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

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This paper presents a high-fidelity multidisciplinary analysis for the NASA lift+cruise vertical takeoff and landing urban air mobility concept aircraft. The reported simulations couple comprehensive rotorcraft aeromechanics and high-fidelity computational fluid dynamics (CFD). Aerodynamic solutions are computed on dynamic, deforming, unstructured, overset grid systems by an unsteady CFD solver, FUN3D, developed at the NASA Langley Research Center. An integrated overset-grid assembler, Yoga, is used for communications between component grids. Two turbulence models are compared for loose-coupling simulations in hover and low-speed forward flight conditions. One model is the negative variant of the one-equation Spalart-Allmaras model (SA-neg), and the other model is the SA-neg-R model adding a simple rotation correction term to the SA-neg model. The rotation correction in the SA-neg-R turbulence model significantly improves resolution of secondary vortices and wake interactions for rotorcraft simulations.

I. Introduction

The need to provide a mobile alternative for everyday ground transportation is growing rapidly for various economic and environmental reasons. NASA is conducting research in advanced air mobility (AAM) aircraft and operations [1], which include air transportation systems that move people and cargo between places previously not served or underserved by aviation. New AAM vehicles require increased automation and innovative propulsion systems, and most of them need vertical takeoff and landing (VTOL) capability [2]. Urban air mobility (UAM), a subset of AAM, focuses on highly automated aircraft that operate and transport passengers or cargo at lower altitudes within urban and suburban areas. UAM is projected to be the most economically beneficial, but also the most difficult to develop. The NASA Revolutionary Vertical Lift Technology (RVLT) project is developing UAM VTOL concept vehicles [3–6] to guide aircraft development for emerging aviation markets. NASA concept vehicles provide specific configurations for the NASA UAM research. The Lift+Cruise VTOL aircraft is one of three UAM conceptual configurations recently presented by Silva et al. [4].

The RVLT project invests in development of cutting-edge technology and tools for analyzing and designing VTOL vehicles that can operate safely and reliably with reduced environmental impact. Current multidisciplinary analysis tools and workflows, from a lower-fidelity comprehensive analysis (CA) tool to higher-fidelity multidisciplinary simulations, are applied to a variety of VTOL concept vehicles. Johnson and Silva [7] performed comprehensive analysis of several VTOL UAM concepts. Subsequently, Diaz et al. performed the high-fidelity computational fluid dynamics (CFD) simulations of the side-by-side air taxi
concept [8], ducted and coaxial air taxis [9], and the quadrotor concept [10] using the CFD solver, OVERFLOW [11], loosely coupled with the Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics II (CAMRADII) model [12]. OVERFLOW is a finite-difference CFD solver that uses overset, dynamic, multiblock, body-fitted, structured grids for moving-body aerodynamic simulations. Recently, Druyor and Wang [13] conducted a high-fidelity analysis of a six-passenger quadrotor air taxi concept vehicle using a finite-volume, unstructured-grid, CFD solver, FUN3D [14], coupled with CARMADII. FUN3D provides capabilities to compute high-fidelity solutions on dynamic, deforming, overset grids. This paper applies the developed FUN3D/CAMRADII workflow for high-fidelity multidisciplinary analysis of the lift+cruise VTOL UAM concept aircraft.

The one-equation Spalart-Allmaras (SA) [15] turbulence model is often used for Reynolds-averaged Navier-Stokes (RANS) rotorcraft simulations due to its simplicity and robustness. In such simulations, an excessive turbulent eddy viscosity (TEV) may lead to a premature dissipation of the rotor tip vortices. Recent OVERFLOW solutions [16–18] using a hybrid RANS/Large Eddy Simulations (LES) approach showed an improved prediction of single rotor performance and resolved fine details of a rotor wake in hover and forward flight conditions. The Detached Eddy Simulation (DES) [19–20] method used in these simulations employs the SA model inside the boundary layer and switches to LES in regions of flow separation where the larger eddies are to be grid resolved. High-resolution grids are needed for LES regions beyond the boundary layer. Grids with more than 55 million points are used in Refs. [17–18] for analysis of a single rotor without fuselage. Currently, simulations on grids of such sizes are not practically scalable for the lift+cruise aircraft, which has 9 rotors, fuselage, wings, supporting boom, landing gears, etc. To reduce TEV generation within the vortex core, Shur et al. [21] introduced an SA model correction to account for rotation and curvature effects; the corrected model is referred as SA-RC on the turbulence modeling resource (TMR) website*. The SA-RC model improves the boundary layer profile for highly curved flows and reduces the TEV levels in the vortex core regions. However, it requires evaluation of the Lagrangian derivative of the strain-rate tensor. This evaluation is computationally expensive, especially in a time-dependent flowfield, where the time derivative term cannot be ignored. An alternative and simpler rotation correction to the SA model is based on the works of Dacles-Mariani [22, 23]. This rotation correction, designated by suffix –R on the TMR website, mitigates generation of spurious eddy viscosity within a mature vortex. Both the SA-RC and SA-R models were assessed in Ref. [16] and provided similar results. The SA-R model has been initially implemented in FUN3D and demonstrated improvements in isolated rotor simulations [24]. It is a computationally efficient model. As described in Section III, implementation of the SA-R model requires only a few additional code lines.

The negative variant of the SA turbulence model (SA-neg) [25] is commonly used in RANS simulations due to its superior numerical behavior. Integration of the –R correction with the SA-neg model is not straightforward. In preparation to the high-fidelity CFD verification workshop (HFCFDVW)$^\dagger$, a group of researchers clarified implementation of the SA-neg–R model. The clarification has been reflected on the TMR website. Several verification test cases have been presented in Ref. [26] for the updated model with a quadratic constitutive relation (SA-neg-QCR2000-R). These test cases are steady simulations and do not involve a solid-body rotation. In this paper, we investigate the effects of the SA-neg-R turbulence model on resolution of a complex wake of the lift+cruise concept aircraft. Coupled FUN3D/CAMRADII simulations are conducted with the SA-neg and SA-neg-R turbulence models in hover and low-speed forward flight conditions and demonstrate the importance of controlling vortex-core TEV levels in rotorcraft simulations.

