HIGH-FIDELITY COMPUTATIONAL ANALYSIS OF NASA'S AIR TAXI CONCEPTS

P. VENTURA DIAZ[1]

[1]NASA Ames Research Center, Moffett Field, California, 94035, USA

ABSTRACT

High-fidelity Computational Fluid Dynamics (CFD) simulations have been carried out for NASA's air taxi concepts. The high-fidelity approach uses high-order accurate schemes and dual-time stepping, which simulates the rotor with its individual rotating blade grids. The delayed detached-eddy simulation model has been employed. A loose-coupling approach between the flow solver and a rotorcraft comprehensive code is utilized to include vehicle trim and motion variables. NASA's air taxi conceptual designs are intended to focus and guide NASA's research activities in support of aircraft development for vertical take-off and landing air taxi operations.

INTRODUCTION

With the rise of Urban Air Mobility (UAM), high-fidelity methods are required for accurate modeling of UAM vehicles under development. NASA's Revolutionary Vertical Lift Technology (RVLT) project has designed several UAM concepts with the aim of demonstrating relevant technologies [1]. The concept vehicles include a quiet single-main rotor (QSMR) helicopter, a side-by-side aircraft, a quadrotor, and a tiltwing aircraft. Predicting rotorcraft performance and acoustics is particularly challenging due to the unsteady, nonlinear, and complex nature of the flow, especially in multi-rotor configurations where aerodynamic interactions between rotors and vehicle components significantly complicate the analysis. While low-fidelity tools offer the advantage of a short turnaround and low computational cost, only high-fidelity methods can capture the complex flow details and the aerodynamic interactions. A large computational effort using high-fidelity Computational Fluid Dynamics (CFD) to advance the understanding and development of UAM vehicles has been carried out over the past few years by our research group [2-6].

NUMERICAL APPROACH

The flow solver used in this study is NASA's OVERFLOW CFD solver [7]. OVERFLOW is a finite-difference, structured overset grid, high-order accurate Navier-Stokes flow solver. NASA's Chimera Grid Tools (CGT) overset grid generation software [8] is used for generating the overset grids of rotors and complete vehicles. Figure 1 shows the overset surface grids for NASA's conceptual designs. OVERFLOW is loosely coupled with the helicopter comprehensive code CAMRAD II [9]. The CFD provides high-fidelity, nonlinear aerodynamics that corrects the comprehensive lifting line aerodynamic analysis from CAMRAD II. The comprehensive code performs the structural dynamics and trim calculations and gives the information to OVERFLOW. The loose coupling allows for a modular approach and communication through input/output.

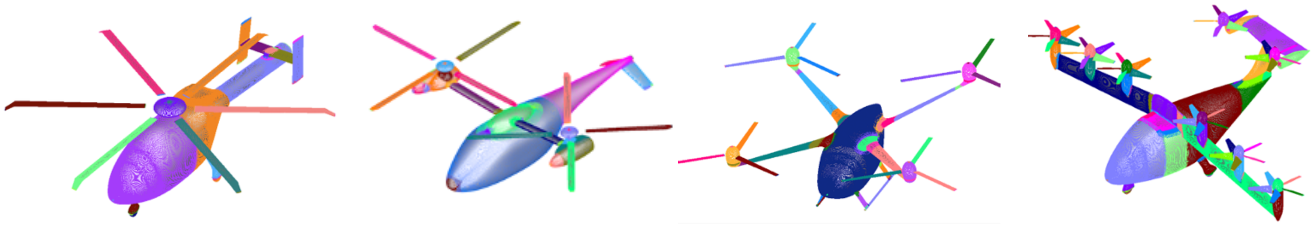

(a) QSMR (b) Side-by-side (c) Quadcopter (d) Tiltwing

Fig. 1 Overset surface grids of NASA's conceptual designs.

High-Order Navier-Stokes Solver

The Navier-Stokes equations can be solved using finite differences with a variety of numerical algorithms and turbulence models. The time-dependent Reynolds-Averaged Navier-Stokes (RANS) equations are solved in strong conservation form:

$$\frac{\partial \boldsymbol{q}}{\partial t}+\frac{\partial(\boldsymbol{F}-\boldsymbol{F}_v)}{\partial x}+\frac{\partial(\boldsymbol{G}-\boldsymbol{G}_v)}{\partial y}+\frac{\partial(\boldsymbol{H}-\boldsymbol{H}_v)}{\partial z}=0 \tag{1}$$

