High-fidelity Analysis of Lift+Cruise VTOL Urban Air Mobility Concept Aircraft

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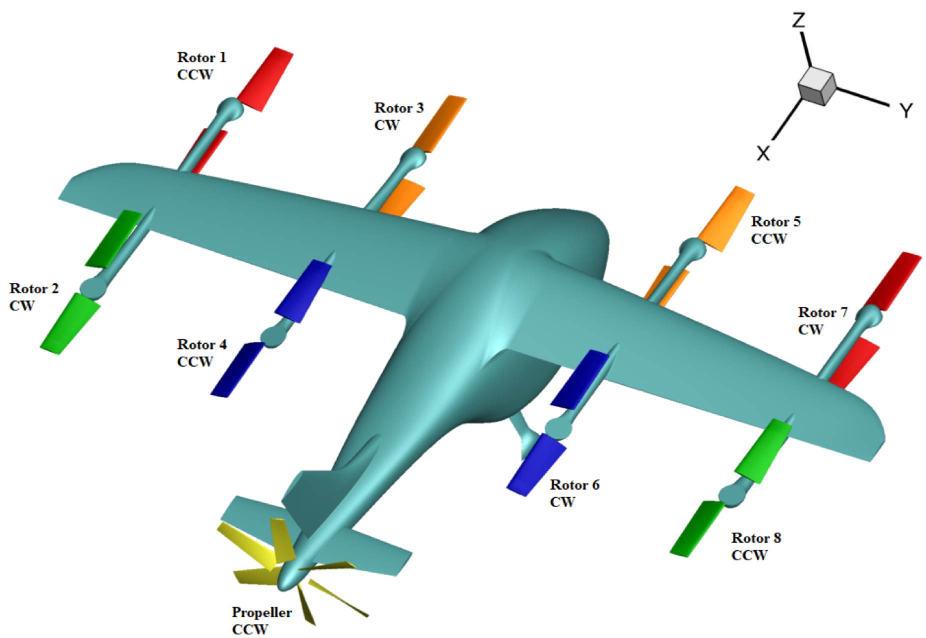
Motivation

- **NASA research in advanced air mobility (AAM) aircraft and operation**
  - Provides a mobile alternative for everyday ground transportation
- **Urban air mobility (UAM) is a subset of AAM**
  - Focuses on highly automated aircraft that operate and transport passengers or cargo at lower altitudes within urban and suburban area
- **The Lift+Cruise vertical takeoff and landing (VTOL) aircraft is one of several conceptual configurations recently presented in NASA UAM research[1]**



The Lift+Cruise aircraft is a stopping-rotor thrust- and lift-compound helicopter

- Cruise flight (airplane mode)
- Hover flight (helicopter mode)
- Low-speed forward flight (transition mode)
- 8 two-bladed lifting rotors
- 1 six-bladed pusher propeller

1.Silva, C., Johnson, W., Antcliff, K.R. and Patterson, M.D. "VTOL Urban Air Mobility Concept Vehicles for Technology Development." AIAA 2018-3847.

High-fidelity Multidisciplinary Analysis for NASA UAM Research

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- **Coupling CFD solver using Reynolds-averaged Navier-Stokes (RANS) method, with rotorcraft Comprehensive Analysis (CA) code**
- **Turbulence models used in the RANS simulation**
  - The Spalart-Allmaras (SA) turbulence models and its variants, listed in NASA turbulence modeling resource (TMR) website[2], are often used in rotorcraft RANS simulations
  - The SA-DES model combines SA with the Large Eddy Simulation (LES)
    - Recent OVERFLOW solutions[3,4] showed improved predictions of single rotor performance and resolved fine details of rotor wakes
    - Adequate grid support is needed and currently not practically applicable for lift+cruise.
  - The SA-RC model introduces a correction for rotation and curvature effects
    - Expensive to compute the Lagrangian derivative of the strain rate tensor
  - The SA-R model is a simpler way to add rotation correction to the SA model[5,6]
    - Recently, the clarification of implement SA-neg-R model has been reflected on the TMR website

2. https://turbmodels.larc.nasa.gov/spalart.html
3. Chaderjian, N. M., and Buning, P. G., "High Resolution Navier-Stokes Simulation of Rotor Wakes," AHS 67th Forum, 2011
4. Chaderjian, N. M., and Jasim U. A., "Detached Eddy Simulation of the UH-60 Rotor Wake Using Adaptive Mesh Refinement." AHS 68th Forum, 2012
5. Dacles-Mariani, J., Zilliac, G. G., Chow, J. S., and Bradshaw, P., "Numerical/Experimental Study of a Wingtip Vortex in the Near Field," AIAA Journal, Vol. 33(9), 1995, pp. 1561-1568.
6. Dacles-Mariani, J., Kwak, D., and Zilliac, G. G., "On Numerical Errors and Turbulence Modeling in Tip Vortex Flow Prediction," Int. J. for Numerical Methods in Fluids, Vol. 30(1), 1999, pp. 65-82

