# A Comparison of High-Fidelity Simulation Approaches for eVTOL Rotor Flows in Descent Conditions

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## ABSTRACT

There is a significant interest in operating electric vertical take-off and landing (eVTOL) vehicles in complex urban environments, and thus, there is a need to understand how eVTOL rotors perform at steep descent rates. In descent, a complex flow state can arise near the rotor which requires a thorough analysis. This work employs high-fidelity numerical simulations. Specifically, two approaches are considered: blade-resolved DDES (i.e., BR-DDES), and actuator line model/ALM-based LES (i.e., ALM-LES). The goal of this paper is to compare results from these two approaches at various descent conditions. Three descent regimes/cases of high-speed (windmill brake state), low-speed (vortex ring state), and very low-speed are studied. Overall, both approaches show a good agreement for all three cases, however, some differences are also observed between the two approaches, e.g., mean thrust is found to be different by up to 13%.

## **INTRODUCTION**

Electric vertical take-off and landing (eVTOL) aircraft are an attractive option for urban air mobility (UAM). In order to reliably design such vehicles, complex interactional aerodynamics must be studied using experiments and high-fidelity simulations for different flight conditions. One such flight condition involves descent with very low forward speed. During this condition, the dominant vortical structures are susceptible to perturbations and reside in the near-wake region rather than in the far wake, causing significant oscillations in rotor forces due to highly unsteady flow that develops near the rotor (Ref. 1).

In lack of physical experiments, such complex and unsteady aerodynamics can be investigated using high-fidelity simulations. Specifically with delayed detached eddy simulation (DDES) or large eddy simulation (LES) to accurately capture the highly turbulent vortical flow generated around the rotor and in the wake. However, such high-fidelity simulations are computationally expensive when the blade geometry is fully resolved (i.e., with a body-fitted mesh). To reduce the computational cost, actuator models have been developed and used. In an actuator model, the rotor blades are not explicitly represented in the computation and instead modeled based on body force or momentum source terms. These include actuator disc model (ADM), actuator line model (ALM), or actuator surface model (ASM) (Ref. 2). The forces in an actuator model are calculated using the blade element theory, which utilizes sectional airfoil data along with the induced velocity obtained from lower-order methods like momentum theory (i.e., oneway coupling) or the local flow velocity computed in the simulation (i.e., two-way coupling) (Ref. 3). The use of actuator models significantly reduces the computational cost (since a blade-resolved mesh is not needed) and, at the same time, accurately captures the primary flow features (Ref. 4).

The two high-fidelity approaches of particular interest are blade-resolved DDES, referred to as BR-DDES, and ALM-based LES or ALM-LES in short. Other options such as ADM/ALM-based Reynolds-averaged Navier-Stokes (RANS) in steady or unsteady forms are computationally attractive but lack in accurately predicting vortical structures and dynamics. On the other hand, the computational cost of BR-LES is very high and often prohibitive, and thus ALM-LES is an attractive option. Note that ALM-DDES is equivalent to ALM-LES when the geometry is not resolved in the mesh. BR-DDES approach is extensively used in current research studies (e.g., see Refs. 5-8) due to its capability to capture both the boundary layer flow over the blades and detailed wake structures/dynamics. However, it is not clear how well a DDES approach will perform when the rotor interacts with its turbulent wake under descent conditions due to the use of the RANS model in the vicinity of the blades. On the other hand, actuator models have shown promising prospects in the rotorcraft community (Refs. 9-11). Still it is not clear how well actuator models will perform under descent conditions because of three-dimensional effects and a large induced velocity/flow at the rotor plane.

The vortex ring state (VRS) is considered to be one of the most complicated flight regimes for rotorcraft from an aerodynamic perspective. VRS is typically characterized by a toroidal vortex ring around the rotor. This can lead to reingestion of the wake flow and is associated with

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dramatically reduced rotor performance (Ref. 12). Because the wake builds up and remains near the rotor plane in VRS, low fidelity methods such as momentum theory do not work well. As a result, experiments and high-fidelity simulations are necessary to accurately determine the rotor performance in VRS. Experimental data relating to rotors in VRS is also limited, making it challenging to compare with the computational results. In Ref. 13, experimental data was used to develop an empirical model as an extension of momentum theory. However, this model does not account for rotor parameters such as collective pitch and blade twist, which are important because they affect the conditions under which VRS exists. In order to address these shortcomings, Chen et al. (Ref. 14) developed an inflow model for VRS that goes more in-depth than a parametric extension of momentum theory. The boundaries of VRS are difficult to define and are strongly dependent on the parameters of the given rotor. Chen et al. (Ref. 15) also developed a method to predict the boundaries of VRS for a given rotor and its flight conditions, emphasizing the sensitivity of the boundaries for VRS.