being $\boldsymbol{q} = [\rho, \rho u, \rho v, \rho w, e]^{\mathrm{T}}$ the vector of conserved variables; $\boldsymbol{F}$, $\boldsymbol{G}$ and $\boldsymbol{H}$ the inviscid flux vectors; and $\boldsymbol{F}_v$, $\boldsymbol{G}_v$, and $\boldsymbol{H}_v$ the viscous flux vectors. The simulation is advanced in time using the 2nd-order accurate backward Euler method, where dual time-stepping is used to march in dual-time $\Delta\tau$ to steady-state. The physical time step Δt corresponds to 0.25° of rotor rotation, together with up to 50 dual-time sub-iterations to achieve 2.5 to 3 orders of magnitude drop in sub-iteration residual. The inviscid flux vectors at the cell interfaces use 6th-order central differences and 5th-order artificial dissipation to damp out high-frequency errors, resulting in a 5th-order accurate discretization. The viscous terms are differenced to 2nd-order. The diagonalized form of the diagonally-dominant alternating direction implicit (DDADI) factored scheme is used to solve Eq. (1). The one-equation Spalart-Allmaras (SA) turbulence model together with the delayed detached eddy simulation (DDES) approach are used in this work. Simulations for each concept vehicle were carried out with NASA's supercomputers using 1000 to 2500 processors.

UAM CONCEPT VEHICLES

The rotor properties and geometry for NASA's UAM concept vehicles are summarized in Table 1.

Table 1 Rotor geometry of NASA's UAM vehicles

Aircraft	**QSMR**	**Side-by-side**	**Quadrotor**	**Tiltwing**
Number of rotors	1	2	4	8
Number of blades/rotor	6	4	3	5
Radius R	5.378m	3.203m	2.809m	1.117m
Linear twist θ_{tw}	-12.0	-16.0	-12.0	–
Root chord c_{root}	0.290m	0.217m	0.234m	0.382m
Tip chord c_{tip}	0.174m	0.130m	0.176m	0.139m
Thrust-weighted solidity σ	0.099	0.0832	0.0647	0.2825
Hover tip speed	137.2m/s	167.6m/s	167.6m/s	167.6m/s

The QSMR is a helicopter concept designed for the UAM mission. It has a shorter range and has been specifically designed for low noise operations. It includes a NOTAR (NO TAil Rotor) anti-torque system to remove noise from the tail-rotor. To reduce the main rotor noise, the rotor has low disk loading and low tip speed. The tip of the blade is also drooped to reduce noise from blade-vortex interactions (BVI). Three different rotor geometries were studied: (a) baseline geometry with three blades, (b) low-noise geometry with six blades, and (c) low-noise geometry with six-blades and 30° tip droop.

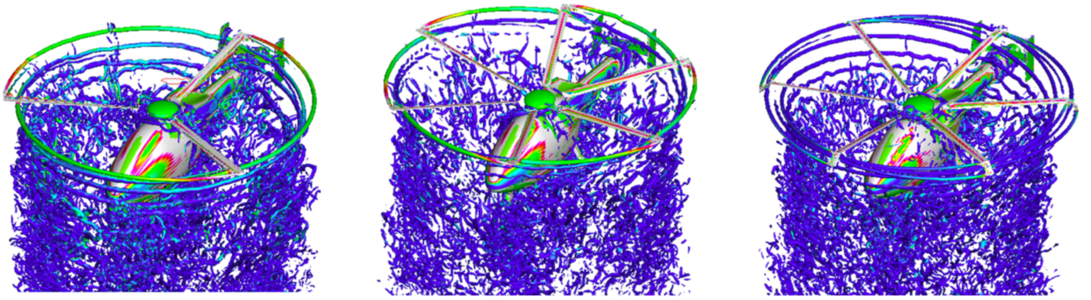

(a) Baseline geometry. (b) Low-noise geometry no blade droop. (c) Low-noise geometry 30° blade droop.

Fig. 2 Vortex wake visualization for the QSMR with three different rotor geometries.

The wake geometry in hover is shown for the three geometries in Figure 2 by plotting Q-criterion iso-surfaces colored with the vorticity magnitude. Vortex wake breakdown happens after 2 to 4 revolutions. There is a similar vorticity magnitude on the vortices between the baseline and low-noise no-droop configurations (Figures 2a and 2b). The tip droop changes the position of the primary tip vortex and decreases its strength, as seen by the lower vorticity magnitude (Figure 2c). In addition, a secondary weak vortex is formed where the droop starts, due to the change in aerodynamic distribution at that section of the blade.

