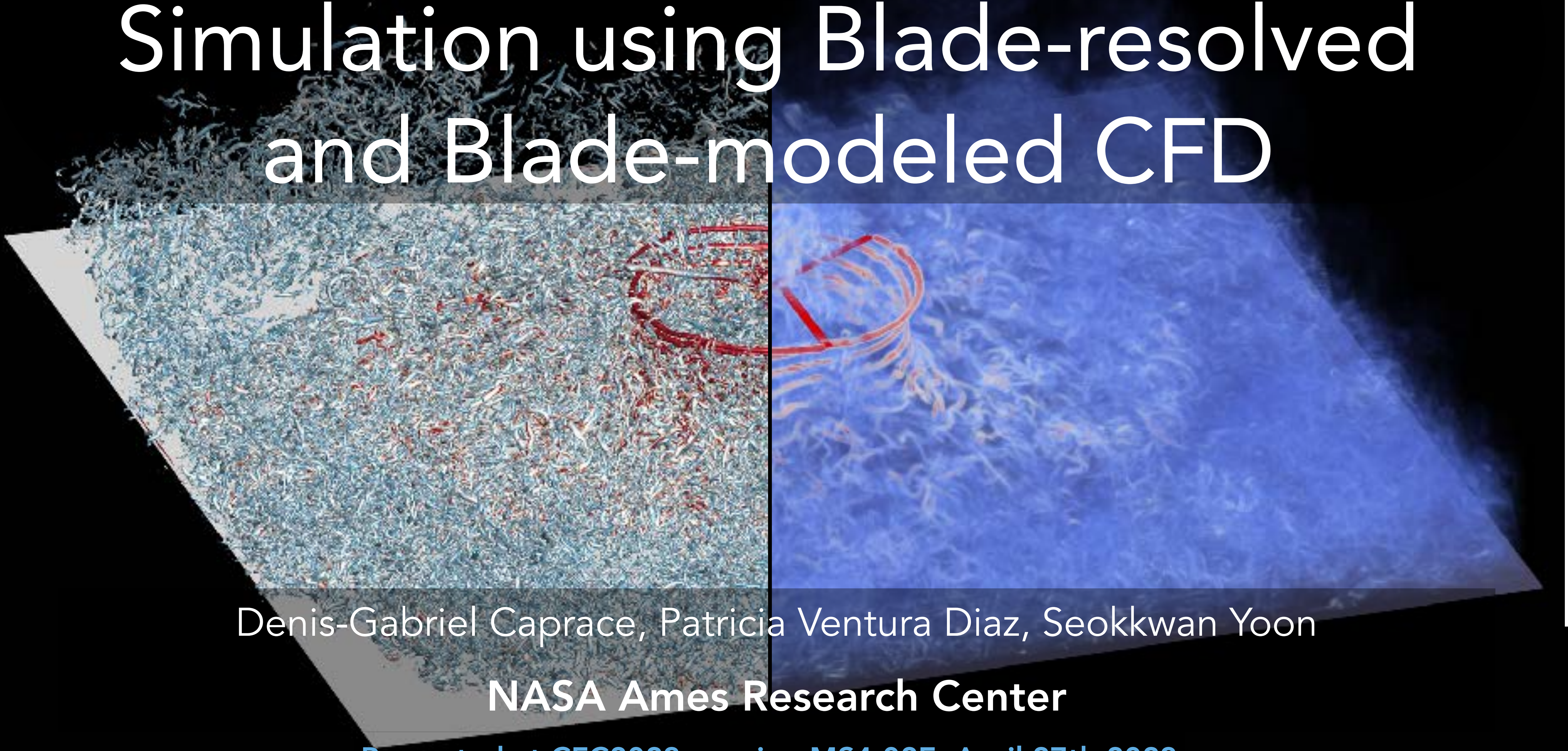
Validation of Rotorwash Simulation using Blade-resolved and Blade-modeled CFD



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Presented at CFC2023, session MS4-02E, April 27th 2023

Urban Air Mobility

- Urban Air Mobility (UAM) will enable on-demand **passenger-** or **cargo-carrying air services** in metropolitan environments.

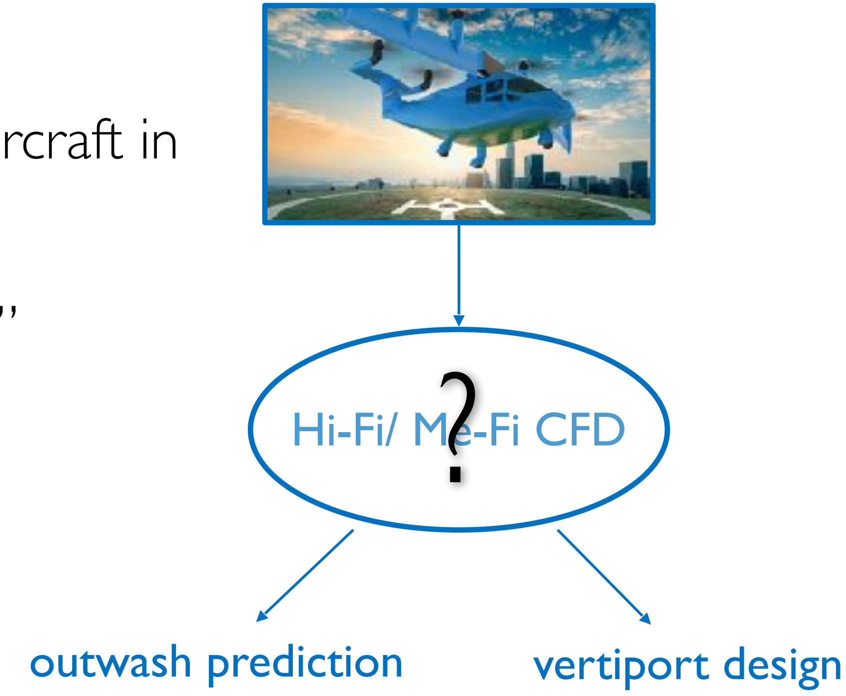
- Many different concepts **Vertical Take-Off and Landing** vehicles are under development.