The material in this paper is presented in the following order. Section II briefly describes the discipline models and the loose-coupling process. Section III describes the SA-neg-R turbulence model. Section IV describes the lift+cruise VTOL UAM concept aircraft and the CFD composite grid system. Section V presents the multidisciplinary analysis of the aircraft in hover and low-speed forward flight conditions and

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* https://turbmodels.larc.nasa.gov/spalart.html; Accessed March 2023

$^\dagger$ https://HighFidelityCFDVerificationWorkshop.github.io; Accessed March 2023
compares simulations conducted with the SA-neg and SA-neg-R models. Section VI contains concluding remarks and future work.

II. Multidisciplinary Analysis

This section provides an overview of the discipline models used in the multidisciplinary analysis of the lift+cruise concept aircraft. A brief description of the loose-coupling process is provided.

A. CFD model

CFD solutions are computed by FUN3D [14]. FUN3D is a node-centered, unstructured-grid, RANS solver, which is widely used for high-fidelity analysis and adjoint-based design of complex turbulent flows [27–31]. FUN3D solves RANS equations discretized on unstructured mixed-element grids that may contain tetrahedra, pyramids, prisms, and hexahedra. The residuals are evaluated on a set of median-dual control volumes centered at grid points. Edge-based inviscid fluxes are computed at edge midpoints using an approximate Riemann solver. In the current study, Roe’s flux-difference splitting [32] is used. For second-order accuracy, density, pressure, and velocity are reconstructed at edge midpoints by a UMUSCL (unstructured monotonic upstream-centered scheme for conservation laws) scheme [33–34]. For the discretization of viscous fluxes, the Green-Gauss theorem is used to compute cell-based gradients. For nontetrahedral grids, cell-based Green-Gauss gradients are combined with edge-based gradients [35–36] to improve the stability of viscous operators and prevent odd-even decoupling. Two turbulence models listed in TMR website*, SA-neg [25] and SA-neg-R [22–23], are used for the current simulations. The spatial discretization of the turbulence models uses a first-order accurate convection scheme. To advance in time, a library of implicit time integration schemes is available in FUN3D. In the current simulations, a second-order backward difference scheme, BDF2opt [37], is used.

Previous FUN3D rotorcraft simulations (e.g., Ref. [24]) have been supported by Suggar++ [38] and DirRTlib [39] domain-connectivity libraries. Recently, a new overset-grid assembler for unstructured-grid systems, Yoga [40], has been developed and integrated into FUN3D. Yoga is a parallel overset-domain assembly code that uses a modified wall-distance criterion to select overset boundary locations and leverages dynamic load balancing to achieve high performance on thousands of MPI processing cores. Yoga improves scalability of overset-grid assembly and enables solutions on larger grid systems than those possible with the serially implemented Suggar++ and DirRTlib libraries currently in FUN3D. A very large composite overset-grid system is needed to capture details of complex interactions of wake from multiple rotor blades. As demonstrated in Ref. [13], Yoga is able to support CFD simulations of complex VTOL aircraft involving multiple moving bodies. This capability is critical for simulation of the lift+cruise aircraft that includes 22 moving bodies.

B. CA model

A CA model, CAMRADII [12], is developed by W. Johnson and used for simulating structural dynamics of rotor blades. CAMRADII incorporates various computational models including multibody dynamics, nonlinear finite elements, structural dynamics, and rotorcraft aeromechanics. Each blade is modeled with a set of nonlinear beam elements. This structural-dynamics analysis predicts blade deflections and responses to aerodynamic loads. The internal aerodynamics model in CAMRADII is a low-fidelity approximation based on the lifting line theory and vortex wake models. In addition, CAMRADII trims solutions for a specific flight condition.

C. Loose coupling process

A FUN3D/CAMRADII interface for exchange of aerodynamic loads and structural responses has been developed and reported in Ref. [40]. In Ref. [13], this interface has been updated and extended to enable multidisciplinary analysis of multiple rotors with different rotation directions. In this work, the interface has been further extended to allow rotors with different blade radii and configurations with rotating and stationary rotors/propellers.
Figure 1 shows the file-based loose-coupling workflow driver from Ref. [13] that is used in the current simulations. The interactions between the CFD solver and the CA solver happen at the end of each coupling cycle. The exchange of CFD airloads and structure deflections is conducted through the file I/O. An intermediate translator code is employed to prepare data in the formats required by CAMRADII and FUN3D. The number of coupling cycles is specified by user through an input parameter.

![Diagram showing the workflow](Image)

**Figure 1. File-based loose-coupling data flow.**

### III. SA-neg-R Turbulence Model

Following the formulation presented at the TMR website, the standard SA turbulence model [15] is given by Eq. 1.

\[
\frac{\partial \hat{\nu}}{\partial t} + \mathbf{u} \cdot \nabla \hat{\nu} - c_{b1}(1 - f_{t2})\hat{S}\hat{\nu} + \left[ c_{w1}f_{w} - \frac{c_{b1}}{k^2} f_{t2} \right] \frac{\hat{\nu}}{d} - \frac{1}{\sigma} \left[ \nabla \cdot ((\hat{\nu} + \hat{v})\nabla \hat{\nu}) + c_{b2}(\nabla \hat{\nu} \cdot \nabla \hat{\nu}) \right] = 0 \tag{1}
\]

Here, \( \nabla \equiv (\partial_x, \partial_y, \partial_z)^T \) denotes a formal vector of spatial derivatives. The boundary conditions are defined in Eq. 2.

\[ \hat{\nu}_{wall} = 0, \quad \hat{\nu}_{farfield} = 3 \nu_{ref} \tag{2} \]

Here, \( \hat{\nu} \) is the turbulence variable, \( d \) is the distance to the nearest wall, \( \nu = \mu/\rho \) is the kinematic viscosity, and \( \nu_{ref} \) is the reference kinematic viscosity. The turbulent eddy viscosity is computed as in Eq. 3.