Betzina (Ref. 16) investigated a tiltrotor setup experimentally in a wind tunnel, using a flat plane to simulate the effects of a second rotor. They found that this setup has similar effects as an isolated rotor in VRS. Taghizad et al. (Ref. 17) conducted flight tests to understand the mechanics of VRS better and verify their theoretical models, focusing primarily on dynamic flight maneuvers. Taghizad found that changing collective, once in VRS, does not amplify the effects but also does not allow the aircraft to leave this state. Stack et al. (Ref. 18) conducted experiments in a water tank on an isolated rotor in descent under VRS conditions. The experiment focused on observing the flow phenomena associated with VRS as well as the thrust history. They observed the toroidal shape associated with the vortex ring as well as the "leapfrogging" phenomena where tip vortices jump each other and merge between vortex rings. Besides, they found that at low and high descent rates, the thrust time history remained relatively stable, but at moderate descent speeds associated with VRS, significant fluctuations in thrust were observed. Hoinville et al. (Ref. 19) also observed, using numerical simulations in the VRS regime, stable thrust time histories at a low descent speed and large fluctuations at moderate descent speeds. They also observed a decrease in mean thrust after entering VRS. Leishman et al. (Ref. 20) investigated in detail the wake of a rotor in descent using a free-vortex filament method. They noted several phenomena associated with the vortex ring in the wake, such as formation of bow-ties where the wake twists over itself. Another primary flow behavior reported was the formation of the vortex ring, its deformation, bursting, and spreading out radially. This cycle was found to repeat indefinitely as further revolutions were computed. Such a cycle repeats at a subharmonic frequency of the rotational frequency of the rotor.

#### Aim and outline of the study



Figure 1: Relation between induced velocity and descent velocity based on momentum theory (Ref. 12) in addition to the descent rates tested

In this study, the overall goal is to employ both BR-DDES and ALM-LES high-fidelity approaches to evaluate their performance. This paper considers three descent cases:  $V_c/v_h = -2$ , -1, and -0.5, as marked in Fig. 1. ALM-LES and BR-DDES are performed for all three cases. The first case involves relatively simpler aerodynamics than the other two cases and is used to validate ALM-LES against BR-DDES. This validation then paves the way for the other two cases, which have more complex and interactional aerodynamics. The utility of high-fidelity simulations is for those descent conditions, where the momentum theory is not applicable. Using the control volume analysis of a rotor in descent, see Fig. 2, momentum theory analysis yields:



Figure 2: Control volume for momentum theory analysis of a rotor in descent (Ref. 12)

$$\frac{v_i}{v_h} = -\left(\frac{V_c}{2v_h}\right) - \sqrt{\left(\frac{V_c}{2v_h}\right)^2 - 1} \tag{1}$$

where  $v_i$  is the induced velocity,  $V_c$  is the descent velocity, and  $v_h$  is the induced velocity in hover. Eq. 1 is only valid for descent when  $V_c/v_h \le -2$ . Hence, as shown in Fig. 1, momentum theory cannot be used for the descent velocity range of  $-2 < V_c/v_h < 0$ , which is where vortex ring state exists. Previous studies on descent rotor flights have used the ADM approach (Ref. 21). However, this work focuses on the ALM approach due to its attractive computational cost, ease of implementation, and capability to accurately capture the transient flow features of relevance. The latter is crucial to predict the aerodynamic performance of a rotor in descent accurately. Note that the ADM approach is even more attractive from a computational viewpoint (Ref. 11); however, it does not capture the unsteadiness in the rotor wake. To the best of authors' knowledge, this is the first study in which an actuator line model with LES has been applied to descent under VRS.