The Spalart-Allmara Turbulence Model with Rotation Correction (SA-neg-R)

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The SA turbulent transport equation for the turbulence variable $\hat{\nu}$

$$\frac{D\hat{\nu}}{Dt} = \boldsymbol{P(\hat{\nu})} - D(\hat{\nu}) + \mathcal{D}(\hat{\nu})$$

When $\hat{\nu} \geq 0$, positive branch of the SA-neg model, same as the SA model

- All notations are consistent with those defined in TMR website and explained in the paper

Production term: $P = c_{b1}(1 - f_{t2})\hat{S}\hat{\nu}$

where $\hat{S} = \Omega + \frac{\hat{\nu}}{\kappa^2 d^2} f_{v2}$, and $\Omega = \sqrt{\left(\partial_y w - \partial_z v\right)^2 + (\partial_z u - \partial_x w)^2 + \left(\partial_x v - \partial_y u\right)^2}$

In SA-R variant of the turbulence model with rotation correction

Production term: $P = c_{b1}(1 - f_{t2})\left(\hat{S} + c_{rot}\min(0, S - \Omega)\right)\hat{\nu}$

where $S = \sqrt{\left(\partial_y w + \partial_z v\right)^2 + (\partial_z u + \partial_x w)^2 + \left(\partial_x v + \partial_y u\right)^2 + 2(\partial_x u)^2 + 2\left(\partial_y v\right)^2 + 2(\partial_z w)^2}$

$c_{rot} > 1$, production term may become negative and suppress production of eddy viscosity

When $\hat{\nu} < 0$, negative branch of the SA-neg model

Production term: $P = c_{b1}(1 - c_{t3})\Omega\hat{\nu}$

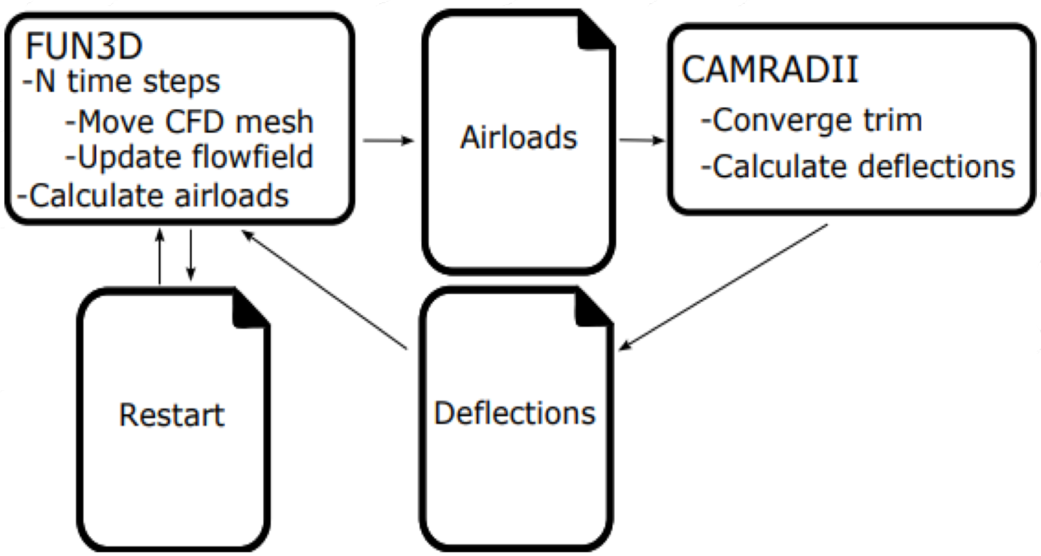
Negative production term is not allowed when $\hat{\nu} < 0$ with rotation correction, thus -R becomes

Production term: $P = c_{b1}(1 - c_{t3})\,|\Omega + c_{rot}\min(0, S - \Omega)|\hat{\nu}$

with $c_{rot} = 2$, the production term is only C0 continuous when $\Omega + c_{rot}\min(0, S - \Omega) < 0$

Multidisciplinary Analysis

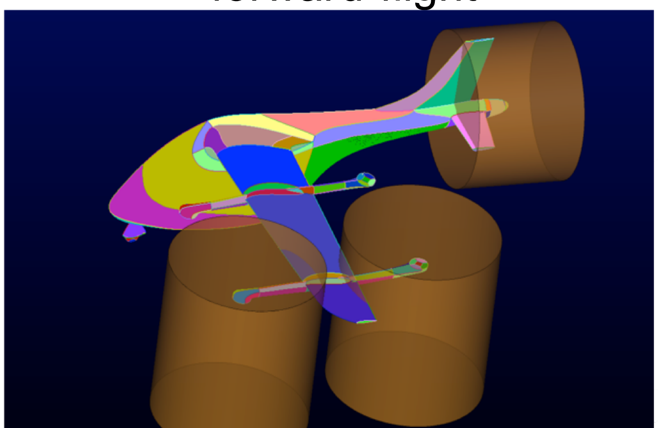
- **CFD solver**
  - FUN3D[7] is a node-centered unstructured-grid RANS solver developed by NASA Langley
  - Widely used for high-fidelity analysis and adjoint-based design of complex turbulent flows
  - Yoga, a new overset-grid assembler for large scale unstructured-grid systems, is developed and integrated into recently released FUN3D V14
- **Comprehensive analysis (CA) model**
  - The Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics II (CAMRADII)[8] code is used for structural dynamics analysis of the rotor blades and aircraft trim
- **Loose coupling process**
  - File-based loose-coupling workflow
  - Interactions at the end of each cycle
  - Alternate executions of CFD/CA with bash scripting