- Aerodynamics are affected by the urban environment, **vertiport design** and **ground effect**.

Artist's impression of UAM

Objectives

- Adapt existing **best practice** for "high-fidelity" CFD of rotorcraft in ground effect (**IGE)**
- **Assess the accuracy and the potential** of "medium-fidelity" methods
- Application to **single rotor** and **quadrotor** [1]



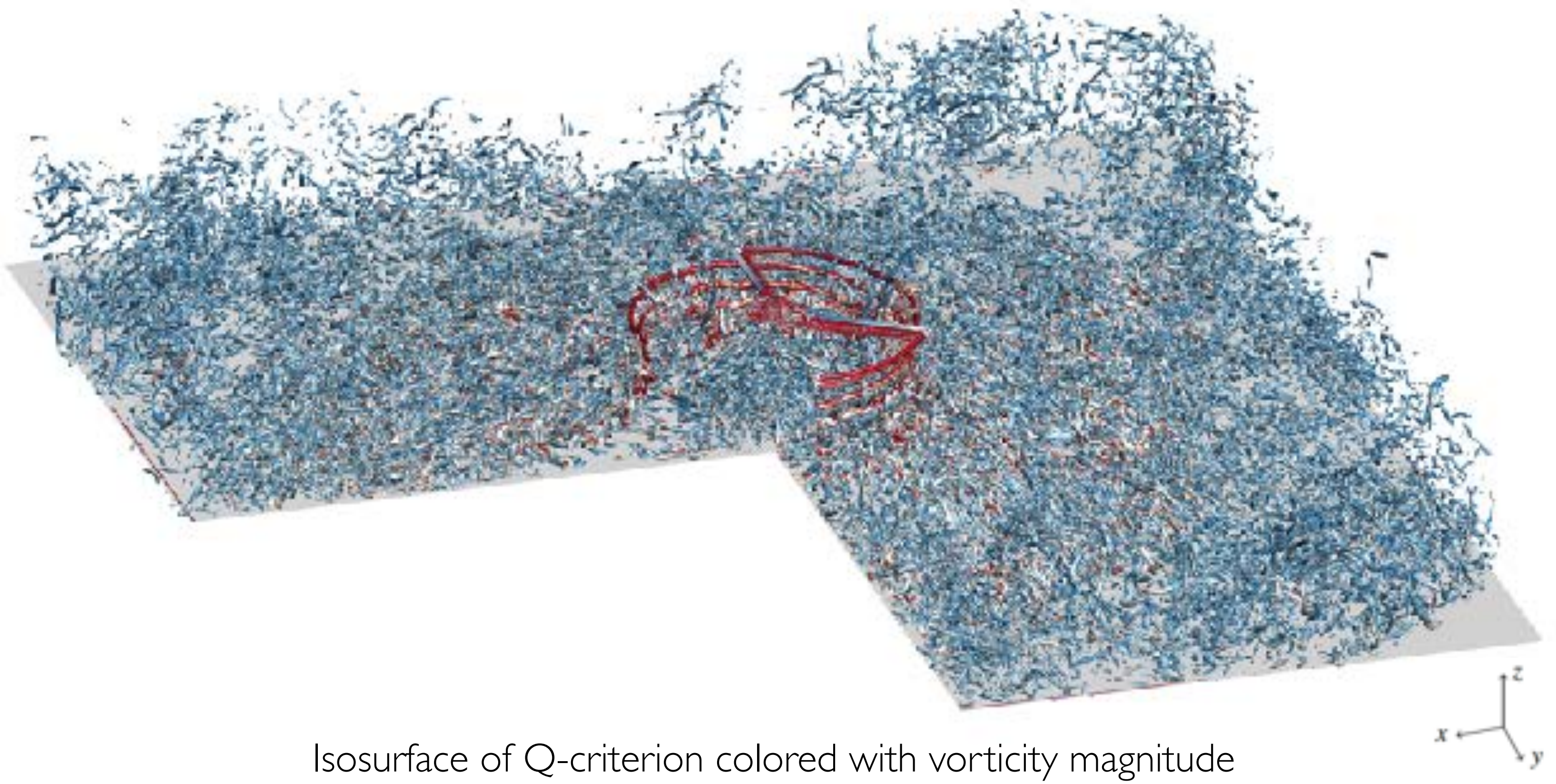
Can the tools be used to **predict outwash hazardousness** for different configurations of multi-rotor UAM vehicles and **support vertiport design?**