\[ \mu_t = \rho \hat{\nu} f_{v1} \tag{3} \]

The production term in the SA model is defined in Eq. 4.

\[ P = c_{b1}(1 - f_{t2})\hat{S}\hat{\nu} \tag{4} \]

The term \( \hat{S} \) is defined as follows.

\[ \hat{S} = \Omega + \bar{S}, \quad \bar{S} = \frac{\hat{\nu}}{k^2 d^2} f_{v2} \tag{5} \]

Here, \( \Omega \) is the magnitude of vorticity defined in Eq. 6.

\[ \Omega = \sqrt{(\partial_y w - \partial_x v)^2 + (\partial_z w - \partial_x v)^2 + (\partial_x v - \partial_y w)^2} \tag{6} \]

To avoid numerical problems associated with \( \hat{S} \leq 0 \), Ref. [25] suggests the following modification.

\[ \hat{S} = \Omega + \frac{\Omega(c_2^2 \Omega + c_3 \bar{S})}{(c_3 - 2c_2)\Omega - \bar{S}} \quad \text{when} \quad \bar{S} < -c_2\Omega, \quad c_2 = 0.7, \quad c_3 = 0.9 \tag{7} \]

Other terms appearing in Eq. 1 are defined as follows.

\[ f_{v1} = \frac{\chi^3}{c_{v1}^3 + \chi^3}, \quad \chi = \frac{\hat{\nu}}{\nu}, \quad f_{v2} = 1 - \frac{\chi}{1 + \chi f_{v1}}, \quad f_w = g \left[ \frac{1 + c_{w3}^6}{g^6 + c_{w3}^6} \right]^{\frac{1}{5}}, \quad g = r + c_{w2}(r^6 - r), \]

\[ f_{t2} = c_{t3} \exp(-c_{t4} \chi^2), \quad r = \min \left[ \frac{\hat{\nu}}{\bar{S} k^2 d^2}, 10 \right] \tag{8} \]
The constants are $\kappa = 0.41$, $\sigma = \frac{2}{3}$, $c_{b1} = 0.1355$, $c_{b2} = 0.622$, $c_{t3} = 1.2$, $c_{t4} = 0.5$, $c_{v1} = 7.1$, $c_{w1} = \frac{c_{b1}}{\kappa} + \frac{1}{\sigma}$, $c_{w2} = 0.3$, and $c_{w3} = 2$.

In the SA-R [22, 23] turbulence model, the production term Eq. 4 is modified as in Eq. 9.
\[ P = c_{b1} (1 - f_{t2}) (\hat{S} + c_{\text{rot}} \min(0, S - \Omega)) \hat{\nu} \]  
(9)

The SA-R model equation is given by Eq. 10.
\[ \partial_t \hat{\nu} + u \cdot \nabla \hat{\nu} - c_{b1} (1 - f_{t2}) (\hat{S} + c_{\text{rot}} \min(0, S - \Omega)) \hat{\nu} \]
\[ + \left[ c_{w1} f_{w} - \frac{c_{b1}}{2} f_{t2} \right] \frac{\hat{\nu}^2}{d} - \frac{1}{\sigma} \left[ \nabla \cdot (v + \hat{\nu} f_{n}) \nabla \hat{\nu} \right] + c_{b2} (\nabla \hat{\nu} \cdot \nabla \hat{\nu}) \] = 0
(10)

Here, the strain magnitude, $S$, is defined as in Eq. 11.
\[ S = \sqrt{(\partial_x u + \partial_y v)^2 + (\partial_x u + \partial_y w)^2 + (\partial_x v + \partial_y u)^2 + 2(\partial_x u)^2 + 2(\partial_y v)^2 + 2(\partial_y w)^2} \]  
(11)

If the strain magnitude is less than the vorticity magnitude, $S < \Omega$, and $c_{\text{rot}} > 1$, the production term may become negative and suppress production of eddy viscosity, which is considered as a desirable property in case of a solid body rotation. References [22, 23] recommend $c_{\text{rot}} = 2$. Computations reported in Ref. [42] use $c_{\text{rot}} = 1$.

The standard SA model equation requires $\hat{\nu} > 0$. The SA model extended to negative values of $\hat{\nu}$ is referred to as the SA-neg model [25]. In the SA-neg model, Eq. 1 is solved for positive $\hat{\nu}$ and Eq. 12 is solved for negative $\hat{\nu}$.
\[ \partial_t \hat{\nu} + u \cdot \nabla \hat{\nu} - c_{b1} (1 - c_{t3}) \Omega \hat{\nu} - c_{w1} \left( \frac{\hat{\nu}^2}{d} \right) - \frac{1}{\sigma} \left[ \nabla \cdot (v + \hat{\nu} f_{n}) \nabla \hat{\nu} \right] + c_{b2} (\nabla \hat{\nu} \cdot \nabla \hat{\nu}) \] = 0
(12)

Function $f_{n}$ is defined in Eq. 13.
\[ f_{n} = \frac{c_{n1} + \chi^3}{c_{n1} - \chi^3}, \quad c_{n1} = 16 \]  
(13)

The SA-neg turbulent eddy viscosity is computed using Eq. 3 when $\hat{\nu} \geq 0$ and set to zero when $\hat{\nu} < 0$.

