Paper 2019–2828, June 2019.
[2] Ventura Diaz, P., and Yoon, S., "High-Fidelity Simulations of a Quadrotor Vehicle for Urban Air Mobility," AIAA Paper 2022–0152, January 2022.
[3] Ventura Diaz, P., Garcia, D., and Yoon, S., "Computational Analysis of a Quiet Single-Main Rotor Helicopter for Air Taxi Operations", VFS Forum May 2022.
[4] Garcia, D., Ventura Diaz, P., and Yoon, S., "High-Fidelity Simulations of a Tiltwing Vehicle for Urban Air Mobility", AIAA Paper 2023-2282, January 2023.

Motivation

- Current design tools for UAM vehicles use empirical models that are based on historical data that is biased toward traditional Vertical Take-Off and Landing (VTOL) vehicle configurations.
- This can result in inadequate models since most UAM vehicles have very non-traditional VTOL configurations.

Use high-fidelity CFD and overset structured grids to accurately model the moving rotors, solve the flow and calculate aerodynamic performance, for NASA's UAM concept vehicles.

Numerical Approach

High-fidelity CFD: OVERFLOW

Overset Grid Generation: Chimera Grid Tools

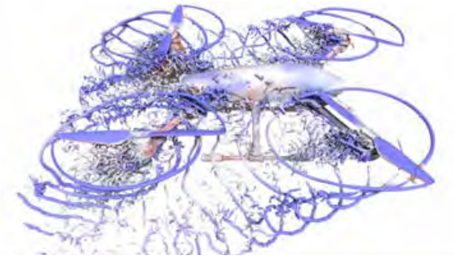
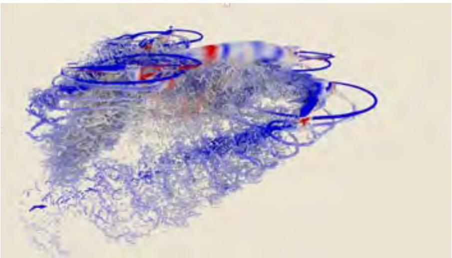
Comprehensive Analysis: CAMRAD II

Loose Coupling Methodology: CAMRAD II – OVERFLOW

High-Fidelity CFD

OVERFLOW

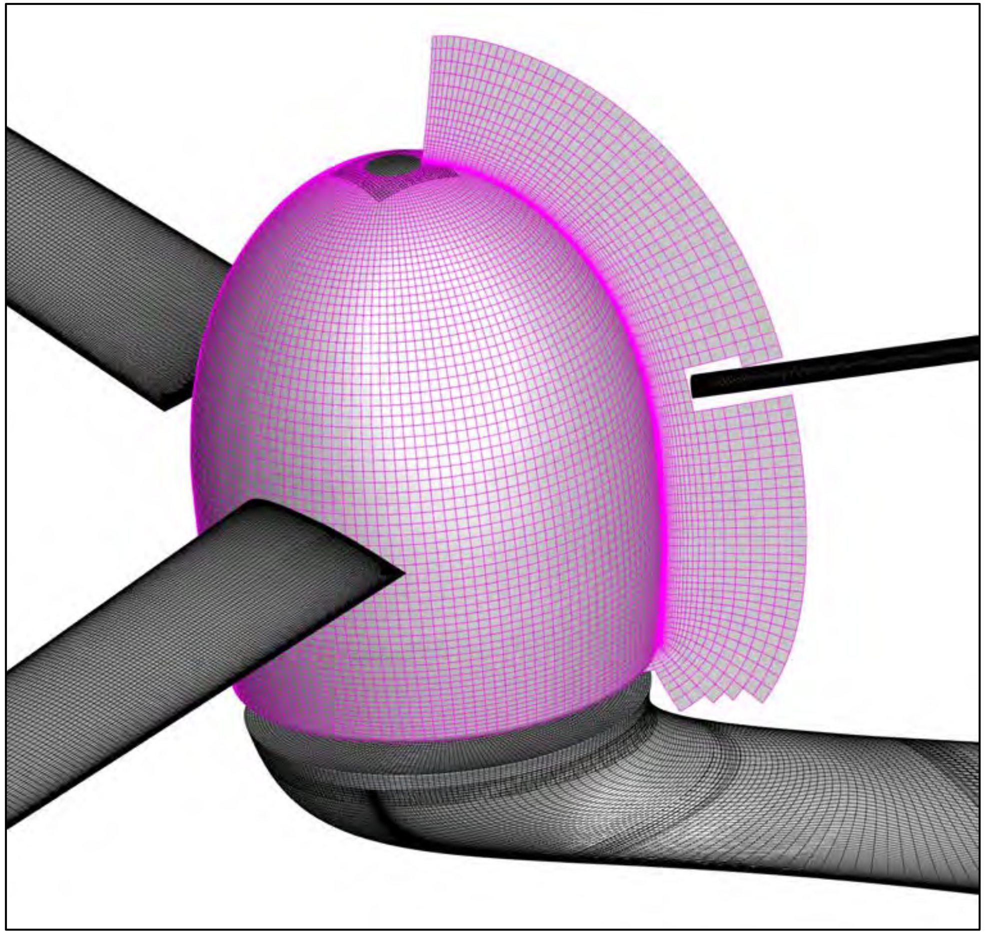
- OVERFLOW is a high-order accurate Navier-Stokes solver
  - Solves the unsteady Reynolds-averaged Navier-Stokes (RANS) equations
  - Structured overset grids
  - 5^{th} order accurate central differences with scalar dissipation for convective terms
  - 2^{nd} order accurate dual time-stepping
  - Hybrid RANS/LES turbulence models
    - Spalart-Allmaras one equation turbulence model
    - DDES length scale
    - $y^{+} \leq 1$


Overset Grid Generation

Chimera Grid Tools (CGT)