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

High-Fidelity CFD

NASA's OVERFLOW solver [2]

- Structured **overset** grids
- **High order** accurate scheme
  - 5th order central differences with scalar/matrix dissipation for convective terms
- **Dual time-stepping**
  - 2nd order accurate
  - 50 implicit sub-iterations
- **Hybrid RANS/LES**
  - Spalart-Allmaras one equation turbulence model near the walls
  - $y^+ \leq 1$

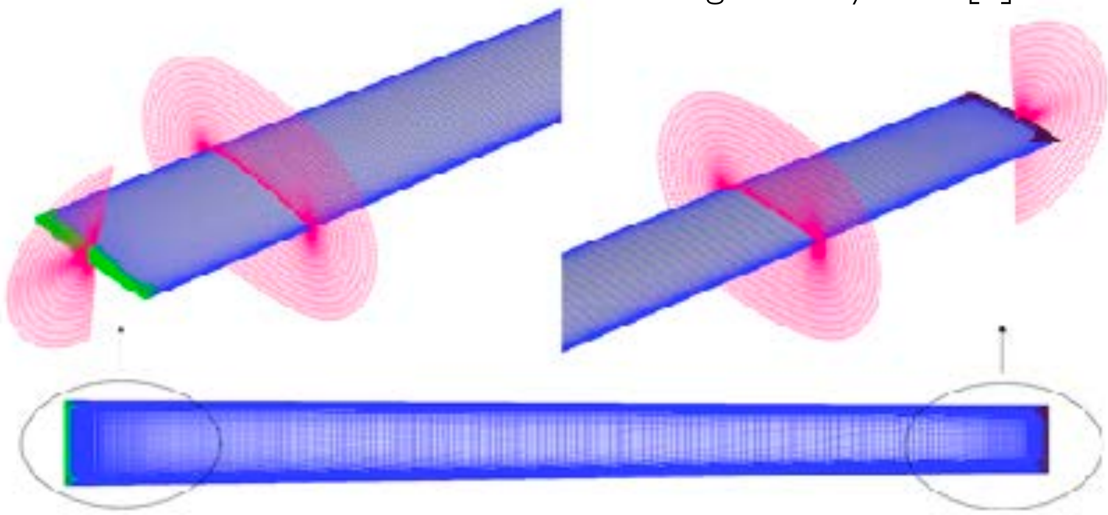


Isosurface of Q-criterion colored with vorticity magnitude

[2] T. H. Pulliam, "High Order Accurate Finite-Difference Methods: as seen in OVERFLOW", AIAA Paper 2011-3851

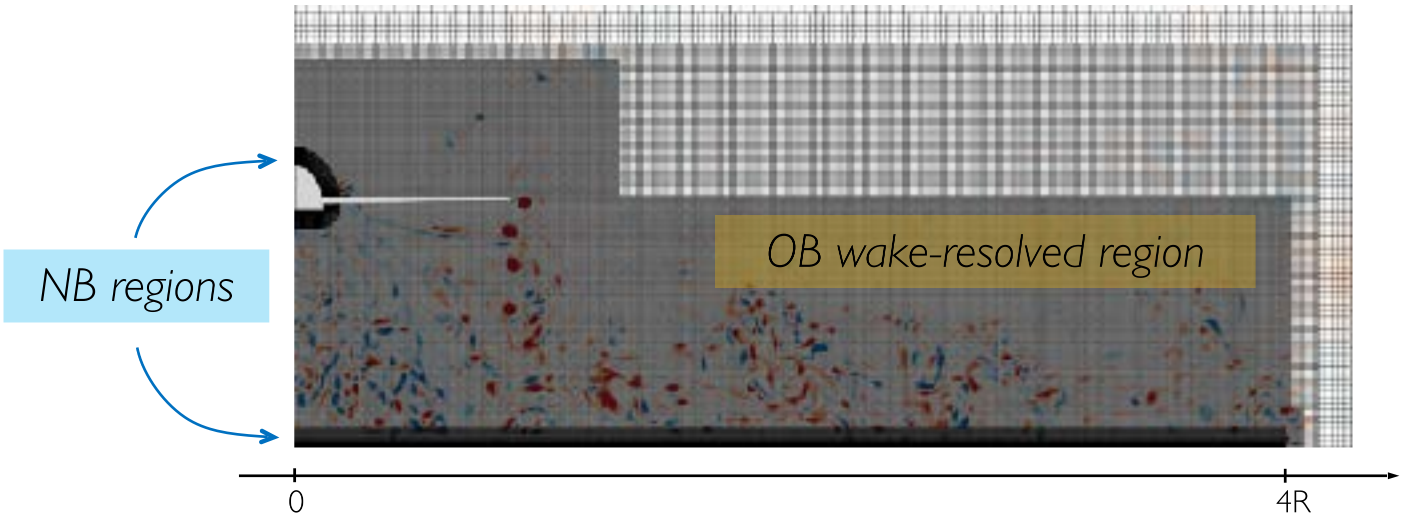
Overset Grid Generation

Same geometry as in [4]