## NUMERICAL METHODOLOGY

The numerical flow simulations presented in this study are conducted using parallel stabilized finite element-based flow solvers for both BR-DDES (AcuSolve) (Ref. 8) and ALM-LES (PHASTA) (Ref. 22). For this study, an isolated three-bladed rotor was chosen, which is representative of an eV-TOL rotor (Ref. 8). The blades are highly twisted with rectangular planform. More details about the rotor properties can be found in Tab. 1. The inflow condition is a uniform axial velocity equal to the descent speed ( $V_c$ ), which varies for different cases as highlighted in Tab. 2. The subsequent subsections describe each of these methods as well as their numerical setup in detail.

Parameter	Specification
No. of blades	3
Diameter	1.6764 m or 5.5 ft
Solidity	0.076
Root cutout	0.2R
Airfoil	NACA 23012
Twist	-10°
Taper	Rectangular planform
Disk loading	239.49 N/m <sup>2</sup> or 5 lb/ft <sup>2</sup>
Chord	0.0834 m or 3.28 in
RPM	167.551608 rad/s or 1600 RPM

Table 1: Rotor properties

Case	Descent ratio	<i>V<sub>c</sub></i> [m/s]	<i>v<sub>i</sub></i> [m/s]	$\theta_0$ (degree)
1	$V_c/V_h = -2.0$	-19.77	9.89	6.50°
2	$V_c/V_h = -1.0$	-9.89	19.45	17.59°
3	$V_c/V_h = -0.5$	-4.94	15.26	18.11°

Table 2: Parameters for three descent cases

#### Numerical setup: ALM-LES approach

For this study, the ALM is implemented in the LES framework based on the incompressible Navier–Stokes version of the solver. It uses the residual-based variational multiscale (RBVMS) model (Ref. 23). Each rotor blade is modeled as an actuator line. The loads over actuator lines are applied as volumetric source terms in simulation over a relatively small region defined around the actuator lines at any given instance. The actuator forces, namely the normal and tangential forces, are obtained from blade element theory (BET) using the local induced velocity as follows (where *z* coordinate is normal to the rotor plane while *x* and *y* coordinates are in the rotor plane):

$$V_{ax} = V_z \& V_t = \sqrt{V_x^2 + V_y^2} + \Omega R$$

$$V_{rel} = \sqrt{V_{ax}^2 + V_t^2} \& \phi = tan^{-1}(V_{ax}/V_t)$$

$$\alpha = \theta - \phi$$

$$\implies C_l(\alpha) \& C_d(\alpha) \text{ (sectional airfoil data)} \qquad (2)$$

$$F_l = \frac{1}{2}\rho V_{rel}^2 C_l c \& F_d = \frac{1}{2}\rho V_{rel}^2 C_d c$$

$$F_n = F_l cos(\phi) - F_d sin(\phi) \& F_t = F_l sin(\phi) + F_d cos(\phi)$$

From above set of equations, attention needs to be p aid particularly to the axial velocity ( $V_{ax}$ ). For initial set of loads to be applied in the simulation, the blade element momentum theory (BEMT) is used to calculate the induced velocity using Eq. (1), given  $V_c/v_h \le -2$ . If  $-2 < V_c/v_h < 0$ , then the Eq. (3) is used (Ref. 12).

$$\frac{v_i}{v_h} = \kappa + k_1 \left(\frac{V_c}{v_h}\right) + k_2 \left(\frac{V_c}{v_h}\right)^2 + k_3 \left(\frac{V_c}{v_h}\right)^3 + k_4 \left(\frac{V_c}{v_h}\right)^4$$
(3)  
where,  $\kappa = 1.15$ ,  $k_1 = -1.125$ ,  $k_2 = -1.372$ ,  
 $k_3 = -1.718$ ,  $k_4 = -0.655$ 

Subsequently, using the obtained induced velocity, axial velocity is calculated as follows:

$$V_{ax} = -|V_c| + v_i \tag{4}$$

Once the velocities are determined, a root pitch is assumed. Using relations in Eq. 2, the angle-of-attack ( $\alpha$ ) is calculated, and airfoil lookup tables are used to obtain the corresponding  $C_l(\alpha)$  and  $C_d(\alpha)$ . These are used to calculate normal ( $F_n$ ) and tangential ( $F_t$ ) components of the sectional force. This process is repeated until the forces obtained from ALM achieve thrust value (at hover) that is equivalent to disk loading shown in Tab. 1. Then the simulation uses these initial BEMT forces for a certain number of revolutions until the initial transients are passed, until five revolutions in this case. After this, the new set of forces are calculated using the local axial and tangential velocities based on the computed flow field at every time step.