In the SA-neg-R model, Eq. 10 is solved for positive $\hat{\nu}$. All models based on SA-neg benefit from smooth transition through $\hat{\nu} = 0$; therefore, it would be preferable to have the production term as $c_{b1} (1 - c_{t3}) (\Omega + c_{\text{rot}} \min(0, S - \Omega)) \hat{\nu}$ in the negative branch of the SA-neg-R model. On the other hand, SA-neg does not allow a negative production term for $\hat{\nu} < 0$. The negative branch of the SA-neg-R model uses the absolute value of the preferable production term, resulting the Eq. 14.
\[ \partial_t \hat{\nu} + u \cdot \nabla \hat{\nu} - c_{b1} (1 - c_{t3}) |\Omega| + c_{\text{rot}} \min(0, S - \Omega) |\hat{\nu}|
\[ -c_{w1} \left( \frac{\hat{\nu}^2}{d} \right) - \frac{1}{\sigma} \left[ \nabla \cdot (v + \hat{\nu} f_{n}) \nabla \hat{\nu} \right] + c_{b2} (\nabla \hat{\nu} \cdot \nabla \hat{\nu}) \] = 0
(14)

When $c_{\text{rot}} = 1.0$, the production term is positive as $\Omega + \min(0, S - \Omega) > 0$ ensuring a smooth transition between the positive and negative branches of the SA-neg-R model. However, it is believed that $c_{\text{rot}} = 1.0$ does not sufficiently suppress spurious eddy viscosity. Thus, for simulations in this paper, $c_{\text{rot}} = 2.0$ is chosen. In this scenario, the SA-neg-R production term is only C0 continuous for flow regimes where $\Omega + c_{\text{rot}} \min(0, S - \Omega) < 0$.

IV. Lift+Cruise Concept Aircraft and CFD Grids

This section briefly describes the lift+cruise concept aircraft and the CFD grid generation procedure.

A. Lift+Cruise concept aircraft

The Lift+Cruise concept aircraft [4] is a stopping-rotor thrust- and lift-compound helicopter. It is intended to operate as a fixed-wing aircraft during cruise flight, where the lifting rotors do not rotate, and forward thrust is provided by a pusher propeller. The lift rotors operate during the VTOL takeoff and landing phases of flight. When hovering, only lift rotors are turning, and the pusher propeller does not
rotate. During low-speed forward flight, the lift rotors and the pusher propeller are operating together to generate enough lift and forward thrust.

Table 1 lists the weight and dimensions of the lift+cruise concept aircraft. Figure 2 shows a computer-aided-design (CAD) model based on the concept configuration from Ref. [4]. The configuration has eight lifting rotors and one pusher propeller. The number and rotation direction are shown for each rotor. The rotor numbering follows a convention that is common for multi-engine fixed-wing aircraft, left to right, front to back. The propeller is sometimes referred to as rotor 9. Table 2 shows coordinates of the rotor rotation centers. The four inboard lifting rotors have a shaft cant angle of 8 degrees (outboard), the outboard rotors are parallel to the ground level. Each lifting rotor has two blades, which are aligned with the travel direction during cruise flight to minimize the drag penalty. The propeller has six blades to produce enough forward thrust. In the current design, the radius of the lifting rotor blade is five feet with a linear taper of 0.75 and a linear twist of -15 degrees from the center of rotation to the tip. The radius of the propeller blade is 4.5 feet with a linear taper of 0.75 and a linear twist of -35 degrees. Both blades use VR12 airfoil from \( r/R = 0 \) to 0.85 and SSC-A09 airfoil between \( r/R = 0.95 \) and tip, with a linear blend from \( r/R = 0.85 \) and 0.95.

### Table 1. Lift+Cruise concept aircraft geometry.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>5903 lb</td>
</tr>
<tr>
<td>Length</td>
<td>31.58 ft</td>
</tr>
<tr>
<td>Height</td>
<td>13.47 ft</td>
</tr>
<tr>
<td>Wing Span</td>
<td>47.69 ft</td>
</tr>
<tr>
<td>Radius of Lift Rotors</td>
<td>5.00 ft</td>
</tr>
<tr>
<td>Radius of Propeller</td>
<td>4.50 ft</td>
</tr>
</tbody>
</table>

![Figure 2. CAD Surface model of lift+cruise concept aircraft (CCW – Counterclockwise rotation; CW – Clockwise rotation)]
Table 2. Coordinates (feet) of rotor rotation centers.

<table>
<thead>
<tr>
<th>Rotor</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.07</td>
<td>-18.75</td>
<td>6.73</td>
</tr>
<tr>
<td>2</td>
<td>19.20</td>
<td>-18.75</td>
<td>9.01</td>
</tr>
<tr>
<td>3</td>
<td>4.63</td>
<td>-8.13</td>
<td>7.04</td>
</tr>
<tr>
<td>4</td>
<td>18.76</td>
<td>-8.45</td>
<td>9.30</td>
</tr>
<tr>
<td>5</td>
<td>4.63</td>
<td>8.13</td>
<td>7.04</td>
</tr>
<tr>
<td>6</td>
<td>18.76</td>
<td>8.45</td>
<td>9.30</td>
</tr>
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<td>7</td>
<td>5.07</td>
<td>18.75</td>
<td>6.73</td>
</tr>
<tr>
<td>8</td>
<td>19.20</td>
<td>18.75</td>
<td>9.01</td>
</tr>
<tr>
<td>propeller</td>
<td>31.94</td>
<td>0.0</td>
<td>7.79</td>
</tr>
</tbody>
</table>

B. CFD composite grid system

Composite, overset, unstructured-grid systems are generated for the high-fidelity CFD analysis performed by FUN3D. There are four types of component grids: near-body grids for clockwise (CW) and counterclockwise (CCW) rotating lifting-rotor blades, near-body grids for propeller blades, and a background grid that includes fuselage, wings, tails, and other stationary structures. Figure 3 illustrates the component grids. The farfield boundary of the background grid shown in Fig. 3d is 300 feet away from the center of the rotorcraft. In the background grid, cylindrical regions of refinement source are added around rotors to match the local spacing of the background grid with the spacing of the outer boundary of the rotor grids. Figures 4 and 5 show the refined regions and a cut of the cluster grids at the outboard rotor plane; for simplicity, only regions around the outboard lifting rotors and the propeller are shown. Because the rotor wake travelling directions are different in hover and forward flight, two different background grids are generated for hover and low-speed forward-flight conditions.

Figure 3. Component grids for lift+cruise concept aircraft.
A coarse composite grid system has been first generated to test the loose-coupling workflow described in Section II. The grid contains approximately 55 million grid points. Simulation results on the coarse grid are not presented. Two fine grids are then generated for hover and forward flight. Yoga assembles the
component grids into a composite grid system, which includes 16 near-body grids for lifting rotor blades, six near-body grids for propeller blades, and the background grid.