NASA's Chimera Grid Tools (CGT) software [3]

- **Geometry processing**
  - Clean geometry definition
  - Obtained from CAD or 3D scan techniques
- **Surface grid generation**
  - Clustering in high-gradient regions
  - Mesh generation with hyperbolic marching or transfinite interpolation
- **Volume grid generation**
  - Hyperbolic near-body (NB)
  - Cartesian off-body (OB)
- **Domain connectivity**



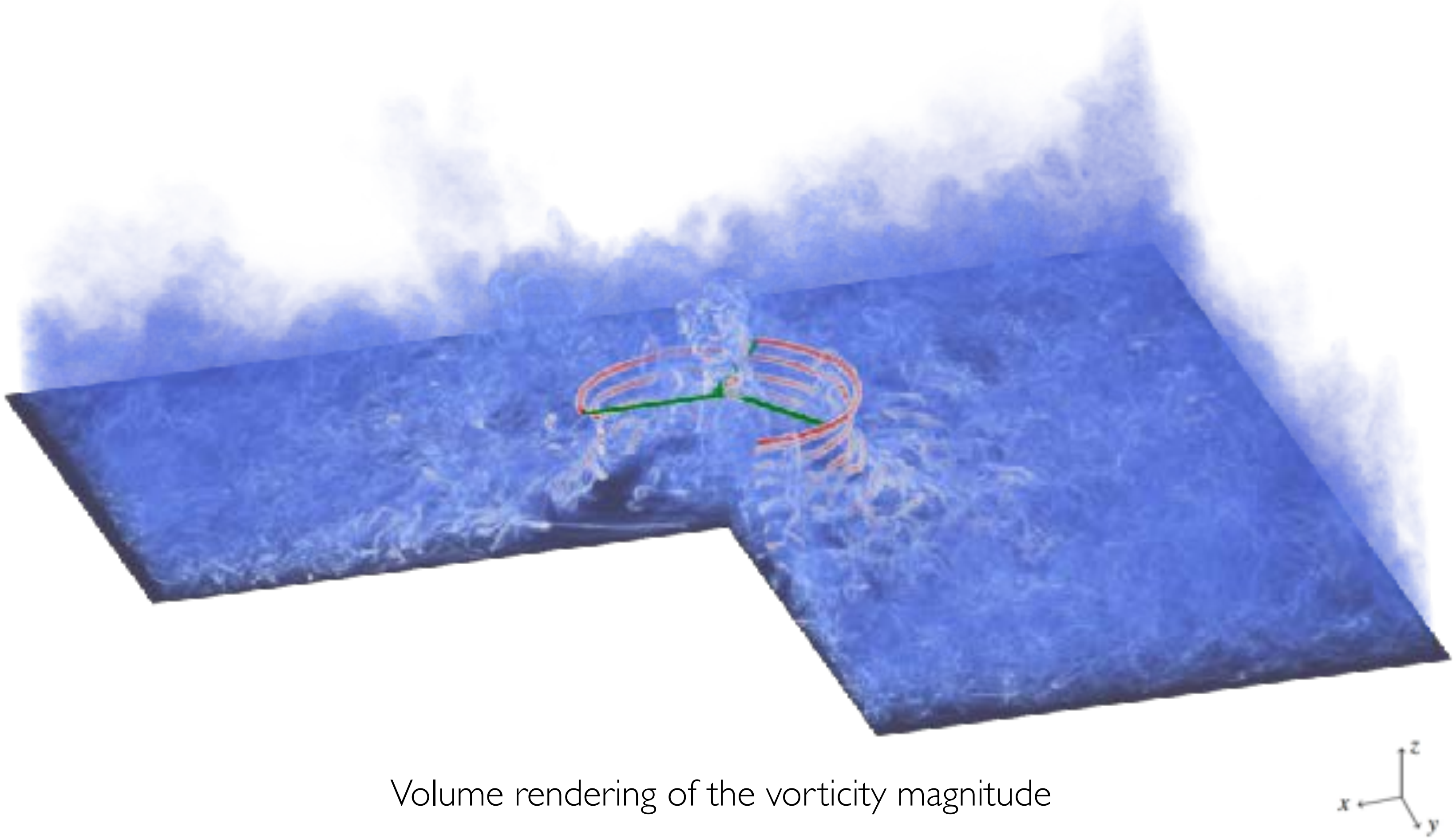
See also CFC23: MS4-02E (Ventura Diaz *et al.*)

[3] W. Chan, R. Gomez, S. Rogers, and P. Buning, "Best Practices in Overset Grid Generation", AIAA Paper 2002-3191.
[4] P. Ventura Diaz and S. Yoon, "High-fidelity simulations of a quadrotor vehicle for urban air mobility," AIAA Paper 2022-0152.