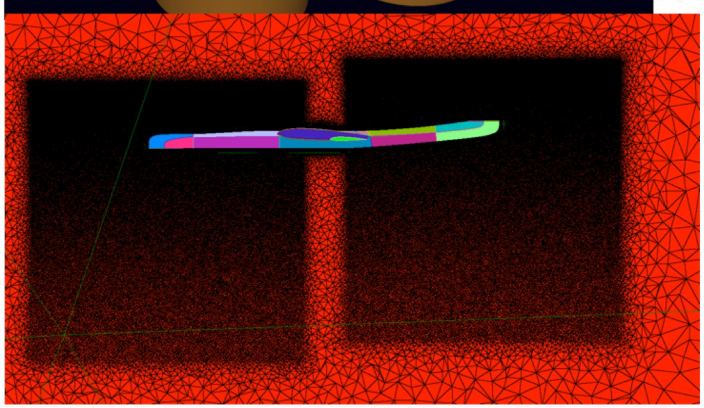


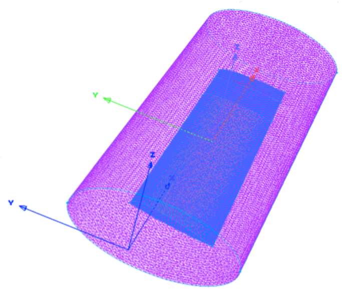
7. https://fun3d.larc.nasa.gov
8. Johnson, W., “Rotorcraft Aerodynamic Models for a Comprehensive Analysis,” AHS 54th Annual Forum, 1998

CFD Composite Grid System

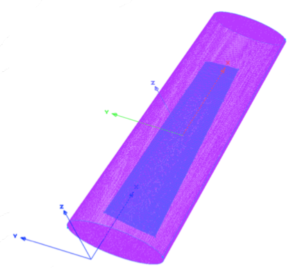
- **A composite, overset, unstructured-grid system is assembled with Yoga[9]**
  - Four types of component grids generated with Pointwise, 22 moving bodies
  - Two different background grids for hover and low-speed forward-flight simulations
  - “Best practices” fine grids for hover-flight has 208 million points and 227 million points for forward-flight