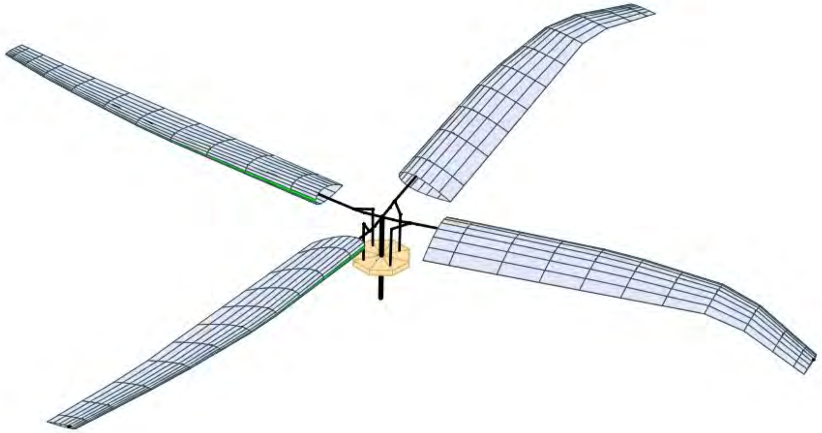
- CGT is NASA's overset grid generation software
- Four main steps in overset grid generation:
  - **Geometry processing**: Geometry obtained from CAD or 3D scan techniques
  - **Surface Grid Generation**: feature based domain decomposition, grid point distribution, mesh fill
  - **Volume Grid Generation**:
    - Hyperbolic Near-Body (NB)
    - Cartesian Off-Body (OB)
  - **Domain Connectivity**: grid points blanking, donor stencil search

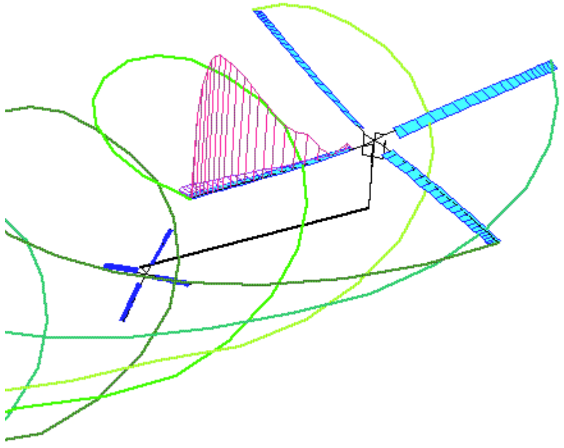


Comprehensive Analysis

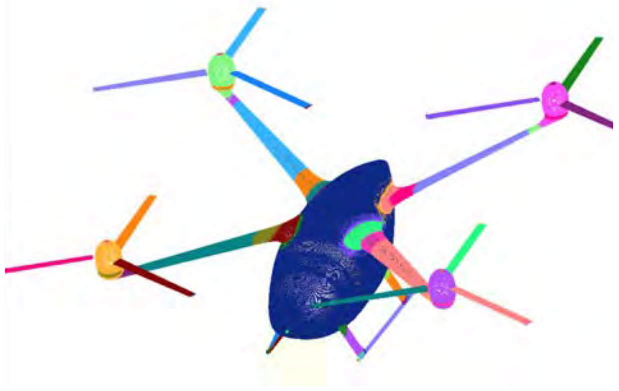
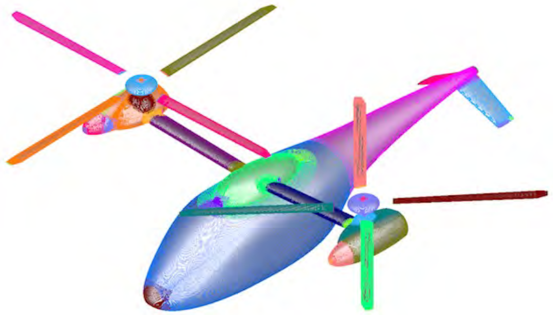
CAMRAD II

- CAMRAD II is an aeromechanics analysis of rotorcraft that incorporates a combination of advanced technologies, including **multibody dynamics**, **nonlinear finite elements**, and **rotorcraft aerodynamics**.
- The **trim task** finds **the equilibrium solution** for a steady state operating condition, and produces the solution for performance, loads, and vibration.
- The **aerodynamic model** for the rotor blade is based on **lifting-line theory**, using two-dimensional airfoil characteristics and a vortex wake model.
- CAMRAD II has undergone extensive correlation with performance and loads measurements on rotorcraft.





W. Johnson, "Rotorcraft Aerodynamic Models for a Comprehensive Analysis", American Helicopter Society 54th Annual Forum, Washington, D. C., May 1998.