It is important to note that the forces obtained from the above equations are sectional forces. For these forces to be applied as volumetric source terms in the simulation, a region is defined around the actuator lines at any given instance. The width of this region is typically chosen to be on the order of blade chord (c). Specifically, the normal and tangential forces are smeared over a width of,  $2\gamma$ , in both the azimuthal ( $\theta$ ) and axial (z) directions. This width is kept fixed along the entire span of the blade. In summary,  $F_n$  and  $F_t$  are used to form BET-based sectional force vector  $\mathbf{f_{1D}}^{BET}(r)$  and in-turn to compute the volumetric source term  $\mathbf{f_{3D}}^{CFD}$  (i.e., force per unit volume) as follows:

$$\mathbf{f_{3D}}^{CFD} = \mathbf{f_{1D}}^{BET}(r)\delta(z)\delta(\theta)$$

where the following cubic spline distribution kernel (for  $|z| \le \gamma$ ) with a unit area is used:

$$t_0 = \frac{z + \gamma}{\gamma}; \quad \delta(z) = \frac{1}{\gamma} \Big[ -2t_0^3 + 3t_0^2 \Big]; \quad z < 0$$
  
$$t_0 = \frac{z}{\gamma}; \quad \delta(z) = \frac{1}{\gamma} \Big[ 2t_0^3 - 3t_0^2 + 1 \Big]; \quad z \ge 0$$

A similar kernel is used in the azimuthal direction. For ALM-LES, the computational domain has a size of 20D x 20D x 30D in x,y, and z-direction, respectively, with the dimensions spanning from -10D to +20D in the axial/descent/z direction and -10D to +10D in the other two directions with the location of the rotor being the reference point or origin. With regards to boundary conditions, at the inlet, velocity is prescribed based on the descent speed ( $V_c$ ) of each case. A no penetration condition is set at the four side surfaces along with a traction-free condition. The outlet is prescribed as zero natural pressure condition. Regarding the mesh, the rotor region has an extruded mesh with a mesh size of c/4 in the x-z plane and c/8 in the z-direction. The mesh refinement zones in the wake are shown in Fig. 3.

Method	Total	Rotor region
ALM-LES	5.06 million	0.26 million
BR-DDES	27.4 million	20.9 million

Table 3: Mesh count (number of elements)

#### Numerical setup: BR-DDES approach

In order to generate blade-resolved CFD simulations, the commercial Navier Stokes solver AcuSolve was used. AcuSolve uses a stabilized second-order upwind finite element method, which has been validated for external aerodynamic flows (Refs. 24, 25). For rotorcraft-specific applications, AcuSolve simulations have been shown to compare well against experimental results for the SUI Endurance rotor (Ref. 26). The AcuSolve simulations were run with the Spalart-Allmaras (SA) DDES turbulence model. The computational domain contains both a rotating and nonrotating volume joined together via a sliding mesh interface. The nonrotating volume consists of a box that extends at least 25 rotor radii in all directions from the rotor, with far-field boundary conditions on all

sides. This domain size is such that the boundaries are sufficiently far away to have little effect on the rotor. The rotating volume is a cylinder with a radius of 1.06 rotor-radii and a height of 4 tip chords centered about the rotor hub. Both volumes are discretized using unstructured meshes.

On the blades, the surface mesh allows for 200 elements around the airfoil contour, and a boundary layer mesh is grown normal to the blade with the first element set to ensure a height in wall units to be below 1, i.e.,  $h_n^+ < 1$ . This boundary layer mesh extends until the last element is within 80% of the local off-body element size with at least 25 layers. A mesh refinement zone off the body is defined for the wake of the rotor and closely matches that used for the ALM-LES method as seen in Fig. 3. For blade resolved simulations, the quarter chord zone is made slightly wider and taller than with ALM-LES in order to maintain similar element sizes across the sliding mesh interface. The resulting size of the mesh is recorded in Tab. 3. These blade-resolved mesh parameters have been used in previous studies (Refs. 7, 8), which also use AcuSolve, and have been shown to provide good spatial convergence. ALM-LES mesh consists about 5.5 times less elements as compared to BR-DDES mesh.