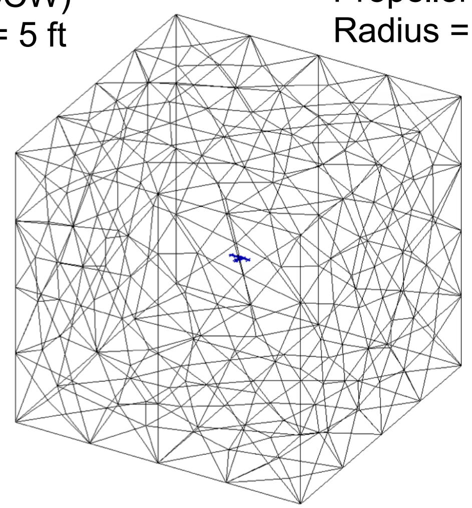


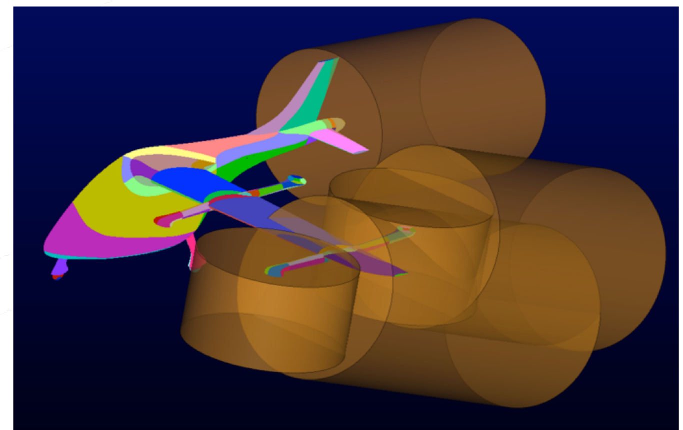


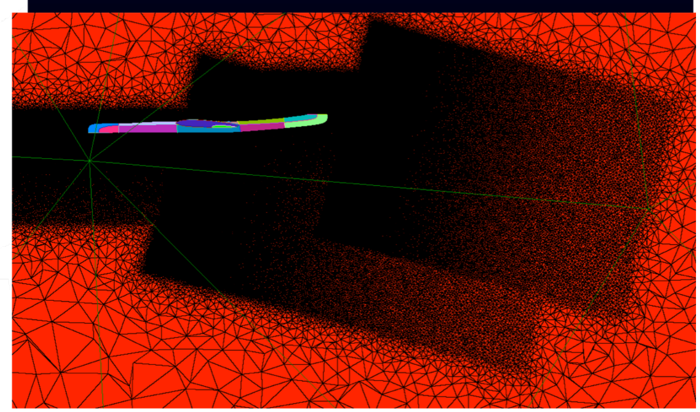
Rotor (CCW)
Radius = 5 ft



Propeller (CCW)
Radius = 4.5 ft







9. Druyor, C., “Enhancing Scalability for FUN3D Rotorcraft Simulations with Yoga: an Overset Grid Assembler,” AIAA 2021-2746.

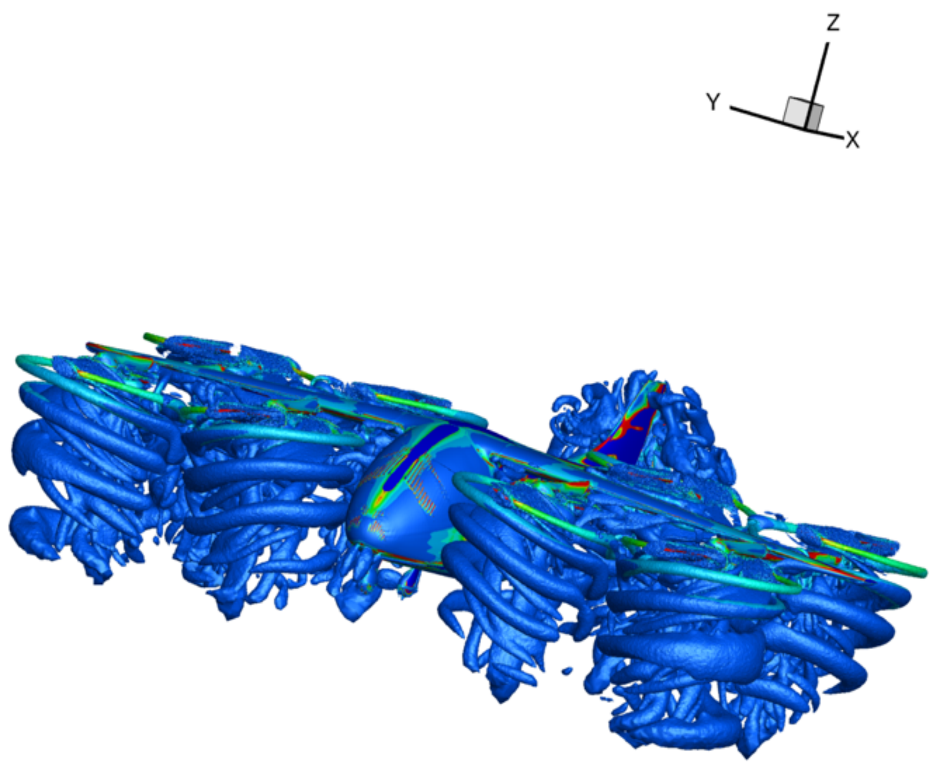
Hover-Flight Simulation Results

- **Hover-flight conditions**
  - Lifting rotors rotates at tip speed of 550 ft/sec, tip Mach = 0.4842 and tip Reynolds number = 2.74 million per foot (grid unit)
  - CAMRADII uses collective pitch control with trim targets of net z-force, x-force and y-moment to be zero (aircraft weight 5903 lb)
  - FUN3D uses a time-step at 0.5 degree of azimuth advancement (720 time steps per revolution), exchanging data with CAMRADII at every half revolution, except the 1st cycle which takes one revolution in CFD