The component grids are generated using Pointwise [43]. For forward flight simulations, a propeller blade grid containing 2.25 million points is used to resolve the propeller wake flow. In hover, the propeller is stationary and contributes little to the aircraft performance. A coarser grid of approximately 1.21 million grid points is used instead, which reduces the cost and improves numerical stability of hover simulations. For both flight conditions, each lifting rotor blade grid contains 2.49 million points. The grid wall distance for propeller and rotor blade mesh is set to 0.00001 grid unit in Pointwise, corresponding to a $y^+ \approx 1$. The background grid for hover flight has 161 million grid points, and the background grid for low-speed forward flight has 173 million grid points. Overall, the composite grid for hover flight has around 208 million grid points, and the grid for low-speed forward flight has around 227 million grid points. The grids generated for these simulations are based on “best practices” with the constraints of available computational resources and deadlines. Given the configuration complexity, finer grids may be required to achieve more accurate performance predictions. A grid convergence study is proposed in the future work.

V. Results

High-fidelity multidisciplinary analyses are presented using the SA-neg and SA-neg-R turbulence models. Two flight conditions are simulated: hover and low-speed forward flight. This paper focuses on the lift+cruse concept aircraft VTOL capabilities, so the cruise flight condition is not investigated.

A. Hover flight

In hover flight, the lifting rotors are operational and the pusher propeller is stationary. The rotational speed of each lifting rotor is 1050.42 revolutions per minute (rpm) with a nominal tip speed of 550 ft/sec. The corresponding tip Mach number is 0.4842 and the tip unit Reynolds number is 2.74 million per foot (grid unit). This study focuses on collective pitch control, and the rotational speed is fixed. In CAMRADII, the trim targets are the total vehicle $z$-force (lift-weight), $x$-force (drag) and $y$-moment, which are trimmed to be zero by varying the collective pitch angles of lift rotors. Currently the fuselage-wing aerodynamic forces are estimated by CAMRADII as zero for hover flight. These forces can be replaced with high-fidelity CFD predictions in the future work.

For hover-flight simulations, CFD analysis is initialized by the freestream initial condition and advances in time with a time step corresponding to 0.5 degree of the azimuth. Eight subiterations are conducted at each time step to reduce the combined meanflow and turbulence-model residuals by about four orders of magnitude. In the first coupling cycle, CFD simulations perform a full revolution (360 degrees); in all other coupling cycles, CFD simulations correspond to a half revolution (180 degrees).

For computations with the SA-neg model, 39 coupling cycles have been performed, which correspond to 20 revolutions. Figure 6 shows convergence of rotor thrust and torque computed by FUN3D versus rotor revolutions. After 20 revolutions, the computed rotor loads still vary, but the thrust and torque appear to reach a steady state for most of rotors. It appears that more revolutions are needed to fully converge forces and moments for outboard rotors. Symmetry of lifting rotors on the left and right side of the fuselage is observed. Figure 7 shows the pitch hinge angles computed from CAMRADII versus the coupling cycles. In each coupling cycle, the front rotors (rotors 1, 3, 5, and 7) have practically identical hinge angles; similarly, the pitch angles of the back rotors (rotors 2, 4, 6, and 8) are almost the same. For hover-flight, the pitch angles of the back rotors are a little bit higher than the angles of the front rotors.
Figure 6. Hover flight: FUN3D thrust and torque with SA-neg model.

Figure 7. Hover flight: pitch hinge angle with SA-neg model.

Figure 8 shows distributions of the sectional normal-force coefficient for the lifting rotors. For a hovering rotor, the normal forces are expected to be uniformly distributed over azimuthal angles. For this lift+cruise concept aircraft, only forces in the midspan regions are close to a uniform distribution. Wake interactions from different rotors and interactions between rotor wake and wing/fuselage structures strongly affect the forces in the rotor tip region. The forces at the rotor root region are affected by the supporting booms; the effect is especially strong for the four front rotors where the booms are on top of the rotor disks. For this aircraft, a significantly unsteady flow field is observed even in hover flight.
Figure 8. Hover flight: sectional normal force computed with SA-neg model.

Figure 9 shows convergence of FUN3D rotor thrust and torque versus rotor revolutions using the SA-neg-R model. In this simulation, 39 coupling cycles (20 revolutions) have been performed. The thrust and torque of rotors 3 and 5 have converged to each other after 20 revolutions. Thrust value for front-outboard rotors (rotors 1 and 7) still changing between revolutions; more revolutions are needed to better converge the thrust. Figure 10 shows the pitch hinge angles estimated by CAMRADII from the coupled solutions computed with the SA-neg-R model. The trends are similar to those observed with the SA-neg model in Fig. 7. Figure 11 shows distributions of the sectional normal-force coefficient in simulations with the SA-neg-R model. In general, the normal forces are similar to the forces computed with the SA-neg model and shown in Fig. 8. For the inboard rotors, the wake interactions generate more disturbances for the normal force distributions with the SA-neg-R model than with the SA-neg model.

![Hover Flight Diagram](image)

**Figure 9. Hover flight: FUN3D thrust and torque with SA-neg-R model.**

a) Outboard rotors 

b) Inboard rotors
Figure 10. Hover flight: pitch hinge angle with SA-neg-R model.

Figure 11. Hover flight: sectional normal force computed with SA-neg-R model.

Figure 12 shows the isosurfaces of Q-criterion (at value of 0.0005) colored by vorticity magnitude computed with the SA-neg and SA-neg-R turbulence models, from a front view of the aircraft. All inputs, such as the grid, flight conditions and the CAMRADII model, are the same for these two simulations; the only difference is the turbulence model. The tip vortices from the lifting rotors are resolved by the clustered grids shown in Fig. 4b. The SA-neg simulation resolves some secondary vortices and the wake interactions among the rotors and with the wing. The SA-neg-R simulation resolves many more details of the secondary vortices and more wake interactions, especially the strong wake/fuselage interactions from the inboard rotors 3, 4, 5, and 6, which are canted at 8 degree (wake towards the fuselage). There is some disturbance near the propeller region, probably due to the wake interactions of the horizontal and vertical tails with the propeller blades.
Figures 13 and 14 compare the Q-criterion contours in constant-y planes for solutions computed with the SA-neg and SA-neg-R models. Figure 13 shows contours in the plane cutting through the center of the inboard rotor 3. Figure 14 shows contours in the plane cutting through the centers of the ourboard rotors 1 and 2. Clearly, the SA-neg-R model better resolves wake structures for all rotors.