Each case is initially run using timesteps corresponding to  $10^{\circ}$  of blade rotation for at least 20 revolutions in order to reduce the cost of developing the initial wake. The  $10^{\circ}$  time steps are possible without numerical divergence due to the stability given by the RBVMS model and generalized- $\alpha$  implicit time integration method used by AcuSolve. The latter method suppresses high-frequency disturbances and allows for solution stability with large time steps (Ref. 27). When the wake is sufficiently developed, the time steps are decreased to  $2^{\circ}$  of a rotation per time step. This allows for an increase in the temporal accuracy.

### Summary of different simulations

Both approaches, ALM-LES and BR-DDES, utilizes the second-order implicit time integration scheme of the generalized- $\alpha$  method (Ref. 27). In this study, various time steps are chosen to compare results for different descent cases. BR-DDES uses 1° or 2° rotation as fine time step and referred to as BR-DDES-FTS, and 10° rotation as the coarse time step which is referred to as BR-DDES-CTS. ALM-LES (only) uses fine time step of 2° and referred to as ALM-LES-FTS. From here on, these terminologies will be used to refer to these three simulations as tabulated in Tab. 4. All simulations performed in this paper utilize the high-performance computing system thart is part of the Rensselaer's Center for Computational Innovation (CCI) with AMD EPYC processors.

## **RESULTS AND DISCUSSION**

The results in this paper are arranged as follows: First, the high-speed descent case of  $V_c/V_h = -2.0$ , where the rotors are in windmill brake state (WBS), will be discussed. This case serves as a good test case because the aerodynamics of



(a) BR-DDES

(b) ALM-LES

Figure 3: Cross sectional slice of mesh for BR-DDES and ALM-LES

Simulation	Time step size
BR-DDES-CTS	10°
BR-DDES-FTS	$1^{\circ} \text{ or } 2^{\circ}$
ALM-LES-FTS	2°

## Table 4: Time step size

WBS closely mimics that of a wind turbine, and the ALM-LES method has been extensively utilized to study windturbine flows (Ref. 28) including the current ALM-LES code (Ref. 22). The more complex descent case of  $V_c/V_h = -1.0$ follows, which falls under a fully developed vortex ring state (VRS) with complicated flow physics near the rotor. Last, the low-speed descent speed of  $V_c/V_h = -0.5$  is discussed, which lies near the boundary of the VRS regime with wake convecting away from the rotor.

## **Case 1:** $V_c/V_h = -2.0$

For this case, three simulations including BR-DDES-CTS, BR-DDES-FTS, and ALM-LES-FTS, were carried out for 90 revolutions. The thrust from each case was averaged over the last ten revolutions, and results are tabulated in Tab. 5. The mean thrust value from all three simulations agrees well with one another. Surprisingly, mean thrust obtained between BR-DDES-CTS and BR-DDES-FTS are very close to each other, even though the former has a significantly coarser time step. A close agreement is expected in this case because the flow structures and interactions are not complicated (at least near the rotor). The ALM-LES-FTS and BR-DDES-FTS show a close prediction in terms of mean thrust, with a difference of 1.57% relative to the BR-DDES-FTS. In this case, root-mean square (RMS) of thrust is negligible.

A snapshot of the wake structure above the rotor from each of the three simulations is shown in Fig. 4. The white box indicates the rotor disk region. All three simulations capture a similar wake structure with regions of velocity deficit. In the near wake, a uniform flow is similarly predicted by

Simulation	Mean thrust (N)
BR-DDES-CTS	470.8323
BR-DDES-FTS	466.2745
ALM-LES-FTS	458.9414

Table 5: Thrust for Case 1 with  $V_c/V_h = -2.0$ 

three simulations. The vectors show that all simulations predict the wake expansion at the rotor and at a similar location. The wake width measured at the 1R location above the rotor shows a difference of 1.3% with ALM-LES-FTS and 2.2% with BR-DDES-CTS, relative to BR-DDES-FTS. The difference in BR-DDES-CTS is due to the coarse time step and therefore it slightly overpredicts the expansion. This trend switches at the 2R location with a relative difference (to BR-DDES-FTS) of 1.2% and 0.5% with ALM-LES-FTS and BR-DDES-CTS, respectively. The slightly higher difference of ALM-LES-FTS than BR-DDES-CTS in this far wake region can be attributed to the turbulence seen at this location.