The side-by-side aircraft has two inter-meshing rotors and has been designed as a high-performance helicopter. The effect of rotor overlap on cruise efficiency was analyzed for four different overlap distances, with an overlap of 15% the radius (Figure 3b) giving the highest rotor lift-to-drag ratio. Overlapped, side-by-side rotor performance in cruise is better than separate non-overlapped twin rotors: the combined wake system approximates that of a single wing with a large span, which reduces the induced power.

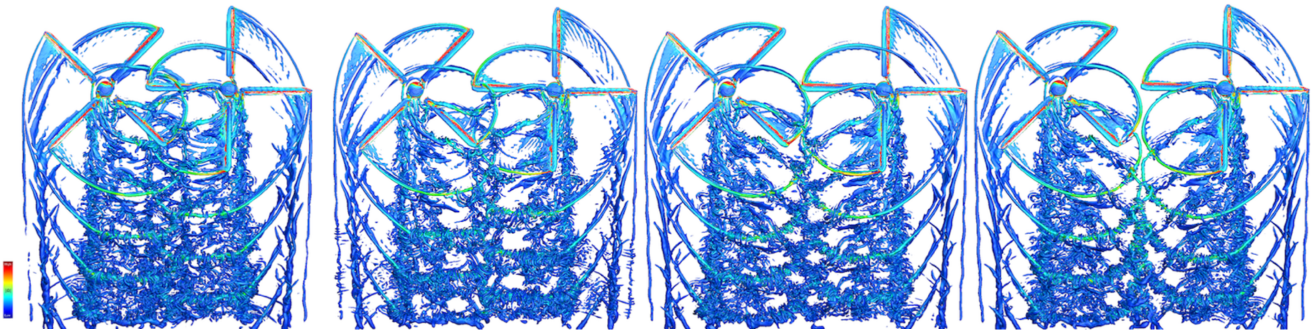
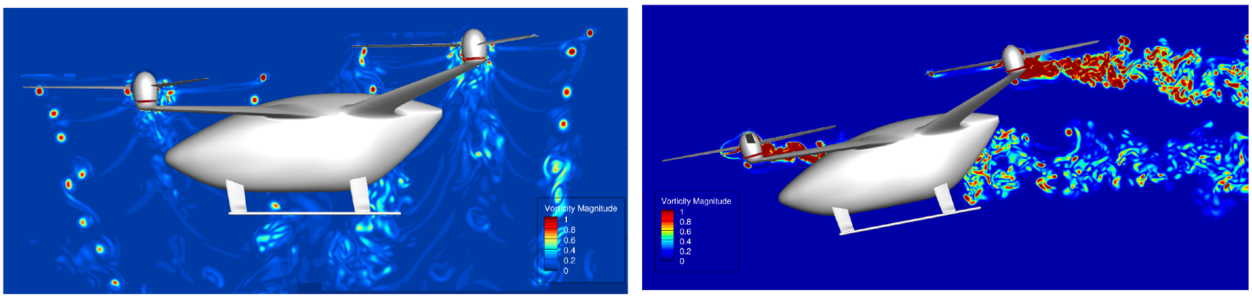

(a) 25% overlap (b) 15% overlap (c) 5% overlap (d) 0% overlap

Fig. 3 Vortex wake visualization for side-by-side rotors in forward flight for different rotor overlaps.

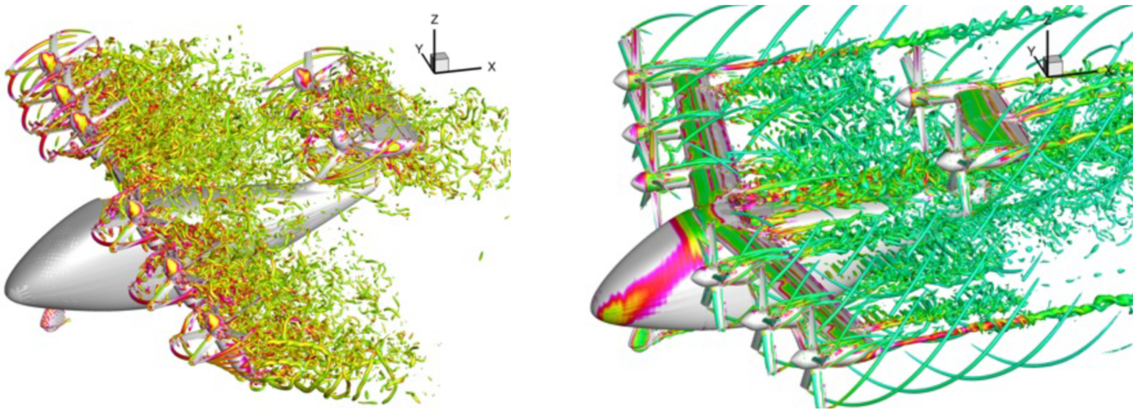
The quadrotor is another example of a multi-rotor aircraft for UAM. The quadrotor has been designed with the rear rotors mounted at a higher position than the front rotors to reduce rotor-rotor aerodynamic interactions in cruise, and the power required for cruise. It uses collective control without cyclic control. Figure 4 shows the quadcopter in hover (Figure 4a) and in cruise (Figure 4b). Vorticity magnitude contours are shown on a vertical plane located at the right-side rotors.