For hover flight, the trim variables are the collective pitch, longitudinal cyclic and the airframe pitch angle. Table 3 lists converged trim angles as evaluated by CAMRADII from coupled solutions computed with the SA-neg and SA-neg-R models. The airframe pitch angles are close to zero for hover flight. The collective pitch and longitudinal cyclic angles are consistent between the SA-neg and SA-neg-R models.
Tables 4 and 5 list the thrust and torque, respectively, for the hover-flight simulation. The thrust and torque are evaluated by FUN3D and CAMRADII from the RANS solutions corresponding to the SA-neg and SA-neg-R models. The differences between FUN3D and CAMRADII evaluations for the same-model solutions are due to the fact that FUN3D forces and moments are computed on the blade surface mesh representing the actual geometry; the CAMRADII loads are based on integration of sectional airloads using specified airstations.

In comparison with solutions computed with the SA-neg model, the thrust values computed with the SA-neg-R model (Table 4) are somewhat lower for the outboard rotors, little higher for the inboard rotors, but overall are similar. As mentioned above, more revolutions are needed to converge thrust for front-outboard rotors. Table 5 shows that the torque values computed from the SA-neg-R solutions are noticeably lower than the values computed from the SA-neg solutions, especially for the inboard rotors 3, 4, 5 and 6. This torque reduction can be explained by strong wake interactions between rotors and fuselage, which are better resolved with the SA-neg-R model. This observation is consistent with previous single-rotor hover-flight studies [16, 17], which showed that a better resolved rotor wake leads to a higher figure of merit.

**Table 3. Hover flight: converged trim angles (degrees).**

<table>
<thead>
<tr>
<th>Trim angles</th>
<th>FUN3D(SA-neg)/CAMRADII</th>
<th>FUN3D(SA-neg-R)/CAMRADII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airframe Pitch</td>
<td>-0.04</td>
<td>-0.02</td>
</tr>
<tr>
<td>Collective</td>
<td>15.55</td>
<td>15.38</td>
</tr>
<tr>
<td>Longitudinal cyclic</td>
<td>0.11</td>
<td>0.18</td>
</tr>
</tbody>
</table>

**Table 4. Hover flight: thrust (lb) for lifting rotors.**

<table>
<thead>
<tr>
<th>Rotor</th>
<th>FUN3D(SA-neg)/CAMRADII CFD</th>
<th>CA</th>
<th>FUN3D(SA-neg-R)/CAMRADII CFD</th>
<th>CA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>737.87</td>
<td>731.49</td>
<td>728.30</td>
<td>724.02</td>
</tr>
<tr>
<td>2</td>
<td>780.33</td>
<td>772.12</td>
<td>768.85</td>
<td>764.15</td>
</tr>
<tr>
<td>3</td>
<td>745.78</td>
<td>734.03</td>
<td>738.07</td>
<td>736.98</td>
</tr>
<tr>
<td>4</td>
<td>730.67</td>
<td>721.23</td>
<td>736.47</td>
<td>731.93</td>
</tr>
<tr>
<td>5</td>
<td>742.87</td>
<td>732.66</td>
<td>746.69</td>
<td>742.40</td>
</tr>
<tr>
<td>6</td>
<td>735.27</td>
<td>726.74</td>
<td>738.13</td>
<td>732.42</td>
</tr>
<tr>
<td>7</td>
<td>737.71</td>
<td>731.28</td>
<td>731.70</td>
<td>726.98</td>
</tr>
<tr>
<td>8</td>
<td>778.71</td>
<td>770.72</td>
<td>768.59</td>
<td>762.16</td>
</tr>
</tbody>
</table>
equations in the frequency domain and uses observations are model predicts almost the same thrust but less torque compared to the SA additional revolutions. The thrust and torque configuration propeller has hover solutions corresponding to 1 propeller. The estimates CAMRADII estimation of the fuselage targets are by var Mach number is 0.4842 and the propeller speed is 0.4358, which gives an advance ratio of 0.2455 with respect to the rotor blades. The trim targets are again the total z-force (lift-weight), total x-force (thrust-drag) and y-moment, which are trimmed to be zero by varying the collective pitch angles of lifting rotors and the propeller. CAMRADII has simple estimation of the fuselage-wing body lift and drag based on the forward flight speed. For this simulation, CAMRADII estimates the wing-body lift of 541 lb, drag of 154.19 lb and pitch moment of -1337.54 lb-ft. The estimates are included in the trim procedure and could be replaced with high-fidelity CFD data in future work. Collective pitch control is used for current simulations.

For the simulation with the SA-neg model, 29 coupling cycles have been performed corresponding to 15 revolutions. For the simulation with the SA-neg-R model, only 19 coupling cycles have been performed corresponding to 10 revolutions, which appears to be enough for lifting rotors but insufficient for the propeller. In both simulations, the time step corresponds to 0.5 degrees of the azimuth advancement. Figure 15 shows convergence of FUN3D thrust and torque for lifting rotors evaluated from the solution with the SA-neg model. At the forward-flight condition, the convergence is faster. At forward flight, the rotor wake is quickly swept downstream and away from the rotor disk. Figure 16 shows convergence of thrust and torque for the propeller. The thrust and torque are evaluated by FUN3D and CAMRADII from the RANS solutions corresponding to the SA-neg and SA-neg-R models. For the propeller, the flow is axial, similar a hover-flight condition, and needs more revolutions to reach convergence. For this lift+cruse aircraft, the propeller has six blades and the fuselage tail fin and tail wings are right in front of the propeller. This configuration complicates the flow around the propeller disk. As shown in Fig. 16a, the FUN3D SA-neg thrust and torque appear to oscillate. The oscillations are due to slight differences in the forces and moments computed on different blades; it seems unlikely that these differences can be reduced simply by performing additional revolutions. More revolutions are needed to study development of the propeller wake. Currently, only 10 revolutions have been conducted using the SA-neg-R model. The thrust and torque exhibit oscillations that are similar to those observed with the SA-neg model. For the propeller, the SA-neg-R model predicts almost the same thrust but less torque compared to the SA-neg model predictions. These observations are consistent with the hover-flight observations for lifting rotors. CAMRADII solves equations in the frequency domain and uses data from a single blade. The CAMRADII thrust and torque converge smoothly as shown in Fig. 16b.