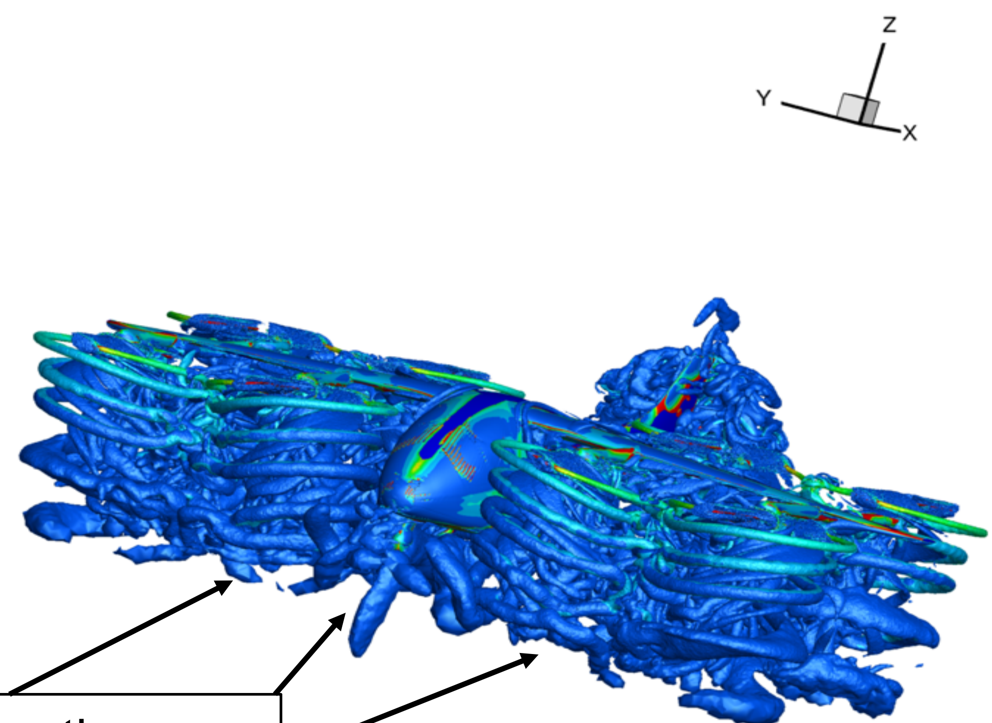
FUN3D	Thrust (lb)		Torque (lb-ft)	
Rotor	SA-neg	SA-neg-R	SA-neg	SA-neg-R
LFO	737.87	728.30 (1.30%)	525.10	512.78 (2.35%)
LBO	780.33	768.85 (1.47%)	561.57	546.57 (2.67%)
LFI	745.78	738.07 (1.03%)	548.14	528.30 (3.62%)
LBI	730.67	736.47 (-0.79%)	554.66	535.23 (3.50%)
RFI	742.87	746.69 (-0.51%)	546.60	529.92 (3.05%)
RBI	735.27	738.13 (-0.39%)	554.06	535.12 (3.42%)
RFO	737.71	731.70 (0.81%)	525.10	514.17 (2.08%)
RBO	778.71	768.59 (1.30%)	560.93	546.55 (2.56%)