(a) Hover (b) Cruise

Fig. 4 Vortex wake visualization of the quadcopter UAM concept in hover and in cruise.

The tiltwing aircraft has six prop-rotors placed on the main wing and two tilting prop-rotors positioned at the horizontal tail. An advantage of the tiltwing design over other multi-rotor concepts for UAM is that it can reach higher cruise velocities more efficiently and quietly, as the rotors do not encounter edgewise flight conditions. On the other hand, a challenge of the tiltwing is to perform safely and efficiently the transition between helicopter mode and airplane mode, and vice-versa. The rotors on the main wing are positioned such that the main wing is fully blown by the rotors to reduce separation during transition at high wing angles-of-attack, and they also spin counter-clockwise on the right-side of the aircraft, and clockwise on the left side, to decrease the wing tip vortex and the consequent induced drag. Figure 5 shows a snapshot in time of the iso-surfaces of Q-criterion colored with vorticity magnitude in transition and in cruise.



(a) Transition (b) Cruise

Fig. 5 Vortex wake visualization of the tiltwing concept during transition flight and in cruise.

SUMMARY

This study presented a flow visualization and high-fidelity CFD analysis of NASA's air taxi concepts, focusing on their aerodynamic performance. Using NASA's OVERFLOW, a structured overset grid, high-order accurate Navier-Stokes solver, we examined the aerodynamics and flow features of various vehicle configurations. The complex multi-rotor flow interactions observed in these vehicles can be analyzed, providing critical insights into their aerodynamic behavior.

ACKNOWLEDGMENTS

This work was supported by the Revolutionary Vertical Lift Technology (RVLT) project (PM: Noah Schiller; TL: Brian Allan). The computations utilized the Pleiades, Electra, and Aitken supercomputers at the NASA Advanced Supercomputing Division.

REFERENCES

(1) Johnson, W., Silva, C., and Solis, E., "Concept Vehicles for VTOL Air Taxi Operations", The AHS International Technical Meeting on Aeromechanics Design for the Transformative Flight, San Francisco, California, January 2018.
(2) Garcia Perez, D., Ventura Diaz, P., Sanguinetti, A., and Yoon, S., "Tiltwing Transition Flight Analysis Using High-Fidelity CFD", Vertical Flight Society's 80th Annual Forum Montreal, Quebec, Canada, May 7–9, 2024.
(3) Ventura Diaz, P., Garcia Perez, D., and Yoon, S., "Computational Analysis of a Quiet Single-Main Rotor Helicopter for Air Taxi Operations", Vertical Flight Society's 78th Annual Forum, Ft. Worth, Texas, May 10-12, 2022.
(4) Ventura Diaz, P., and Yoon, S., "Computational Study of NASA's Quadrotor Air Taxi Concept", AIAA Paper 2020-0302, The AIAA SciTech Forum 2020, Orlando, Florida, January 2020.
(5) Ventura Diaz, P., Johnson, W., Ahmad, J., and Yoon, S., "The Side-by-side Urban Air Taxi Concept," AIAA Paper 2019–2828, June 2019.
(6) Ventura Diaz, P. and Yoon, S., "High-Fidelity Computational Aerodynamics of Multi-Rotor Unmanned Aerial Vehicles", AIAA Paper 2018-1266, AIAA SciTech 2018, Florida, January 2018.
(7) Pulliam, T. H., "High Order Accurate Finite-Difference Methods: as seen in OVERFLOW", AIAA Paper 2011-3851, 20th AIAA CFD Conference, Honolulu, Hawaii, June 2011.
(8) Chan, W., Gomez, R. J., Rogers, S. E., and Buning, P. G., "Best Practices in Overset Grid Generation", AIAA Paper 2002-3191, The 32nd AIAA Fluid Dynamics Conference, St. Louis, Missouri, June 2002.
(9) Johnson, W., "Rotorcraft Aerodynamic Models for a Comprehensive Analysis", American Helicopter Society 54th Annual Forum, Washington, D. C., May 1998.