The difference in the prediction of turbulence is confirmed by Fig. 5 which shows the regions of high vorticity seen in the far wake. The ALM-LES-FTS shows the more pronounced turbulence as evident from Fig. 5c compared to BR-DDES-CTS (Fig. 5a), relative to BR-DDES-FTS (Fig. 5b). Further Fig. 5 also shows the evidence of helical tip vortices using the Q-criterion iso-surface colored in red. Again, all three simulations predict the tip vortices fairly closely. Notable differences are seen in the root vortices, i.e., in BR-DDES-FTS root vortices transition and breakdown away from the rotor plane while in ALM-LES-FTS they are more spread out from the beginning (indicating they become turbulent earlier).

## **Case 2:** $V_c/V_h = -1.0$

This case falls under the deep vortex ring state (VRS), which is prone to significant variation in the thrust due to the presence of a strong vortex system in the vicinity of the rotor.

The temporal variation of thrust predicted by different simulations is shown in Fig. 6 over five revolutions, the selection of



Figure 4: Slice cutting through the rotor hub colored by velocity magnitude with velocity vectors at  $V_c/V_h = -2.0$ 



Figure 5: Slice cutting through the rotor hub colored by vorticity magnitude with red iso-surfaces of Q-criterion at  $V_c/V_h = -2.0$ .



Figure 6: Thrust for Case 2 with  $V_c/V_h = -1.0$ 

which was motivated by the presence of a slow frequency of about five revolutions. The thrust trend between ALM-LES-FTS (shown in red) and BR-DDES-FTS (shown in green) is reasonably close. However, the thrust obtained from BR-

Simulation	Mean thrust (N)	RMS (N)
BR-DDES-CTS	131.2579	13.5736
BR-DDES-FTS	192.5964	27.4374
ALM-LES-FTS	216.5457	22.0675

Table 6: Mean and RMS of thrust for Case 2 with  $V_c/V_h = -1.0$ 

DDES-CTS (shown in blue) has large differences. This mean and RMS of thrust over 5 revolutions are presented in Tab. 6. The mean thrust from ALM-LES-FTS and BR-DDES-FTS show a difference of 12.4%. In contrast, a difference of 31.5% is seen between BR-DDES-CTS and BR-DDES-FTS. Under VRS, a coarse time step is found to be incapable of resolving relevant flow features that are important to the prediction of thrust. Unlike the other descent speeds, the thrust history for  $V_c/V_h =$ -1.0 (Fig. 6) shows a large oscillatory behavior within a revolution, which is predicted by all three simulations. To make this more evident, Tab. 6 shows the RMS of thrust. In general, the RMS values are much higher at  $V_c/V_h = -1.0$  than at  $V_c/V_h = -2.0$  or  $V_c/V_h = -0.5$ . As seen with mean of thrust, a similar trend is observed in RMS of thrust values when comparing the three simulations. The RMS predicted by ALM-LES-FTS and BR-DDES-CTS relative to BR-DDES-FTS have a difference of 19.6% and 50.5%, respectively. The latter showing a significant difference means that the coarser time step is not able to capture the high frequency present in the flow. While the three simulations show some disagreement in thrust prediction under this flight condition, they do predict very similar characteristics. For example, in Fig. 6, all three simulations predict a predominantly 3/rev signal in thrust. However, only ALM-LES-FTS and BR-DDES-FTS capture the frequencies higher than 3/rev. The high-frequency content is important for studies involving fluid-structure interaction/FSI and aeroacoustics. A more rigorous frequency analysis will be performed in the future.

Despite some discrepancy in mean and RMS of thrust, each simulation does capture many key flow characteristics in VRS. Fig. 7 shows the velocity field around the rotor region at two time instances of T + 1 and T + 4 revolutions (see Fig. 6). The rotor disk is shown for reference using a white box. Coherently, the presence of a strong toroidal vortex around and near to the rotor is captured by all three simulations remarkably well. The size of the toroidal vortex is significantly large, and it has a dominant influence on the rotor plane region, as shown by the vectors in Fig. 7. This torroidal vortex exhibits unsteady movement axially and radially, which can be seen in Fig. 7 by comparing the two time instances for each simulation. For example, when comparing the two instances of BR-DDES-CTS (Figs. 7a and 7d), the right side of the vortex moves radially outwards and above the rotor. This movement causes more upwards flow through the rotor disk and thereby decreases the thrust. The two instances of BR-DDES-FTS (Figs. 7b and 7e) show similar behavior of the right side of the vortex, although it causes a marginal decrease in thrust due to a distorted vortex system. In contrast, Figs. 7c and 7f show the downward movement of the left side of the vortex. causing more downwash through the disk and thus marginal increase in thrust.