L – Left, R – Right, F – Front, B – Back, O – Outboard, I – Inboard

Hover Flight



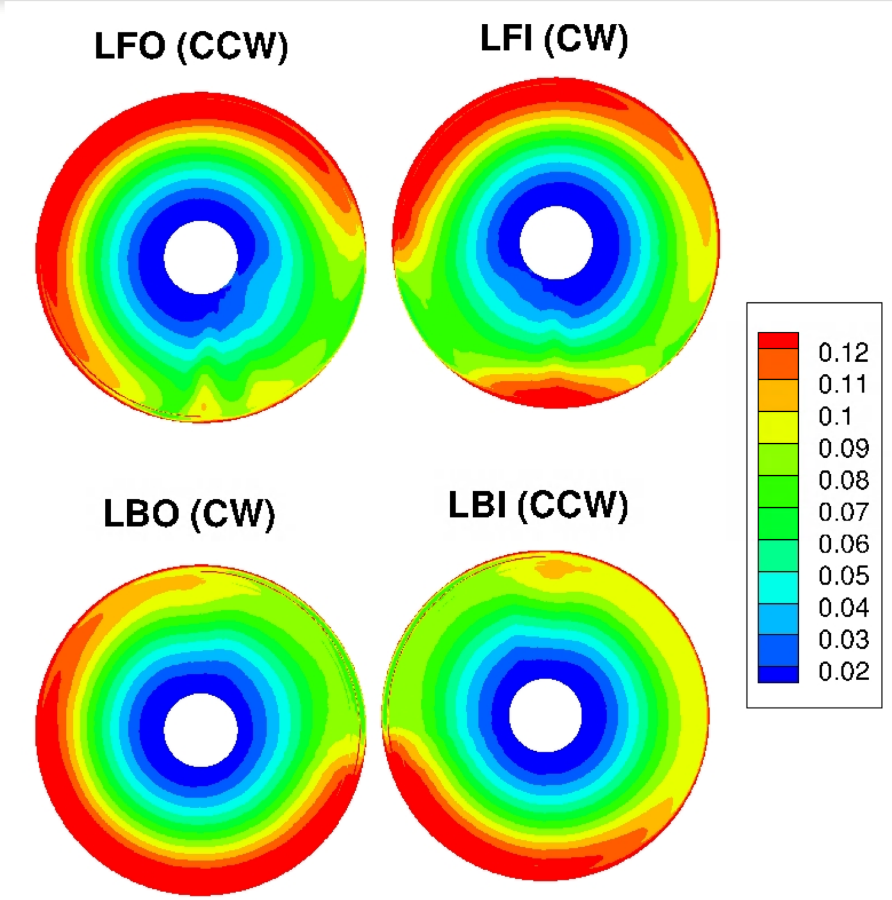
SA-neg Model



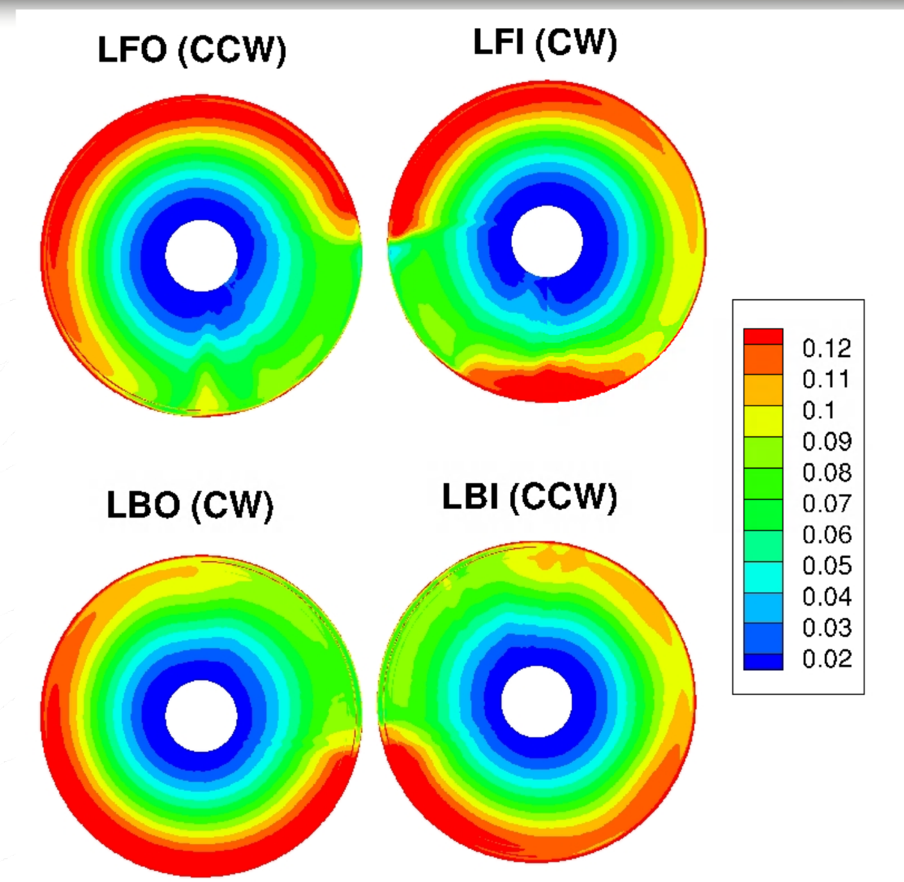
SA-neg-R Model

Q-criterion isosurfaces colored by vorticity magnitude in hover flight simulations (Frontview).

Hover Flight



SA-neg Model



SA-neg-R Model

Sectional normal force (M^2C_N) of the lifting rotors in hover flight (Rotors on the left side are compared)

L – Left, F – Front, B – Back, O – Outboard, I – Inboard

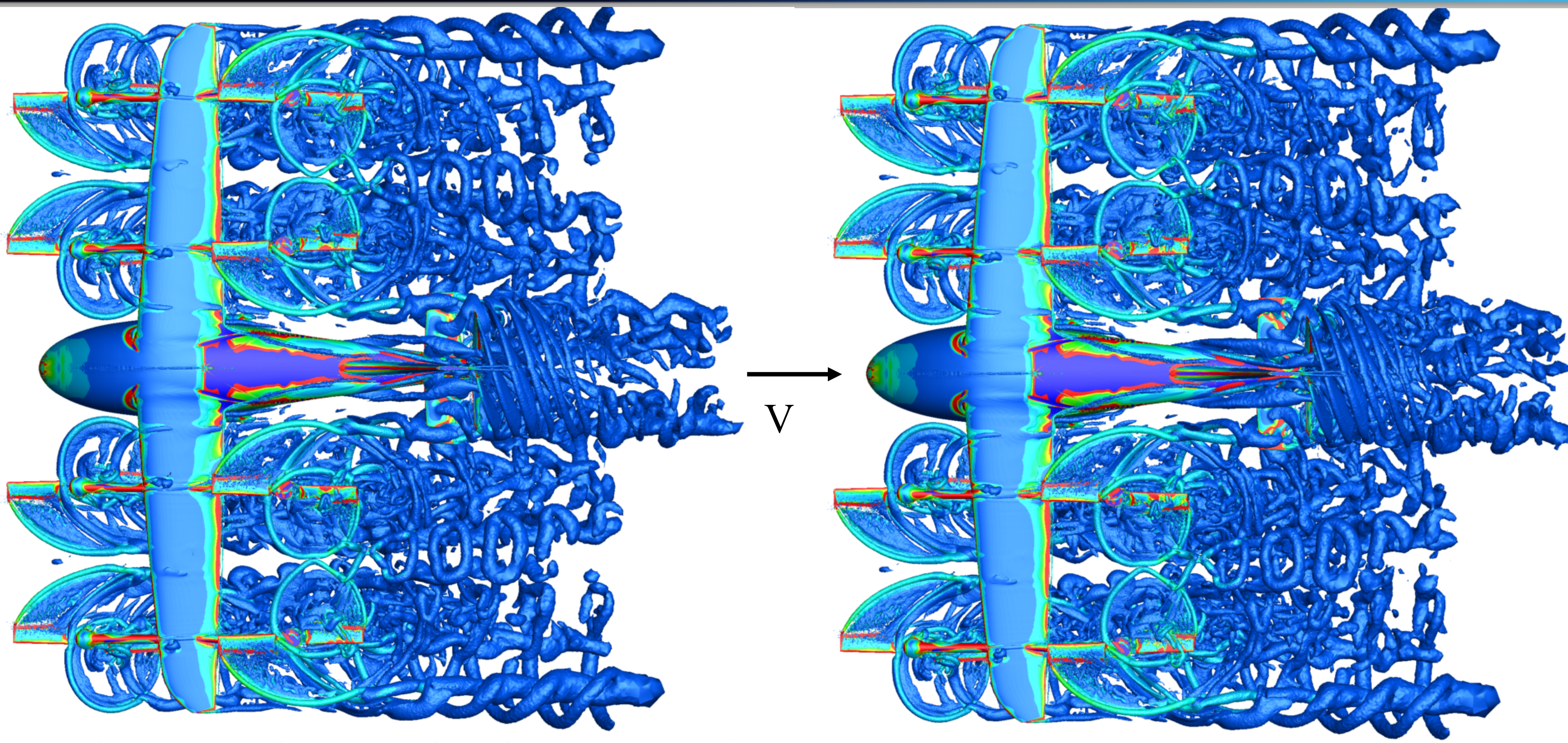
Low-Speed Forward-flight Simulation Results