Results

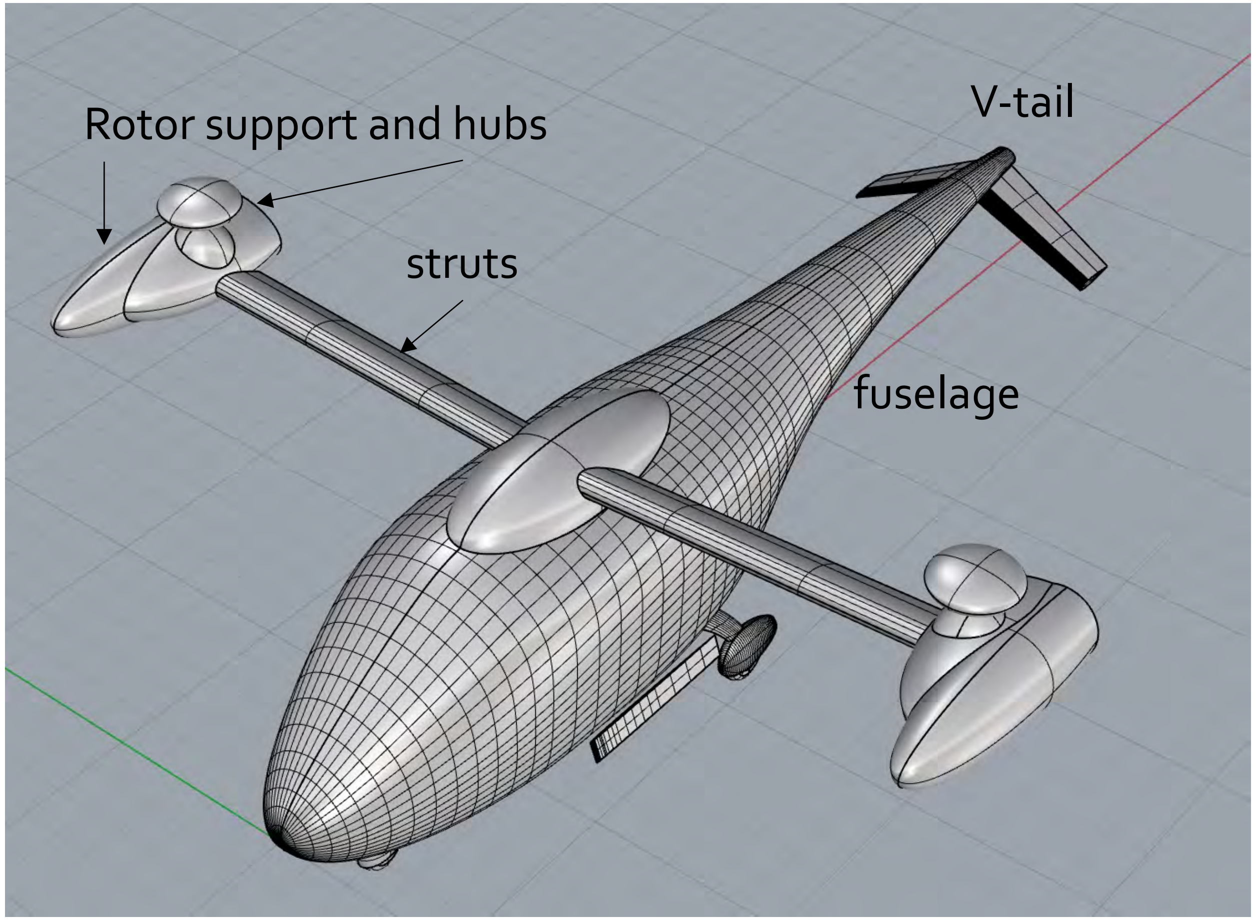
Side-by-side

Quadcopter

QSMR

Tiltwing

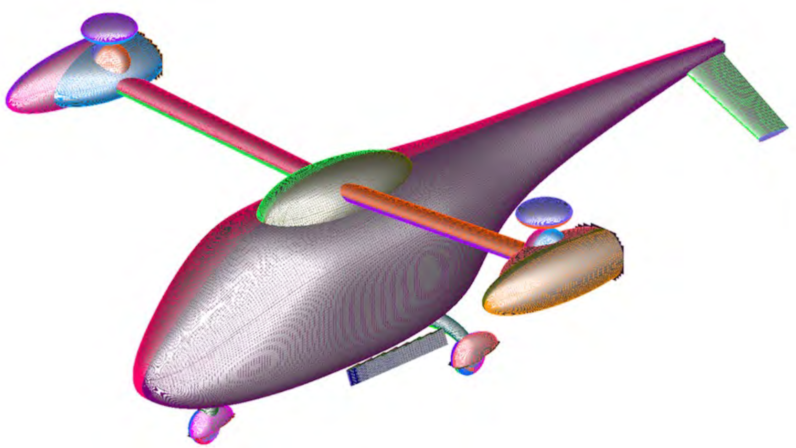
Side-by-side air taxi



Boundary Representation (BRep)

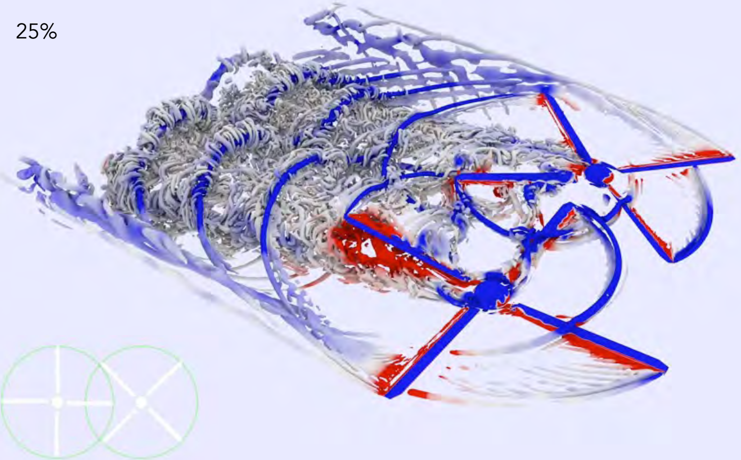
CAD file for SbS aircraft (IGES or STEP)

- Imported into CGT using EGADS API from Engineering Sketch Pad
- *egads2srf* tool → Discrete representations are generated from each solid.



Structured untrimmed patches obtained from the CAD geometry using EGADS

25%



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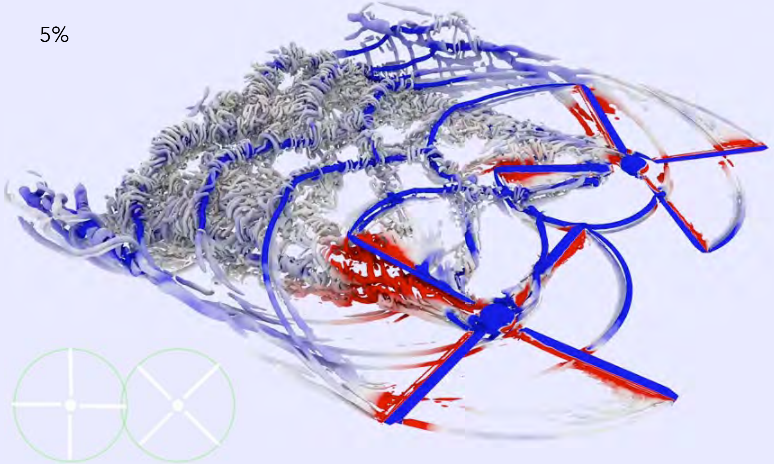

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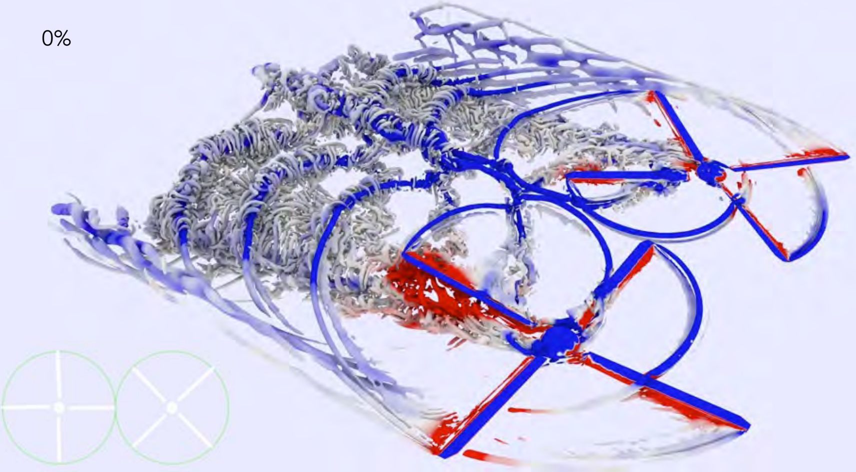