The flow and the vortex structure in BR-DDES-CTS look more uniform and coherent than the other two simulations. Comparatively, the BR-DDES-FTS and ALM-LES-FTS show more unsteadiness in the flow and a distorted vortex system due to the presence of turbulence. Fig. 8 shows the higher level of flow unsteadiness and complex phenomenon arising due to turbulence in the fine time step simulations. To better understand the movement of the toroidal vortex, the rotor plane is shown with the red line. The moving position of the vortex cores discussed in Fig. 7 can also be seen here. Comparing turbulence prediction, for any given time instance, the high vorticity contours below the rotor indicate higher turbulence in BR-DDES-FTS and ALM-LES-FTS than BR-DDES- CTS. The extent of turbulent region is larger in ALM-LES-FTS as compared to BR-DDES-FTS, see Figs. 8b and 8e, and Figs. 8c and 8f. A key point to note here is that the strength of vortices, shown by pure white color (highest vorticity contour), are predicted to be similar by all three simulations.

Further, Fig. 8 shows the presence of multiple (secondary) regions of relatively lower vorticity than the high vorticity region of the (primary) toroidal vortex. These secondary vorticity regions are related to so-called "halo" vortices (terminology adopted from Ref. 29). The three-dimensional nature of this complex vortex system is shown using Q-criterion iso-surfaces from the top view in Fig. 9. The side view of Q-criterion iso-surfaces in Fig. 10 shows that the halo vortices roll up around the primary toroidal vortex. These figures provide evidence of induced disturbance in the form of Kelvin waves, as mentioned in Ref. 20, which distorts the toroidal vortex both azimuthally and axially at specific locations. Though all three simulations capture the presence of halo vortices, BR-DDES-CTS captures them with a poor resolution. Notably, ALM-LES-FTS exhibits the existence of these vortex structures quite well. However, there is a difference between these secondary vortices indicated by ALM-LES-FTS and BR-DDES-FTS; the latter show more halo vortices of slightly higher strength in the exterior of the toroidal vortex.

Another critical inference drawn from Fig. 10 is the number of vortical structures present at the rotor plane (in the interior of the toroidal vortex). The blue color indicates that flow is moving in the negative z-direction (downwash on the rotor disk), which will reduce thrust. In any given instance of time, the BR-DDES-CTS shows fewer structures at the rotor plane than BR-DDES-FTS (Fig. 10b) and ALM-LES-FTS (Fig. 10c), hence lower thrust is predicted by this simulation (Tab. 6). This trend can also be seen between the two instances (Figs. 10a and 10d) of BR-DDES-CTS where the number of vortices decreases from instance of T + 1 to T + 4revolutions and this leads to decrease in thrust as seen in Fig. 6. This can be extended to BR-DDES-FTS (Figs. 10b and 10e) and ALM-LES-FTS (Figs. 10c and 10f) as well where such temporal variations are smaller but still exist.

**Case 3:**  $V_c/V_h = -0.5$ 

This case at  $V_c/V_h = -0.5$  falls at the boundary of VRS and is a very low-speed descent case closer to hover. In this case, the vortex ring tends to move away and below the rotor, with instabilities being caused far below the rotor.

Simulation	Mean thrust (N)	RMS (N)
BR-DDES-CTS	455.5786	3.2336
BR-DDES-FTS	469.4952	6.1465
ALM-LES-FTS	534.6188	7.4651

Table 7: Mean and RMS of thrust for Case 3 with  $V_c/V_h = -0.5$ 



Figure 7: Slice cutting through the rotor hub colored by velocity magnitude with velocity vectors at  $V_c/V_h = -1.0$  for two instances



Figure 8: Slice cutting through the rotor hub colored by vorticity magnitude at  $V_c/V_h = -1.0$  for two instances