Medium-Fidelity CFD

Vortex Particle-Mesh method [4]

- Hybrid **Lagrangian-Eulerian**
  - Vorticity-velocity form. of N.-S.
  - Advection solved with **particles**
  - Background **Cartesian grid** to solve RHS with **4th order finite differences**
  - High-order particles-grid interpolation
  - RK3 time integration
- **Features**
  - Regularized Variational Multiscale Model **sub-grid scale model** [5]
  - **Remeshing** and **reprojection**
  - **Immersed lifting line** method [6]
  - Unbounded and **no-slip BC**



Volume rendering of the vorticity magnitude

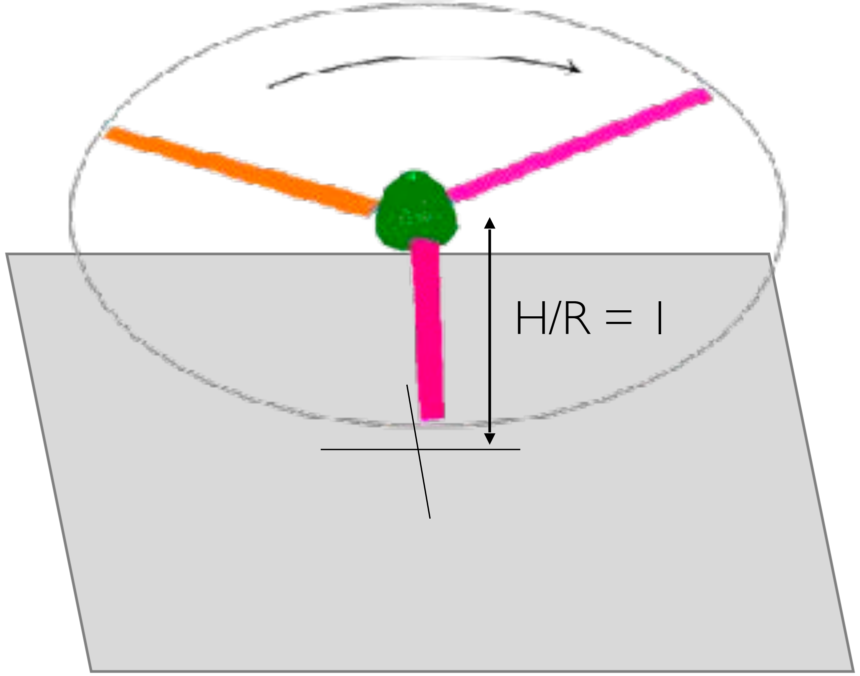
See also CFC23: MS2-03A (Colognesi *et al.*), MS5-01E (Billuart *et al.*)

[4] P. Chatelain, A. Curioni, M. Bergdorf, D. Rossinelli, W. Andreoni, and P. Koumoutsakos, "Billion vortex particle Direct Numerical Simulations of aircraft wakes," Comp Meth in Appl Mech and Eng, vol. 197, Feb 2008.
[5] H. Jeanmart and G. Winckelmans, "Investigation of eddy-viscosity models modified using discrete filters," Physics of Fluids, vol. 19, May 2007.
[6] D.-G. Caprace, A. Ning, P. Chatelain, and G. Winckelmans, "Effects of rotor-airframe interaction on the aeromechanics and wake of a quadcopter in forward flight," Aerospace Science and Technology, 2022.

Computational Setup – Single Rotor

OVERFLOW

- based on validated best-practice for rotorcraft simulation [7,8]
    - grid resolution 10% c_{tip} (439M points)
    - 4th order, matrix dissipation, 0.25° per time step
- ~ 2000 CPUs × 1 month = 1.89M CPUh