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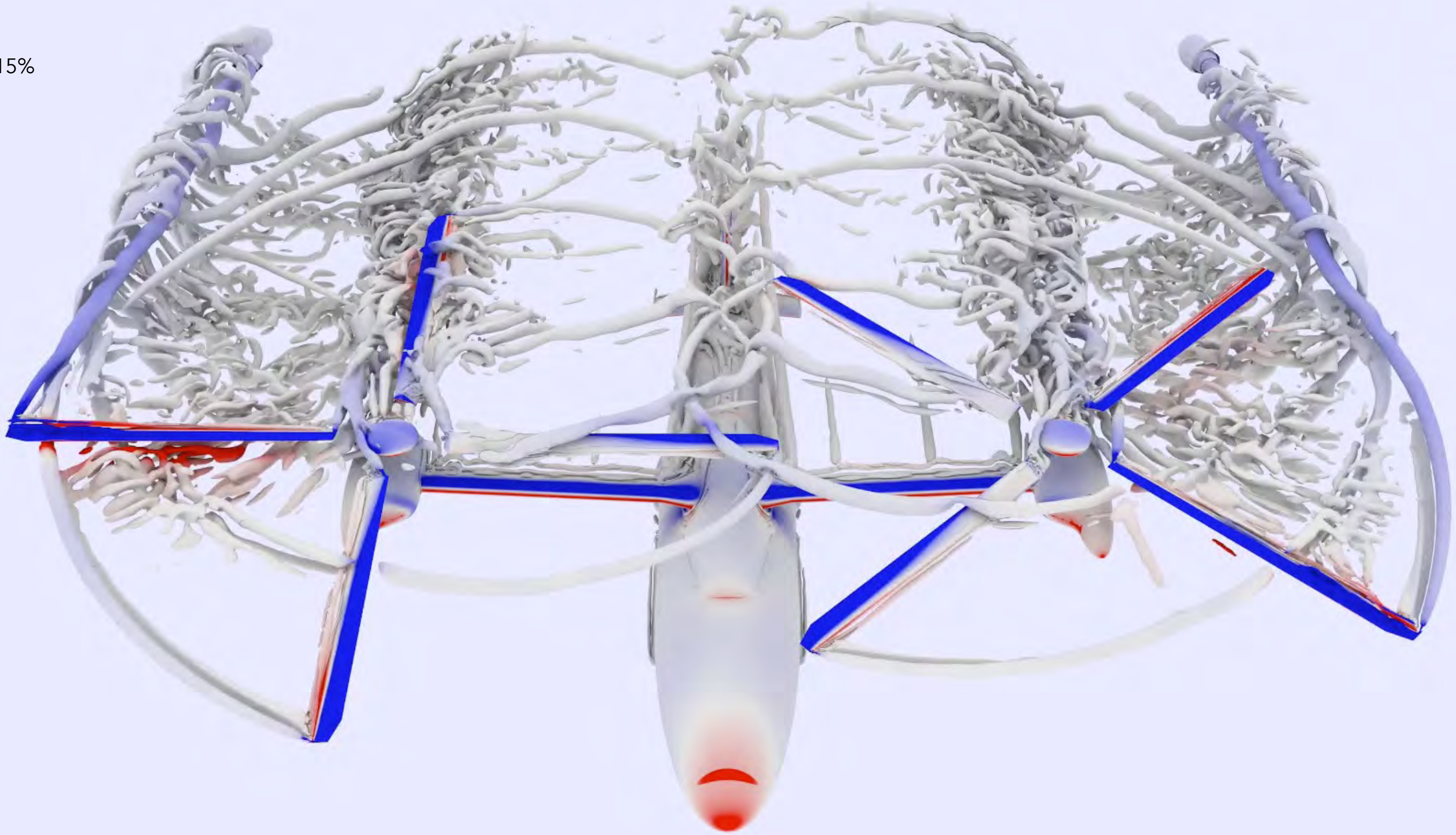


Motivation: Overlapped, side-by-side rotor performance in cruise is better than separate non-overlapped rotors:

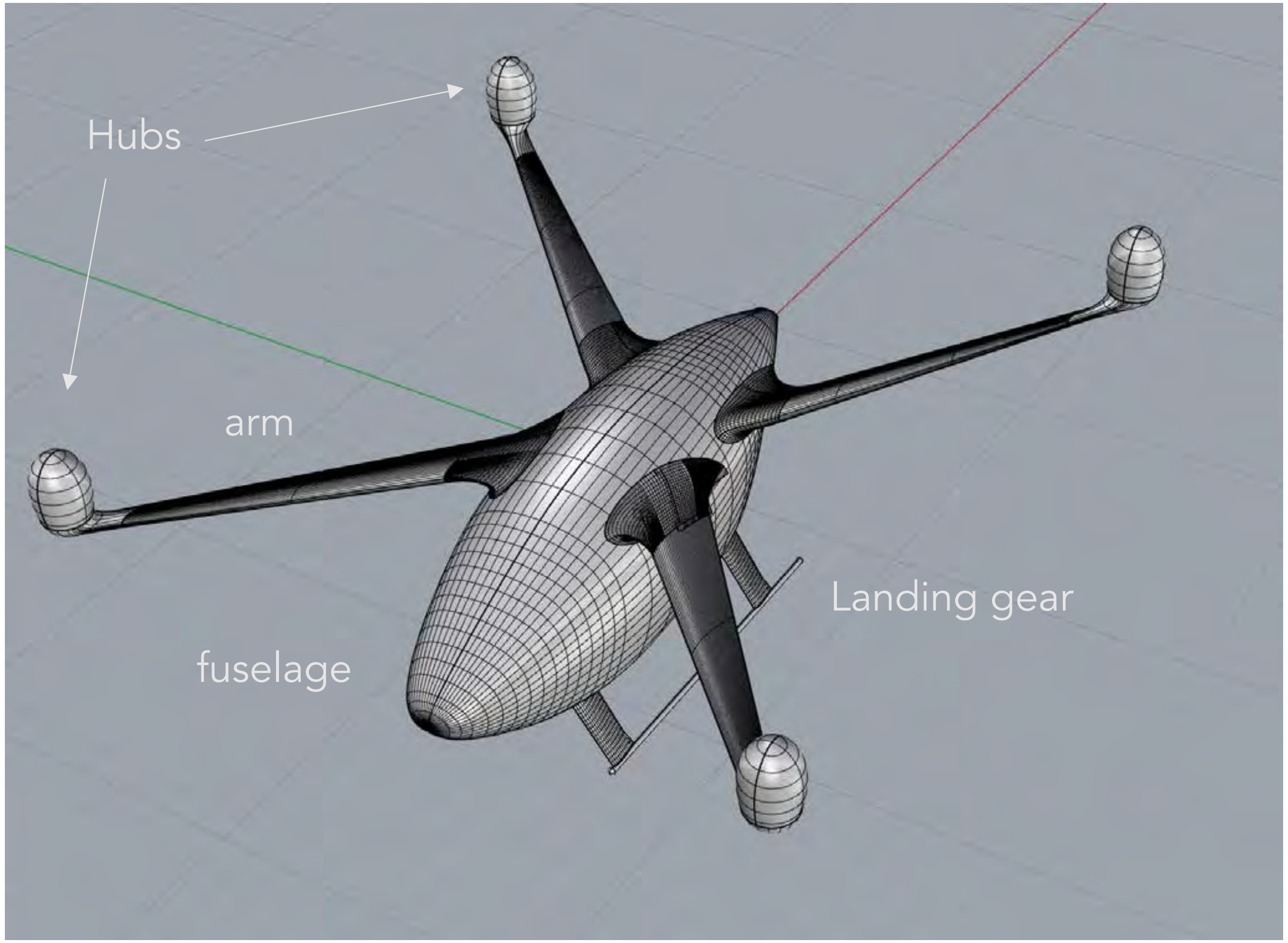
- *The combined wake system approximates that of a single wing with a large span, which reduces the induced power.*

