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Advances in Rotor Performance and Turbulent Wake Simulation using DES and Adaptive Mesh Refinement

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Abstract: Time-dependent Navier-Stokes simulations have been carried out for a rigid V22 rotor in hover. Emphasis is placed on understanding and characterizing the effects of high-order spatial accuracy, grid resolution, and the use of detached eddy simulation in predicting the rotor figure of merit (rotor efficiency) within experimental error for the first time. Moreover, a new adaptive mesh refinement procedure is demonstrated, and reveals a complex and more realistic turbulent rotor wake. Time-dependent flow visualization plays a crucial role in understanding the numerical and physical mechanisms involved in these complex viscous flow simulations.

Keywords: Higher-order methods, adaptive mesh refinement, detached eddy simulation, vortex dynamics.

1. Introduction

The accurate simulation of rotorcraft flow fields with computational fluid dynamics (CFD) continues to be a challenging problem. Unlike fixed-wing applications, a rotor blade can encounter its own tip vortex, and the tip vortices of other blades. This interaction can strongly affect the rotor-blade loads and performance, and generate high levels of noise. The situation is further complicated by flexible rotor blades, which require the coupling of fluids and structures solvers, and a trim algorithm for static flight conditions. Resolving the rotor vortices continues to be a basic challenge for CFD rotorcraft simulations.

For more than two decades, the accurate prediction of figure of merit (FM) has eluded CFD simulation of rotors in hover using the Navier-Stokes equations. The FM is a measure of the rotor blade efficiency, which typically differs from experiment by 2-6%, depending on the thrust coefficient (C_T). To bring this into perspective, each 0.5% of FM can be viewed as one passenger, where a helicopter typically carries 2-6 passengers. This shortcoming has been attributed to poor resolution of the rotor vortices. Typical grid resolution in the rotor wake is $\Delta S=10\%C_{tip}$ (blade tip chord), which is the approximate size of the physical vortex core. Uniform refinement in the wake region would be computationally prohibitive, resulting in billions of grid points. A better approach is needed. It will also be shown that the spatial accuracy and turbulence model also play a crucial role in accurately predicting FM.

This goal of this paper is to demonstrate a dramatic improvement in the prediction of FM using Overflow's new high-order spatial accuracy [1] and Spalart-Allmaras (SA) [2] detached eddy simulation (DES) for a three-bladed V22 Osprey rotor. Moreover, the use of a new adaptive mesh refinement (AMR) procedure [3] will reveal a complex and dynamically changing turbulent rotor wake.

2. Numerical Results

The Overflow code is used to simulate the V22 isolated rotor in hover over a range of collective (pitch) angles. These time-accurate Navier-Stokes simulations were carried out in an inertial overset structured grid system using 2^{nd}-order time accuracy. Body-fitted curvilinear grids attached to the rigid blades rotate through a fixed Cartesian grid system. The latter was used to resolve the vortex wake and extend the computational domain to the far field. Baseline computations were carried out on a wake grid with uniform grid spacing of $\Delta S=10\%C_{tip}$. Figure 1 shows a dramatic reduction in vortex diffusion when using 5^{th}-order accuracy rather than 3^{rd}-order accuracy. Moreover, the 5^{th}-order accurate FM (0.4% error) is greatly improved from the 3^{rd}-order value (6% error) for the high-thrust collective ($\theta=14^\circ$). The Cartesian wake-grid can also be seen in Fig. 1.

Overflow simulations were carried out with the SA turbulence model using 5^{th}-order spatial accuracy for a collective range of $6^\circ \leq \theta \leq 16^\circ$. FM variation with thrust coefficient is shown in Fig. 2. Notice the excellent agreement of the baseline Overflow FM with experiment for the high collectives, but the poor agreement at the lower collective angles. The FUN3D Reynolds-averaged Navier-Stokes (RANS) code results are also shown in Fig. 2. This unstructured code is 2^{nd}-order accurate in space and uses the SA turbulence model. Note the under-prediction of FM for the high collectives (due to the lower spatial accuracy). However, both codes significantly