VPM method

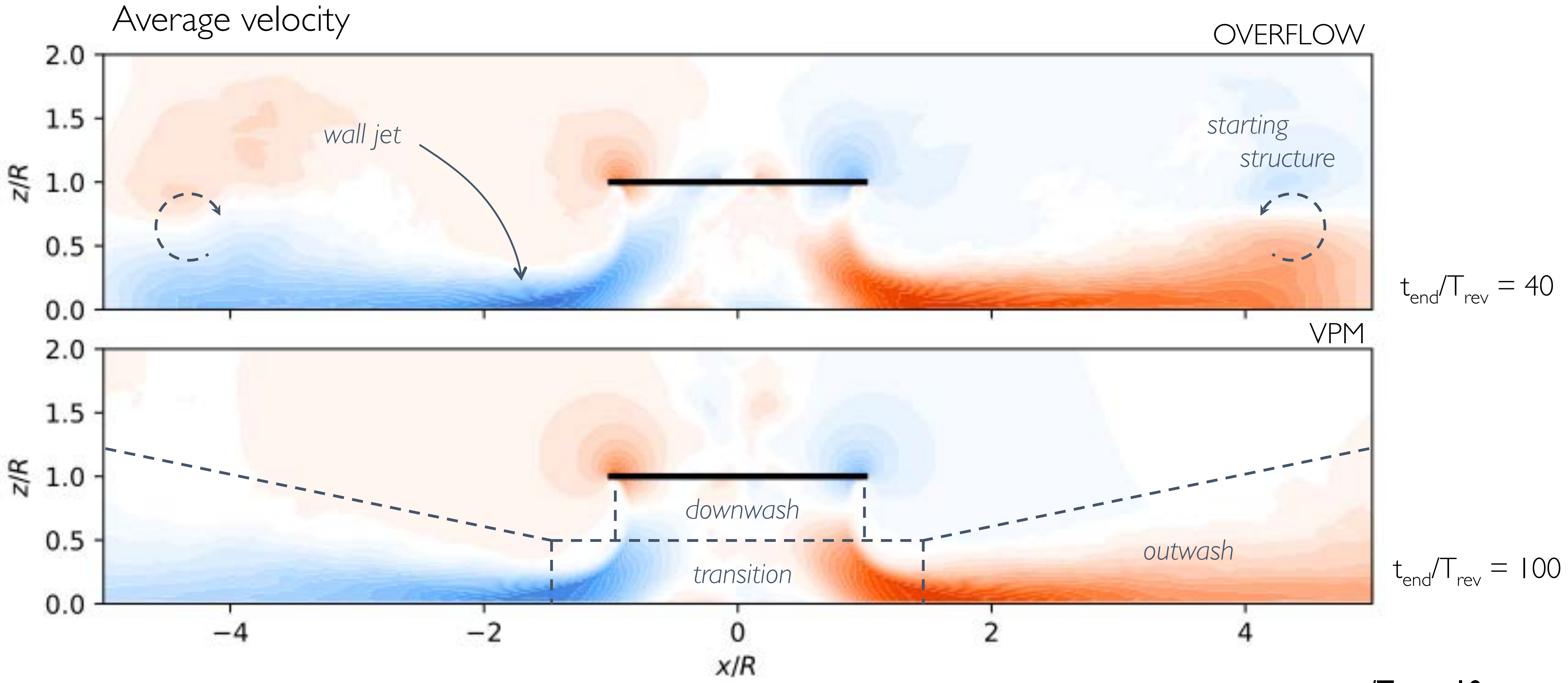
- 3 different mesh resolutions
    - 32 particles per R (19M particles)
    - 48 particles per R (65M particles)
    - 64 particles per R (153M particles)
- $CFL_{tip} = 4$
- ~ 288 CPUs × 24 h = 7k CPUh

Operating conditions

- hover
- Re = 1.7M
- $M_{tip} = 0.48$
- CT_{OGE} intermediate

[7] S. Yoon, N. M. Chaderjian, T. H. Pulliam, and T. L. Holst, "Effect of Turbulence Modeling on Hover- ing Rotor Flows," Paper AIAA 2015-2766, 2015.
[8] N. M. Chaderjian, and J. Ahmad, "Navier-Stokes Assessment of Test Facility Effects on Hover Performance," 71st Annual Forum of the AHS, May 2015.