Objectives: Study the aerodynamics and performance of NASA's side-by-side UAM concept:

- *High-fidelity CFD loosely coupled with rotorcraft comprehensive analysis.*
- *The tools developed can be used to explore the noise and performance for different configurations of multi-rotor UAM vehicles in support of eVTOL air taxi operations.*

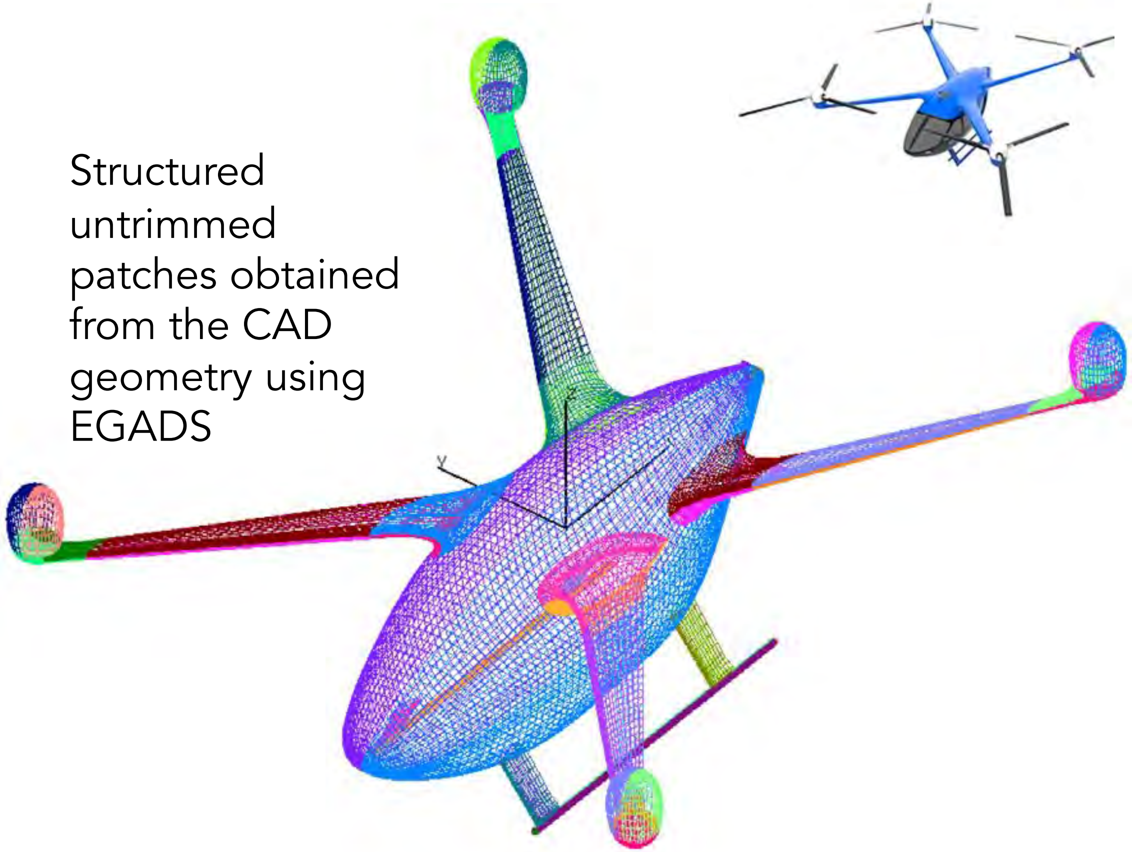
"The Side-by-side Urban Air Taxi Concept",
P. Ventura Diaz, W. Johnson, J. Ahmad and S. Yoon, AIAA Paper 2019-2828