- **Low-speed forward-flight conditions**
  - Lifting rotors rotating at tip speed of 550 ft/sec, tip Mach = 0.4842
  - Pusher propeller rotating at tip speed of 450 ft/sec, tip Mach = 0.4358
  - Forward flight speed is 80 knots with an advance ratio of 0.2455 respect to lifting rotors
  - CAMRADII trim targets and FUN3D time step same as hover flight
  - CAMRADII uses a simple estimation of the fuselage-wing body lift, drag and moments based on forward flight speed in the trim procedure

FUN3D	Thrust (lb)		Torque (lb-ft)	
Rotor	SA-neg	SA-neg-R	SA-neg	SA-neg-R
LFO	595.35	595.30 (0.01%)	122.33	121.38 (0.78%)
LBO	777.30	774.81 (0.32%)	286.08	282.21 (1.35%)
LFI	623.75	624.19 (-0.07%)	115.67	115.30 (0.32%)
LBI	743.25	742.37 (0.12%)	299.46	296.32 (1.05%)
RFI	623.27	624.63 (-0.22%)	115.58	115.37 (0.18%)
RBI	745.25	742.32 (0.39%)	299.29	296.35 (0.98%)
RFO	593.94	595.59 (-0.28%)	121.85	121.46 (0.32%)
RBO	777.42	775.86 (0.20%)	286.09	282.39 (1.29%)
Propeller	432.40	430.37 (0.47%)	693.68	680.62 (1.88%)