Rotorwash – Single Rotor

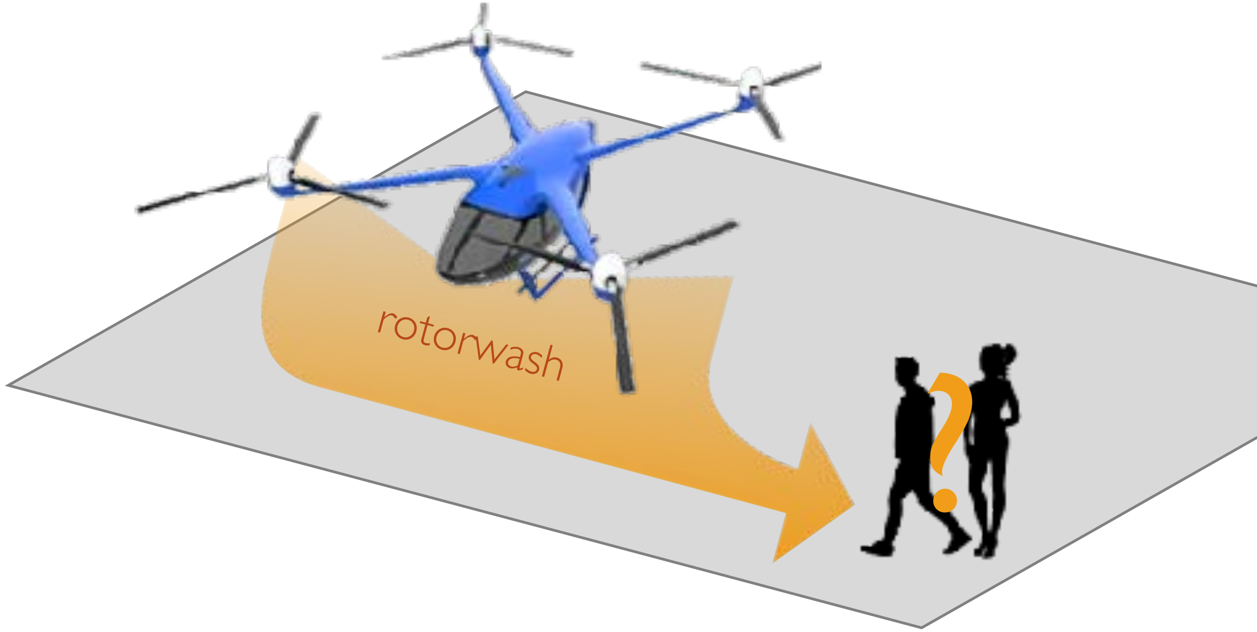


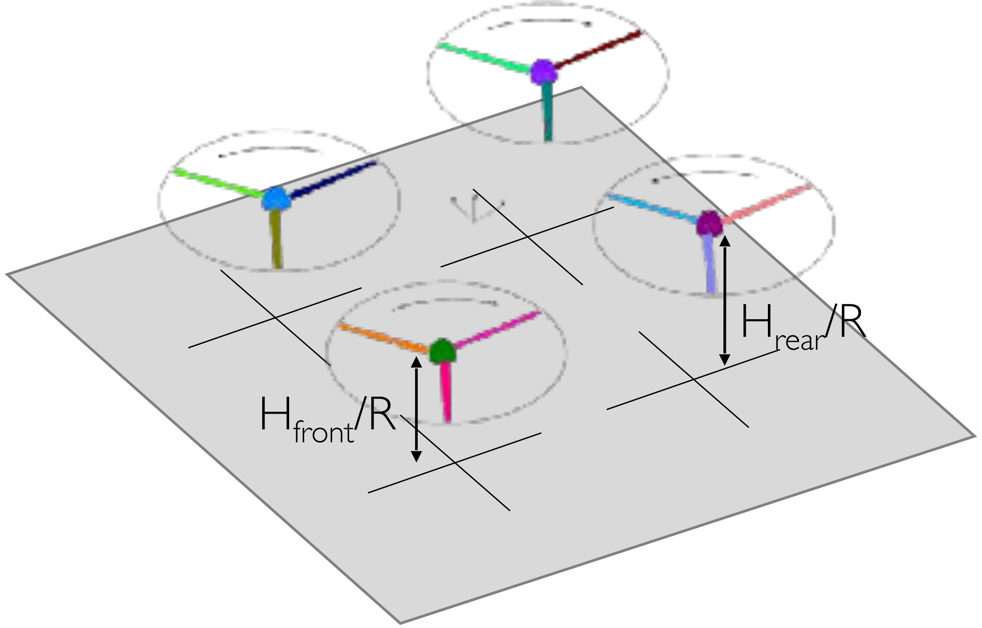
t_{avg}/T_{rev} = 10

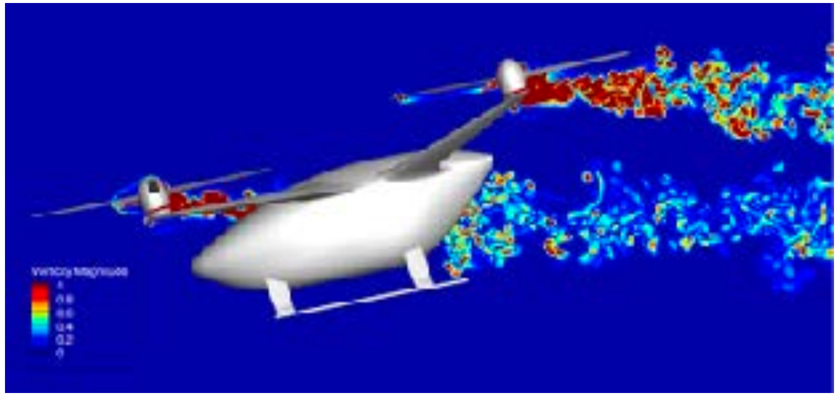
Practical Use Case – Quadcopter Air Taxi

Objectives

- Determine **dangerous areas** in the rotorwash…
  - overturning forces and moments
  - biophysical injury
- …for **different vehicle designs**