Quadcopter air taxi



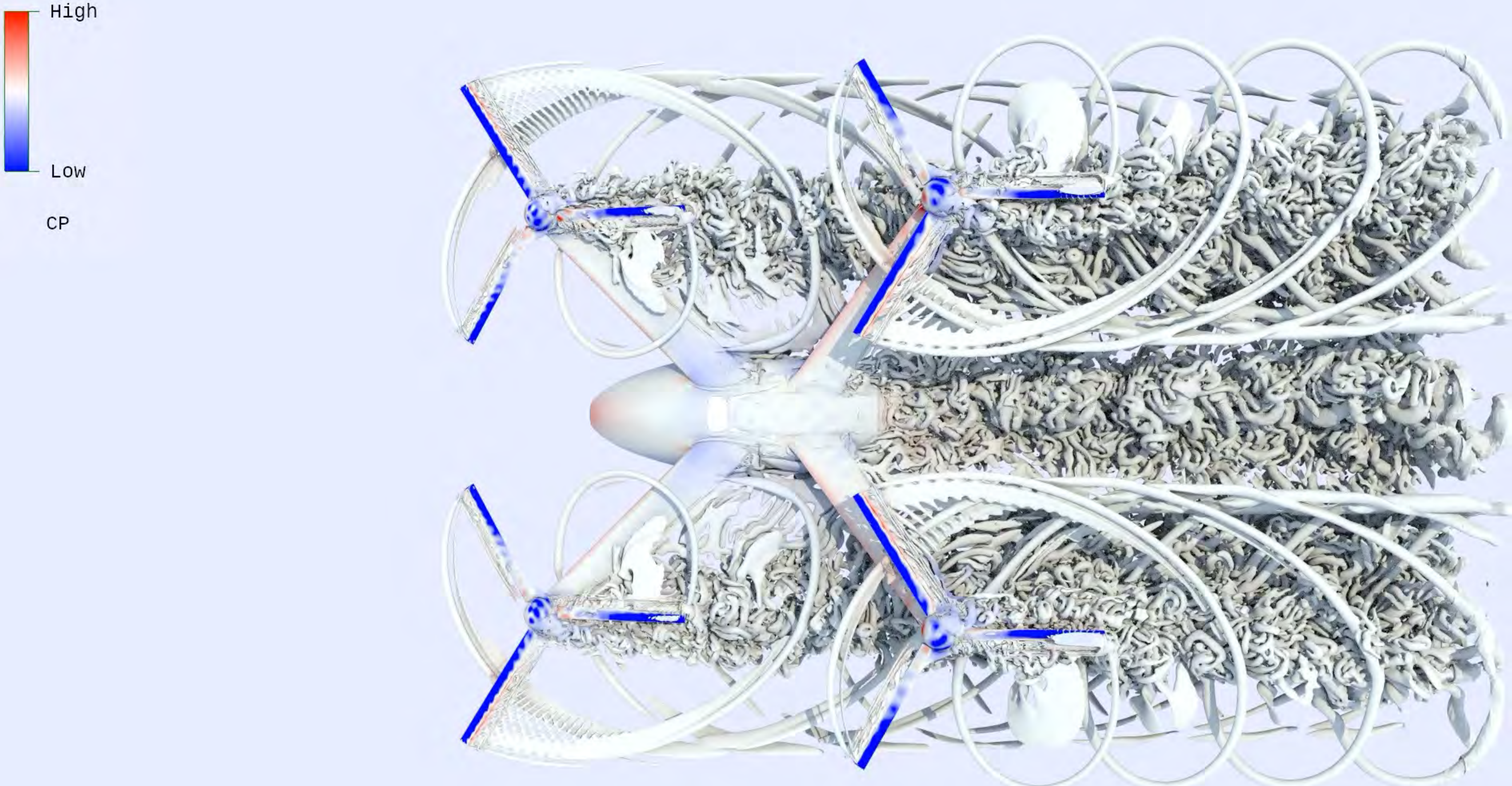
Boundary Representation (BRep)

Structured untrimmed patches obtained from the CAD geometry using EGADS



Vertical separation between front and rear rotors to reduce rotor-rotor interactions in cruise, and decrease power required for forward flight [1]

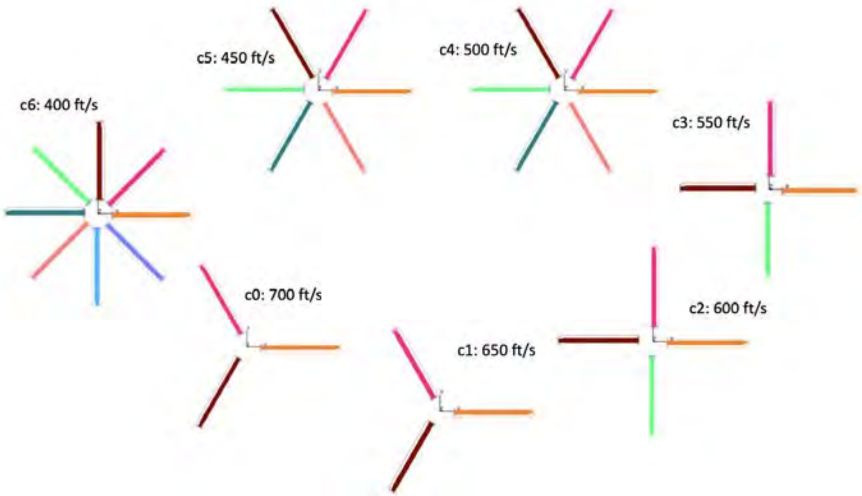
[1] Ventura Diaz, P., and Yoon, S., "High-Fidelity Computational Study of NASA's Quadrotor Urban Air Taxi Concept" AIAA Paper 2020–0302, January 2020.



Ventura Diaz, P., and Yoon, S., “High-Fidelity Simulations of a Quadrotor Vehicle for Urban Air Mobility,” AIAA Paper 2022–0152, January 2022.

Quiet Single-Main Rotor (QSMR)

- Most UAM vehicles designed with multiple rotors
- Often disregarded configuration is the single-main rotor helicopter
  - Known path for certification
  - NOTAR to remove tail rotor noise
  - Specifically designed for low-noise operations
- Based on the work from Johnson [1].