L – Left, R – Right, F – Front, B – Back, O – Outboard, I – Inboard

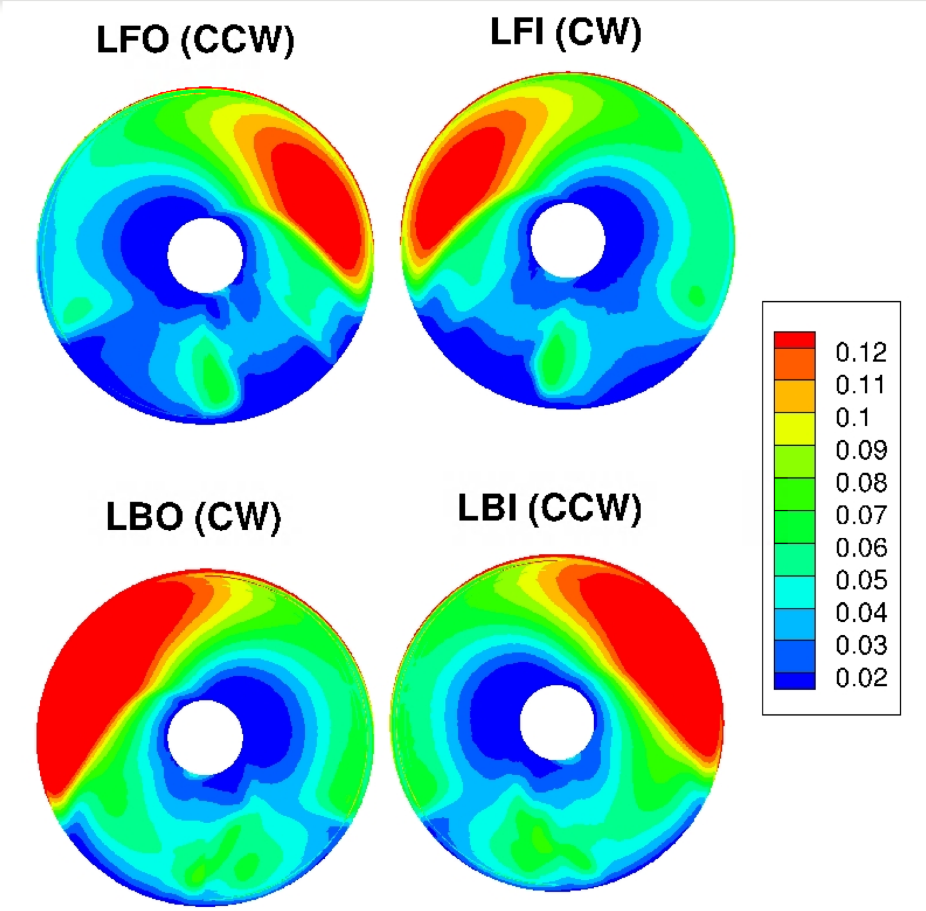
Low-Speed Forward Flight



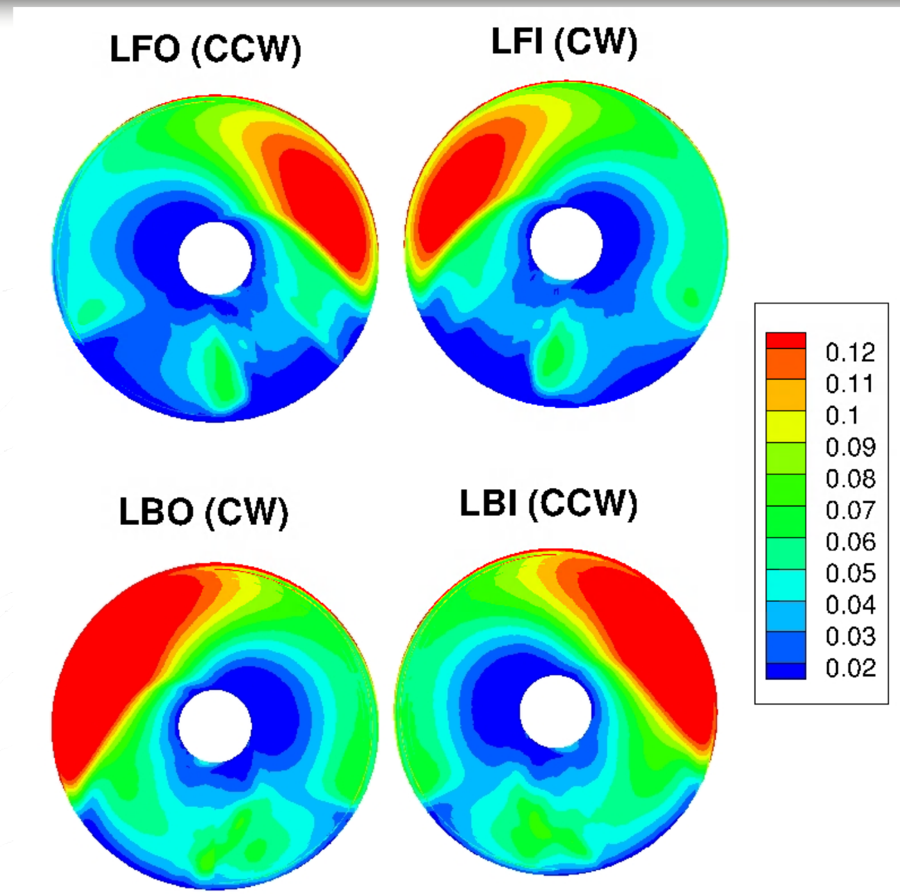
SA-neg Model   SA-neg-R Model

Q-criterion isosurfaces colored by vorticity magnitude in low-speed forward flight simulations (Topview)

Low-speed Forward Flight



SA-neg Model



SA-neg-R Model

Sectional normal force (M^2C_N) for the lifting rotors in low-speed forward flight (Rotors on the left side are compared)

L – Left, F – Front, B – Back, O – Outboard, I – Inboard

Concluding Remarks and Future Work

- **Concluding remarks**
  - High-fidelity multidisciplinary simulations using loose-coupling method with FUN3D-Yoga and CAMRADII have been performed for NASA lift+cruise VTOL UAM concept aircraft in hover and low-speed forward-flight conditions. This work extends previously demonstrated capabilities to complex configurations that include a full rigid fuselage and multiple flexible rotors of different radii and different rotation directions and speed
  - The simulation results demonstrate that adding rotation correction to the SA-neg turbulence model significantly improves the RANS rotorcraft simulation capability of resolving the rotor wake secondary vortices and wake interactions
  - A simple and efficient way to add rotation correction is to use the SA-neg-R turbulence model recently updated in NASA turbulence modeling resources (TMR) website for unsteady rotorcraft simulations
- **Future work**
  - Rotational-speed control with CAMRADII
  - Replace CAMRADII estimations of the fuselage-wing body lift, drag and moments with high-fidelity CFD data
  - Grid convergence study for more accurate performance predictions

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