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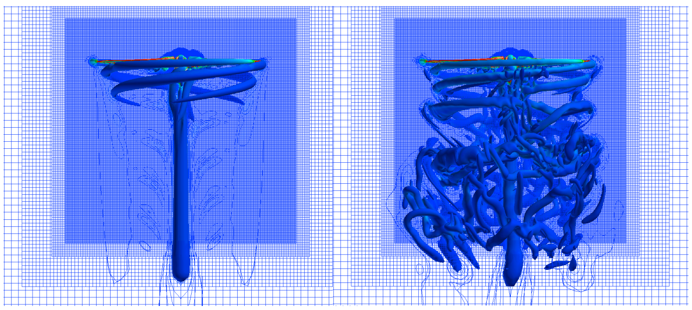
under-predict the FM for the lower collectives, regardless of spatial accuracy. The Helios code solves the RANS equations on the body grids using the SA turbulence model, but only solves the inviscid Euler equations in the rotor wake region. This is a common way to reduce the diffusion of the vortex wake. Helios uses 2nd-order spatial accuracy on the unstructured body grids and 5th-order spatial accuracy on the structured inviscid rotor wake grids. This ad-hoc approach improves the prediction of FM for the lower collectives, but generally under-predicts the FM for all collective angles. These results indicate that high-order spatial accuracy is not enough to accurately predict the FM for the entire collective range. This deficiency has been traced to an excessively large turbulent length scale in the SA RANS model. Using a DES length scale greatly improves the prediction of FM within experimental error for the first time, see the Overflow SA-DES FM in Fig. 2. The final paper will include a detailed description of these improvements, and precisely identify why the RANS FM fails at the lower collective angles.



a) 3rd-order accuracy b)5th-order accuracy

Figure 1 OVERFLOW simulation of the V22 rotor in hover, M_{tip}=0.625, θ=14°, Re=2.1 million.

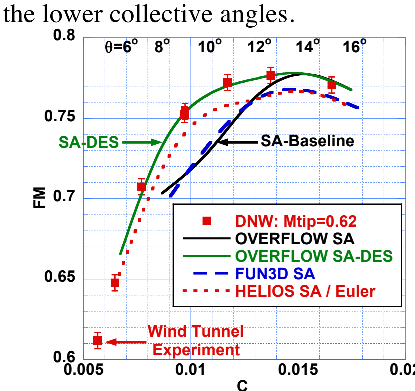


Figure 2 OVERFLOW simulation of the V22 rotor in hover, M_{tip}=0.625, Re=2.1 million.

The wake region was further resolved using a new dynamic AMR procedure, see Fig. 3. Refined Cartesian grids were added or removed in the vortex-wake region based on a vorticity sensor function. Two levels of refinement were used (each level differs by a factor of two), so that the wake region was resolved with Cartesian grids whose grid spacing was ΔS=10%C_{tip}, 5%C_{tip}, and 2.5%C_{tip}. This procedure produced a vortex wake rich in turbulent physics. The tip vortices were much stronger and had smaller core diameters than the baseline result. Moreover, Fig. 4 shows vortical worms (green color) were found to encircle the tip vortices through a process of entrainment of the wake shear layers and vortex stretching. Greater detail will be presented in the final paper, along with experimental evidence of these vortical worms.

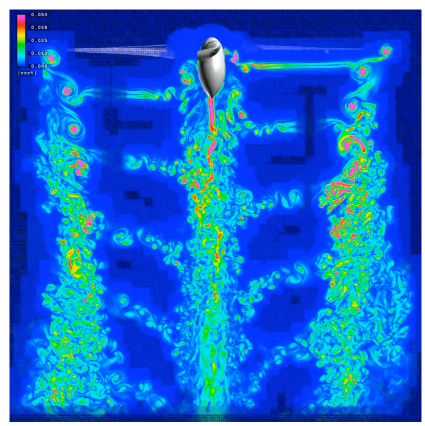


Figure 3 OVERFLOW AMR hover simulation, M_{tip}=0.625, Re=2.1 million.

3. Conclusion and Future Work

FM has been predicted within experimental error for the first time using high-order spatial accuracy and detached eddy simulation. A new AMR procedure was used to better resolve the turbulent wake. The final paper will include more results and a detailed description of the numerical and physical mechanisms. Moreover, it will show that the vortex core size is now in good agreement with experiment.

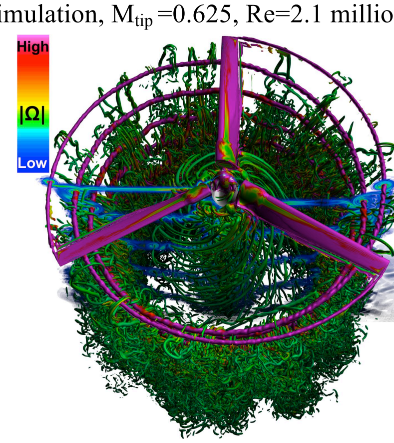


Figure 4 OVERFLOW AMR hover simulation, M_{tip}=0.625, Re=2.1 million.

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