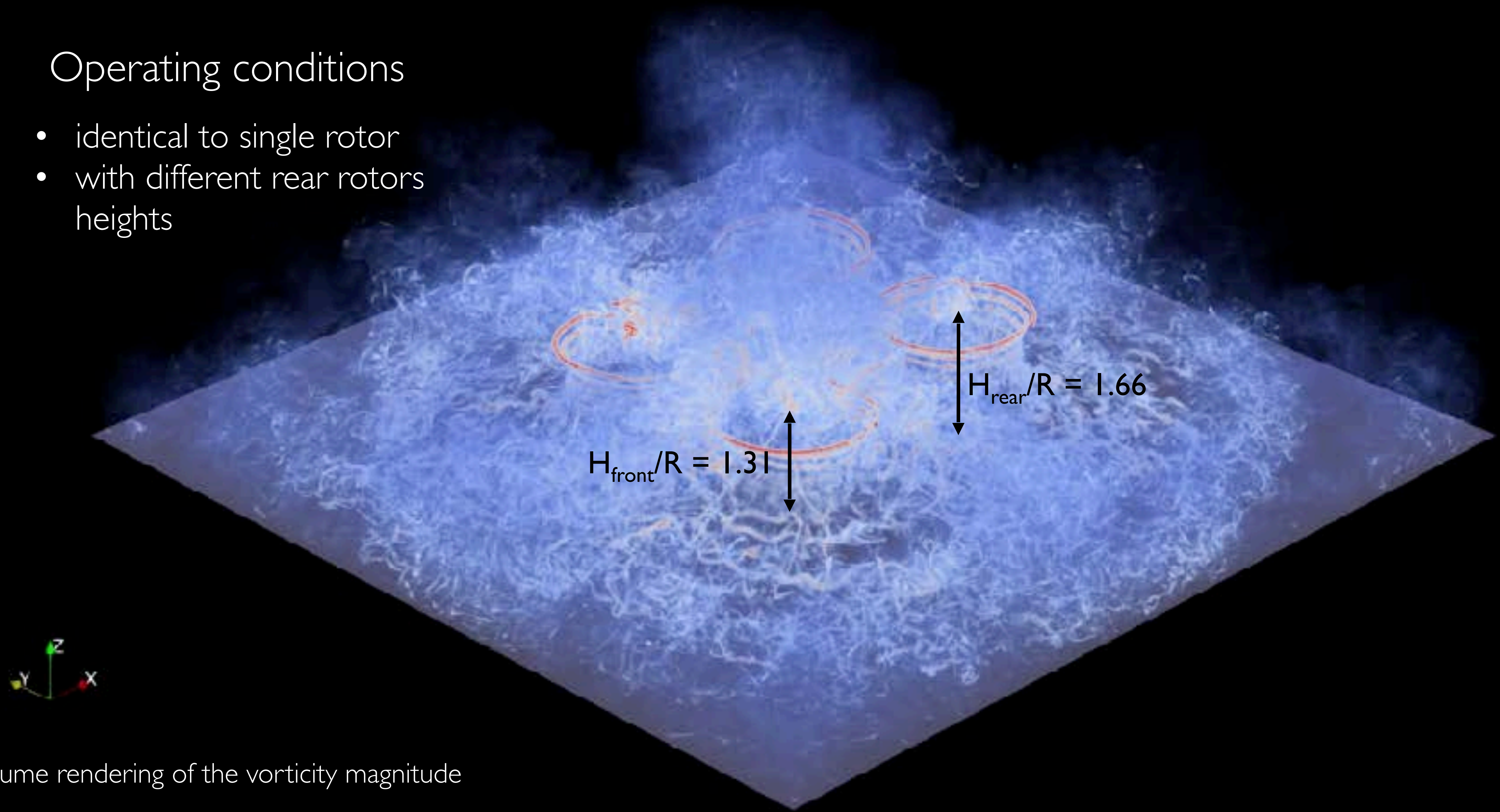
Forward flight simulation from [4]

[4] P. Ventura Diaz and S. Yoon, "High-fidelity simulations of a quadrotor vehicle for urban air mobility," AIAA Paper 2022-0152.

Flow Visualization – Quadcopter Air Taxi

Operating conditions

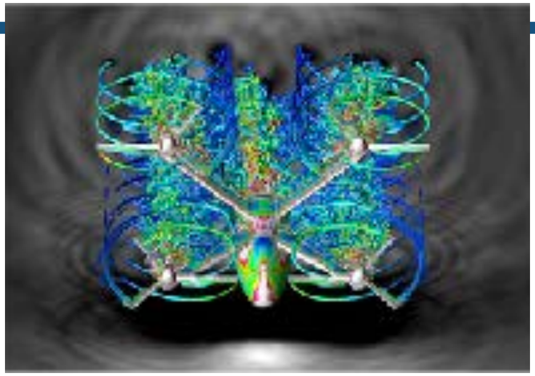
- identical to single rotor
- with different rear rotors heights

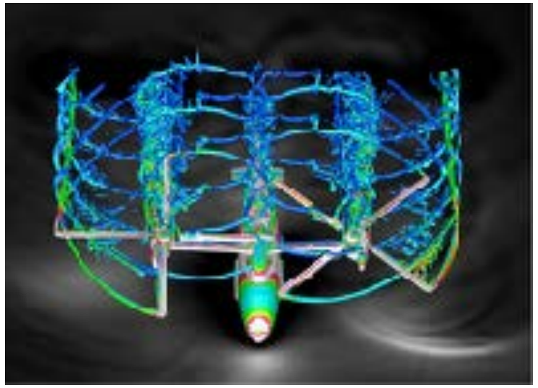


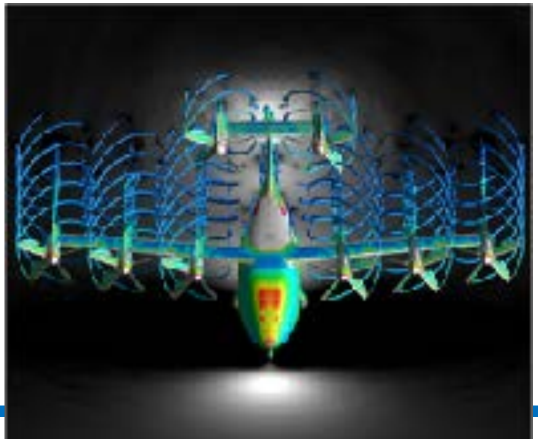
Volume rendering of the vorticity magnitude

Summary

- Although **blade-resolved simulation** is computationally intensive, it can be used to **verify lower fidelity tools**.
- **Blade-modeled** simulation enables parametric studies with a **reasonable accuracy.**
- High velocity regions are found between the rotors of a **quadcopter air taxi**.
- Further **experimental validation** is needed towards more complex geometries.







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