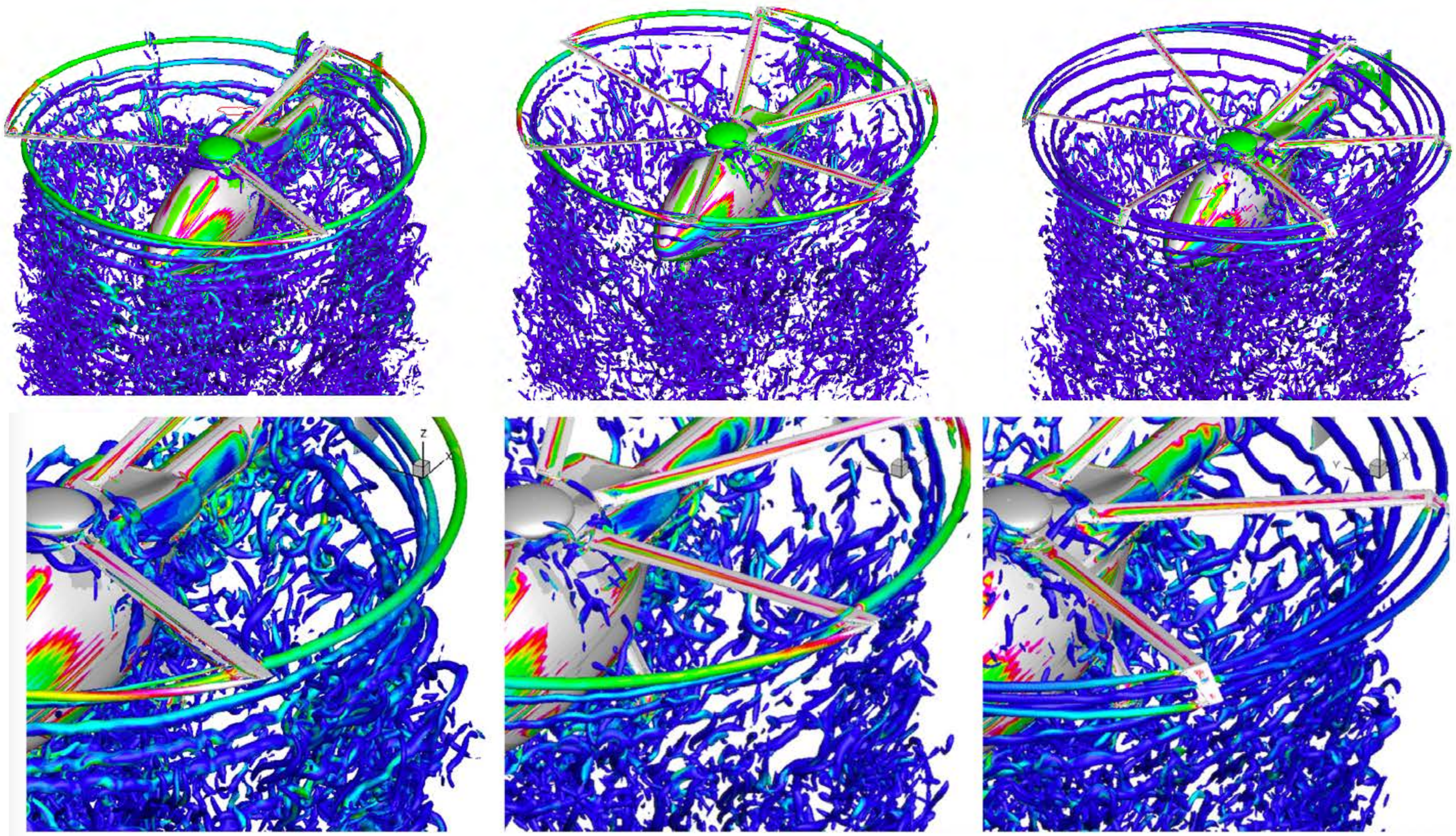
[1] Johnson, W., "A Quiet Helicopter for Air Taxi Operations", VFS Aeromechanics for Advanced Vertical Flight Technical Meeting, San Jose, CA, January 21–23, 2020.

QSMR in Hover

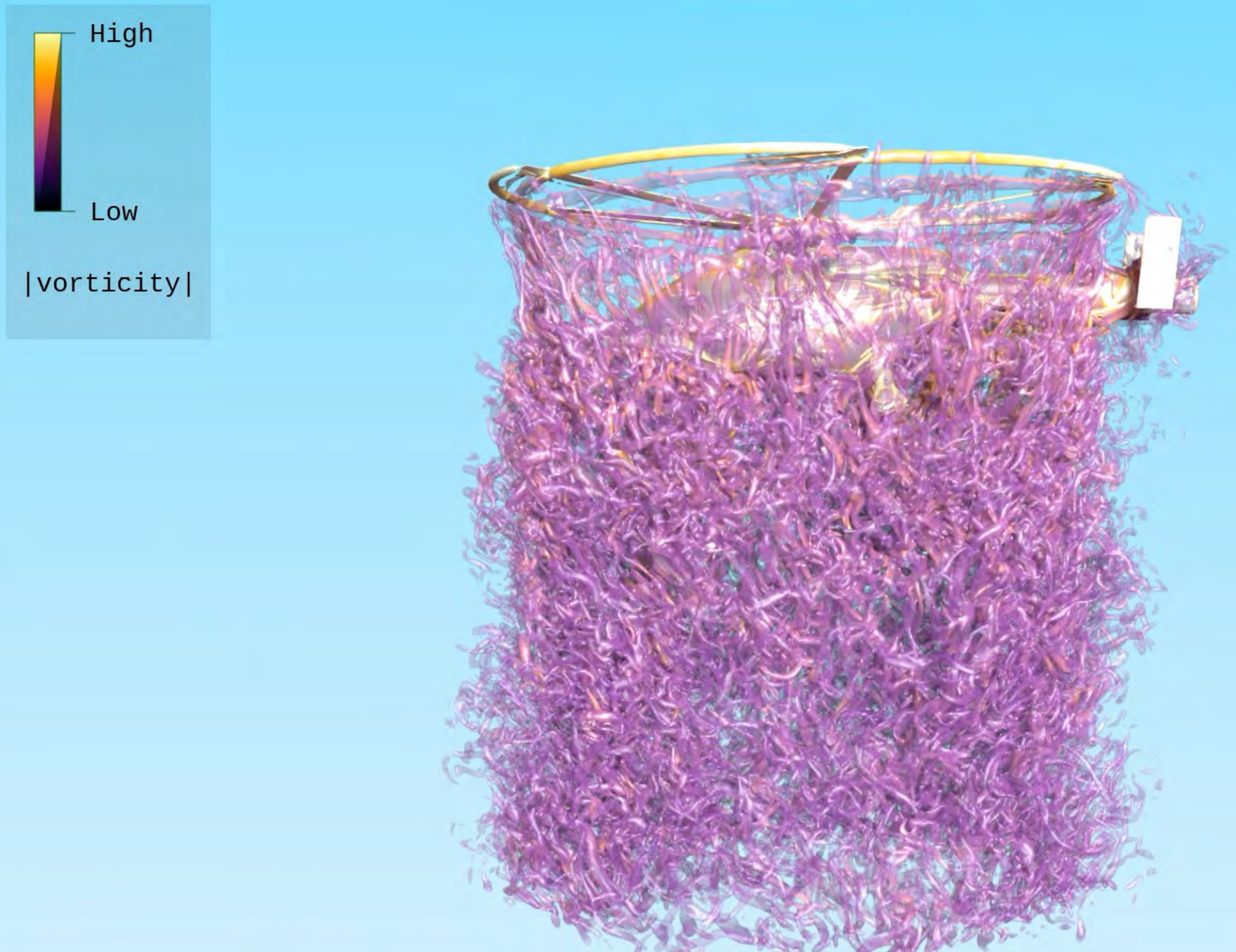
Q-criterion vorticity iso-surfaces colored with vorticity magnitude

- Blade-vortex interactions (BVI).
- The tip droop changes the position of the primary tip vortex and decreases its strength, as seen by the lower vorticity magnitude.
- A secondary weak vortex is formed where the droop starts, due to the change in aerodynamic distribution at that section of the blade.