### Table 5. Hover flight: torque (lb-ft) for lifting rotors.

<table>
<thead>
<tr>
<th>Rotor</th>
<th>FUN3D(SA-neg)/CAMRADII</th>
<th>FUN3D(SA-neg-R)/CAMRADII</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CFD</td>
<td>CA</td>
</tr>
<tr>
<td>1</td>
<td>525.10</td>
<td>523.28</td>
</tr>
<tr>
<td>2</td>
<td>561.57</td>
<td>557.34</td>
</tr>
<tr>
<td>3</td>
<td>548.14</td>
<td>542.31</td>
</tr>
<tr>
<td>4</td>
<td>554.66</td>
<td>546.09</td>
</tr>
<tr>
<td>5</td>
<td>546.60</td>
<td>541.31</td>
</tr>
<tr>
<td>6</td>
<td>554.06</td>
<td>545.91</td>
</tr>
<tr>
<td>7</td>
<td>525.10</td>
<td>523.14</td>
</tr>
<tr>
<td>8</td>
<td>560.93</td>
<td>556.58</td>
</tr>
</tbody>
</table>

### B. Low-speed forward flight

In low-speed forward flight, the lifting rotors and the pusher propeller operate together. The rotational speed is 1050.42 rpm for the rotors and the propeller. Due to different radii, the rotor-blade tip Mach number is 0.4842 and the propeller-blade tip Mach number is 0.4358. The forward-flight speed is 80 knots and the Mach number is 0.1189, which gives an advance ratio of 0.2455 with respect to the rotor blades. The trim targets are again the total z-force (lift-weight), total x-force (thrust-drag) and y-moment, which are trimmed to be zero by varying the collective pitch angles of lifting rotors and the propeller. CAMRADII has simple estimation of the fuselage-wing body lift and drag based on the forward flight speed. For this simulation, CAMRADII estimates the wing-body lift of 541 lb, drag of 154.19 lb and pitch moment of -1337.54 lb-ft. The estimates are included in the trim procedure and could be replaced with high-fidelity CFD data in future work. Collective pitch control is used for current simulations.
Figure 15. Forward flight: FUN3D thrust and torque of lifting rotors with SA-neg model.

Figure 16 Forward flight: thrust and torque of pushing propeller.

Figure 17 shows the pitch hinge angles computed from CAMRADII for forward flight. The pitch angles of back rotors (Figs. 17a and 17b) are much higher than the angles of front rotors for forward flight, and the angles are consistent for the SA-neg and SA-neg-R models. Figure 17c shows the pitch angle of the propeller, which is very high compared to the pitch angles of lifting rotors. The propeller pitch angles of the SA-neg and SA-neg-R models are also consistent with each other.
For forward flight, the trim variables are the collective pitch and longitudinal cyclic angles of lifting rotors and the collective pitch angle of the propeller; the latter is different from the airframe pitch angle used for trimming hover flight. Table 6 lists converged trim angles evaluated by CAMRADII. The propeller collective angle is about 26 degrees. The high collective angle of the propeller provides needed pushing thrust, balances drag of aircraft, and explains the high pitch hinge angle of the propeller (Fig. 17c). The trim angles are consistent between the SA-neg and SA-neg-R models.

**Table 6. Forward flight: converged trim angles (degrees).**

<table>
<thead>
<tr>
<th>Trim angles</th>
<th>FUN3D(SA-neg)/CAMRADII</th>
<th>FUN3D(SA-neg-R)/CAMRADII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propeller collective</td>
<td>25.81</td>
<td>25.84</td>
</tr>
<tr>
<td>Lifting rotor collective</td>
<td>8.1</td>
<td>8.11</td>
</tr>
<tr>
<td>Lifting rotor longitudinal cyclic</td>
<td>2.22</td>
<td>2.19</td>
</tr>
</tbody>
</table>
Tables 7 and 8 list the thrust and torque, respectively, in the forward-flight conditions. The thrust and torque are evaluated by FUN3D and CAMRADII from the simulations conducted with the SA-neg and the SA-neg-R models. In forward flight, the effect of rotation correction in the turbulence model on lifting rotors is small. This is expected because the lifting-rotor wake is swept downstream and away from the rotor disk and has little effect on the rotor performance. The thrust and torque provided by the back rotors are higher than those provided by the front rotors, because the pitch angles are larger for back rotors as shown in Fig. 17. For the pusher propeller, the thrust seems to be insensitive to the rotation correction, but torque is lower in presence of the rotation correction. Figures 18 and 19 show distributions of the sectional normal-force coefficient. For the CCW rotors, the advancing side is in the azimuth range of (0°, 180°), i.e., the right side of rotor disk, and the retreating side is in the azimuth range of (180°, 360°), i.e., the left side of rotor disk. For a CW rotor, the advancing/retreating sides are opposite to those of a CCW rotor. There are strong wake interactions between the front rotors and the wing and there is not much difference between normal forces computed with the SA-neg model and the SA-neg-R models.

Table 7. Forward flight: thrust (lb) for lifting rotors and propeller.