The thrust history for this case is shown in Fig. 11. Unlike Case 2, the thrust here exhibits a more steady behavior, which is similarly predicted by all three simulations. Both BR-DDES-CTS and BR-DDES-FTS show close agreement with a difference of 3% in the mean thrust, tabulated in Tab. 7. In contrast, the ALM-LES-FTS shows an offset of thrust from the BR-DDES with a deviation of about 13% in the mean thrust relative to BR-DDES-FTS. A similar trend to Case 2 is seen for the thrust variation, with ALM-LES-FTS and BR-DDES-FTS showing high RMS compared to BR-DDES-CTS



Figure 9: Iso-surfaces of Q-criterion colored by vertical velocity as viewed from the top at  $V_c/V_h = -1.0$  for two instances

(Tab. 7). In this case, ALM-LES-FTS predicts the highest RMS and is remarkably close to BR-DDES-FTS. In comparison, BR-DDES-CTS shows an RMS of about half of that from BR-DDES-FTS.

Fig. 11 also shows the characteristic 3/rev superharmonics captured by all simulations. The ALM-LES-FTS reveals a number of higher harmonics with frequencies at 6/rev and above being predicted. The BR-DDES-FTS show some high-frequency content, but BR-DDES-CTS fails to predict any of such high frequencies. A more rigorous frequency analysis will be performed in the future.

Fig. 12 shows the wake structure predicted by the three simulations via slices of velocity magnitude. Unlike the other cases, the wake at  $V_c/V_h = -0.5$  is formed below the rotor, with three simulations capturing wake contraction. In the near wake region, the flow field reveals the manifestation of instability that causes wake breakdown. The wake breakdown between each of the three methods occurs at similar locations and leads to perturbations that continue to be convected downstream. Fig. 13 reveals these near-rotor phenomenon using vorticity magnitude. Again, all three simulations predict similar behavior of tip vortices being distinctly produced in the near wake and getting distorted by perturbations as they convect downstream. These adjacent distorted vortices

seem to bundle together far downstream below the rotor to form the toroidal vortex ring.

The evidence of significantly large vortical structure in Fig. 12 indicates the presence of this toroidal vortex ring in all three simulations. This is confirmed by the red Q-criterion iso-surface seen in Fig. 13. In BR-DDES-CTS, the entire vortex ring resides at a similar z location as shown in Fig. 12a. In contrast, a comparison with the other two simulations, BR-DDES-FTS and ALM-LES-FTS, does not show the same behavior. The former (Fig. 12b) having the right side of the toroidal vortex at a higher z location than the left side, and the latter (Fig. 12c) having the left side at a higher z location than the right side. The 3D nature of this toroidal vortex ring is remarkably close between BR-DDES-CTS (Fig. 13a) and BR-DDES-FTS (Fig. 13b). Even with a relatively coarser mesh, the ALM-LES-FTS (Fig. 13c) predicts the 3D toroidal vortex fairly well and similar to the other two simulations. Unlike Case 2, this toroidal vortex is positioned well below the rotor plane and has little to no effect on the rotor thrust (Ref. 20).



Figure 10: Iso-surfaces of Q-criterion colored by vertical velocity as viewed from the side at  $V_c/V_h = -1.0$  for two instances



Figure 11: Thrust for Case 3 with  $V_c/V_h = -0.5$ CONCLUSION

This study used two approaches for high-fidelity numerical simulations, namely BR-DDES and ALM-LES, to investigate eVTOL rotor flows in three descent conditions. For BR-DDES, both coarse and fine time steps were considered, while for ALM-LES only fine time step was used. ALM-LES mesh consisted about 5.5 times less elements as compared to BR-DDES mesh. A three bladed, 5.5 ft rotor was simulated at three descent speeds including high-speed (windmill brake state), low-speed (vortex ring state), and very low-speed corresponding to  $V_c/V_h = -2.0, -1.0$  and -0.5, respectively. Overall, both approaches showed a good agreement for all three cases. However, some differences were also observed be-

tween the two approaches, e.g., mean thrust was found to be different by up to 13%.



Figure 12: Slice cutting through the rotor hub colored by velocity magnitude with velocity vectors at  $V_c/V_h = -0.5$ 



Figure 13: Slice cutting through the rotor hub colored by vorticity magnitude with red iso-surfaces of Q-criterion at  $V_c/V_h = -0.5$ 

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