Baseline | Low-noise no droop | Low-noise 30deg droop



Ventura Diaz, P., Garcia, D., and Yoon, S., "Computational Analysis of a Quiet Single-Main Rotor Helicopter for Air Taxi Operations", VFS Forum 2022.


High
Low
|vorticity|

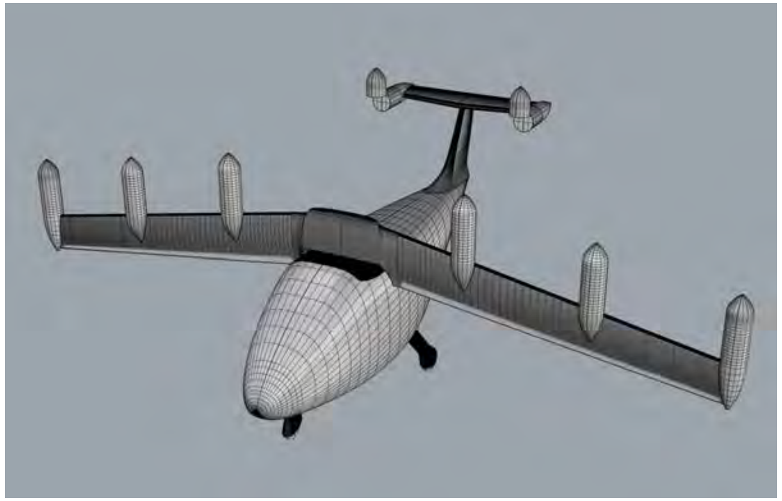
Tiltwing air taxi

Two different CAD geometries

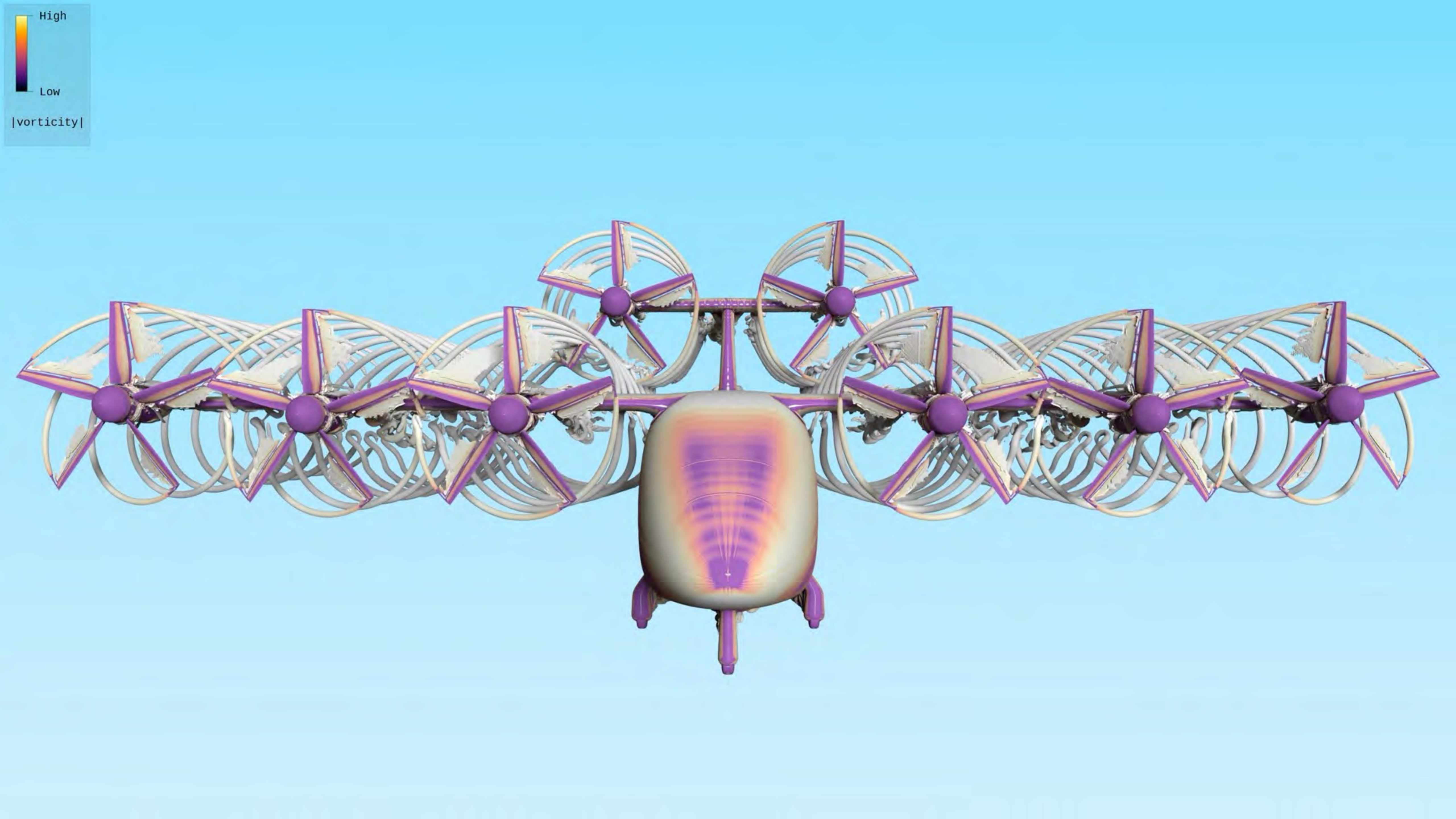
Airplane mode

"Airplane mode" geometry is used for cruise, no wing/fuselage gap

Helicopter mode



"Helicopter mode" geometry is used for hover/transition


High
Low
|vorticity|

Summary and Acknowledgements

SUMMARY

- NASA's air taxi UAM concepts have been analyzed using overset grids, comprehensive tools and high-fidelity CFD.
- The comprehensive code **CAMRAD II** and the high-fidelity CFD flow solver **OVERFLOW** have been loosely coupled for accurate rotor flow simulations.
- NASA's air taxi concepts are designed to focus and guide NASA research activities in support of aircraft development for emerging aviation markets, in particular VTOL activities

ACKNOWLEDGEMENTS

- This work was supported by NASA's **RVLT project** (Susan Gorton, PM; Brian Allan, PI).
- Wayne Johnson, Brian Allan, Gloria Yamauchi and Chris Silva for helpful discussions.
- The computations utilized the Pleiades, Electra, and Aitken supercomputers at the NASA Advanced Supercomputing (NAS) Division.

Questions?