<table>
<thead>
<tr>
<th>Rotor</th>
<th>FUN3D(SA-neg)/CAMRADII</th>
<th>FUN3D(SA-neg-R)/CAMRADII</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CFD</td>
<td>CA</td>
</tr>
<tr>
<td>1</td>
<td>595.35</td>
<td>581.82</td>
</tr>
<tr>
<td>2</td>
<td>777.30</td>
<td>764.92</td>
</tr>
<tr>
<td>3</td>
<td>623.75</td>
<td>610.24</td>
</tr>
<tr>
<td>4</td>
<td>743.25</td>
<td>731.04</td>
</tr>
<tr>
<td>5</td>
<td>623.27</td>
<td>610.73</td>
</tr>
<tr>
<td>6</td>
<td>745.25</td>
<td>732.39</td>
</tr>
<tr>
<td>7</td>
<td>593.94</td>
<td>582.91</td>
</tr>
<tr>
<td>8</td>
<td>777.42</td>
<td>765.22</td>
</tr>
<tr>
<td>Propeller</td>
<td>432.40</td>
<td>414.35</td>
</tr>
</tbody>
</table>

Table 8. Forward flight: torque (lb-ft) for lifting rotors.

<table>
<thead>
<tr>
<th>Rotor</th>
<th>FUN3D(SA-neg)/CAMRADII</th>
<th>FUN3D(SA-neg-R)/CAMRADII</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CFD</td>
<td>CA</td>
</tr>
<tr>
<td>1</td>
<td>122.33</td>
<td>115.51</td>
</tr>
<tr>
<td>2</td>
<td>286.08</td>
<td>277.60</td>
</tr>
<tr>
<td>3</td>
<td>115.67</td>
<td>109.23</td>
</tr>
<tr>
<td>4</td>
<td>299.46</td>
<td>290.24</td>
</tr>
<tr>
<td>5</td>
<td>115.58</td>
<td>109.05</td>
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<tr>
<td>6</td>
<td>299.29</td>
<td>289.99</td>
</tr>
<tr>
<td>7</td>
<td>121.85</td>
<td>115.21</td>
</tr>
<tr>
<td>8</td>
<td>286.09</td>
<td>277.57</td>
</tr>
<tr>
<td>Propeller</td>
<td>693.68</td>
<td>651.31</td>
</tr>
</tbody>
</table>
Figure 18. Forward flight: sectional normal force for the lifting rotors with the SA-neg model.

Figure 19. Forward flight: sectional normal force for the lifting rotors with the SA-neg-R model.

Figure 20 shows top view of the Q-criterion isosurfaces (at value of 0.0005) colored by vorticity magnitude in the low-speed forward-flight condition. The tip vortices from the lifting rotors are swept away and the wake structures around lifting rotor disks look almost the same between the figures corresponding to the SA-neg and SA-neg-R models. The SA-neg-R simulation better resolves secondary vortices at the back of the wake region, but this higher resolution has little effect on prediction of lifting-rotor performance. However, a better resolution of secondary vortices and wake interactions provided by the SA-neg-R model leads to a lower-torque predictions for the pusher propeller. Figures 21 and 22 show the Q-criterion contours at constant-y planes through the centers of the inboard and outboard rotors. Compared with hover flight, the effects of the SA-neg-R model on rotor wake resolution are less significant in forward flight.
Figure 20. Top view: vortex contours of lift+cruise aircraft in forward flight.

Figure 21. Forward flight: Q-criterion contours at plane $y = -8.13$. 
C. Computational Cost

All simulations in the current work have been performed at the NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center. The computations have been conducted in parallel using either 2,800 Pleiades Broadwell processing cores or 2,880 Pleiades Haswell processing cores. The nominal wall-clock time is about 22~24 hours for one revolution, including two loose-coupling cycles between FUN3D and CAMRADII.

VI. Concluding Remarks

High-fidelity multidisciplinary simulations were performed for the NASA lift+cruise vertical takeoff and landing urban air mobility concept aircraft in hover-flight and low-speed forward-flight conditions. The lift+cruise configuration includes eight lifting rotors mounted on the vehicle wings and a pusher propeller at the back of the fuselage. The coupled discipline-analysis tools include a computational fluid dynamics (CFD) solver, FUN3D, and a rotorcraft comprehensive analysis code, CAMRADII. This work extended previously demonstrated high-fidelity multidisciplinary analysis capabilities to complex configurations that include a full rigid fuselage and multiple flexible rotors of different radii and different rotation directions and speed. FUN3D solutions were computed on a composite unstructured-grid system that uses scalable grid assembler, Yoga. Two best-practice unstructured grids were generated to study the lift+cruise concept aircraft in hover and forward flight conditions. Two Reynolds-averaged Navier-Stokes models are used in the studies; both are based on the negative variant of the Spalart-Allmaras (SA-neg) turbulence model. The first model is the baseline SA-neg model. The other model is the SA-neg-R turbulence model that incorporates a simple rotation correction to control generation of turbulent eddy viscosity within vortex core. Both models are described at the NASA turbulence modeling resource website.

The rotation correction in the SA-neg-R turbulence model significantly improves resolution of secondary vortices and wake interactions. This improved resolution has a strong effect on rotor torque and a lesser effect on thrust. In hover flight, the lifting rotors are operational and the propeller is stationary. The lifting-rotor thrust values computed with the SA-neg and SA-neg-R models are close to each other. The torque prediction with the SA-neg-R turbulence model are lower than the predictions obtained with the SA-neg model. In low-speed forward flight, the lifting rotors and the propeller are operational. The lifting rotors experience edgewise downstream flow; the propeller experiences an axial flow. The rotation correction has a small effect on the lifting-rotor performance in forward flight because the rotor wake is swept away. For the propeller, rotation correction does not affect thrust and lowers the torque.
The following developments are envisioned for the future work. Current high-fidelity simulations use collective-pitch control in CAMRADII. Future simulations will be conducted with rotation-speed control that is more commonly used for practical UAV aircraft. The fuselage-wing body forces and moments are needed in the trim procedure. In current simulations, they are roughly estimated by CAMRADII based on forward-flight speed. In future simulations, the CAMRADII estimates will be replaced with high-fidelity CFD data. More revolutions will be performed to improve convergence of axial-flow wake for hover and forward flight. Finer grids with larger clustering regions will be generated and used for grid convergence studies.

Acknowledgments
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References


[43] https://www.pointwise.com