Abstract submitted to the 11th International Conference on Computational Fluid Dynamics
To be held at Maui, HI, July 11-15, 2022

Quantitative Approach for the Accurate CFD Simulation of Hover in Turbulent Flow

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Abstract: Time-dependent Navier-Stokes simulations have been carried out for a V22 rotor in hover using an improved HLLE++ upwind algorithm. Emphasis is placed on understanding and characterizing lessons learned over the past decade regarding 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. A quick-start procedure is described that provides a statistical measure of convergence and reduces hover computations by 5x, similar in efficiency as forward flight. Moreover, adaptive mesh refinement in the rotor wake revealed a complex turbulent flow with LES structures found more than a decade ago. The existence of these turbulent worms has recently been verified experimentally by the DLR.

Keywords: Higher-order accuracy, detached eddy simulation, solution convergence, turbulent wake.

1. Introduction

Time-accurate simulation of rotorcraft flows with computational fluid dynamics (CFD) has played a critical role in the emerging field of electric vertical takeoff and landing (eVTOL) design, e.g., see Fig. 1. Arguably the most important hover performance parameter is the figure-of-merit (FM), defined by a relation using the thrust and torque coefficients ($FM = C_T^{3/2}/\sqrt{2}C_Q$). This parameter is very sensitive to prediction errors where a ½% error (~0.004) is equivalent to the weight of one passenger. Unlike forward flight, which has a freestream advection speed that enables solution convergence in about 5 rotor revolutions, hover is a self-induced low-speed flow that takes 25-30 revolutions from impulsive start to establish the third digit. Hover is much more computationally costly than forward flight, leading many engineers to rely on simulations run only 5-10 revolutions. Chaderjian and Buning [1] first reported the key elements needed to establish FM to three digits in turbulent flow using the OVERFLOW CFD code with central differencing. The purpose of this paper is to describe the progress made and best practices in predicting FM over the past decade, including an improved upwind algorithm and procedures not reported in the literature.

2. Numerical Results

The OVERFLOW CFD code is used to simulate the V22 rotor in hover by solving the time-dependent Navier-Stokes equations with an improved HLLE++ upwind algorithm [2], which was found to be much more robust than central differencing [3]. Body-fitted curvilinear grids attached to rigid blades rotate through a fixed Cartesian grid system like the forward flight case in Fig. 2. A small wake-box surrounds the rotor together with adaptive mesh refinement (AMR) to resolve the vortex wake. The traditional approach uses a large wake-box, see Figs. 3-4. A novel approach uses AMR in such a way so that interpolation errors are eliminated between similar Cartesian grids.

The first element for accurately predicting FM is to use higher-order spatial differencing, see Figs. 3-4, where FM_{exp}=0.779. The high-order differencing is needed only near blade surfaces and not in the rotor wake. However, it's still recommended to use high-order differencing in the wake to reduce vortex diffusion. The second key element is the turbulence model. Figure 5 shows CFD and experimental FM at various collectives (pitch angles). The OVERFLOW SA-RANS model [4] does poorly at the lower collectives. A detailed description of why this occurs will be given in the paper. The solution is to use the hybrid RANS/LES model, i.e., SA-DES. The result predicts the FM within experimental error. Other codes using low-order spatial accuracy and inviscid rotor wakes as add-hoc approaches are also included in the figure. The third key element is adequate solution convergence. Figure 6 demonstrates rapid convergence of the FM using a quick-start procedure. This procedure uses larger time steps and fewer subiterations to obtain a time-like evolution of the flow. Twenty-four revolutions are obtained with the computer work of 1 ½ time-accurate revolutions, thus efficiently establishing the flow. The solution is converged within 4 more time-accurate revolutions, providing a solution in about the same time required as forward flight. The running mean, see Fig. 6, is used to monitor convergence. One standard deviation provides a measure of how much of the data is contained within these bands. Figure 7 is a discreate probability distribution function of the flow showing similar properties as a Gaussian. The solution is considered converged when the running mean is bounded by a specified amount, e.g., ±½%FM for at least two rotor revolutions. This also justifies whether 2 or 3 digits are quantitatively significant. Finally, a highly refined vortex wake mesh reveals turbulent structures called worms, see Fig. 8. The DLR has recently confirmed the existence of worms experimentally, see Fig. 9, almost a decade after their discovery [1].

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3. Conclusion and Future Work

Details of the three key elements for accurately predicting hover FM will be provided in the final paper, along with the quick start procedure, a statistical justification of FM convergence and reporting accuracy, and a comparison of the central and upwind difference vortex core sizes. A detailed description of the physical mechanism responsible for the formation of turbulent worms will be presented, including turbulence model and grid resolution requirements, and the recent DLR experiment confirming their existence. Most of the solutions for the final paper are well underway and will be ready for the final paper.

Figure 1 Example of JOBY eVTOL.

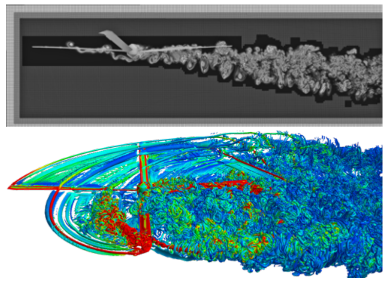

Figure 2 OVERFLOW UH-60A dynamic stall, central differencing.

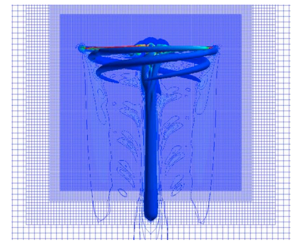

Figure 3 V22 rotor, SA-RANS, 3rd-order space, FM=0.733.

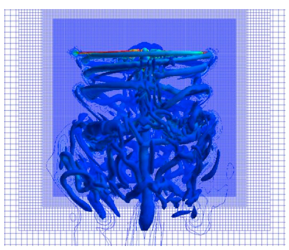

Figure 4 V22 rotor, SA-RANS, 5th-order space, FM=0.775.

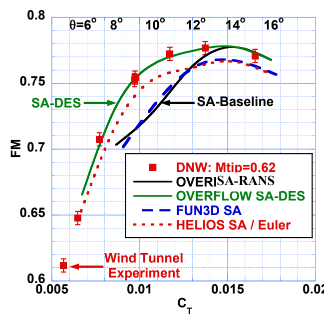

Figure 5 V22 rotor hover, M_{tip} =0.625, Re=2.1x10^6.

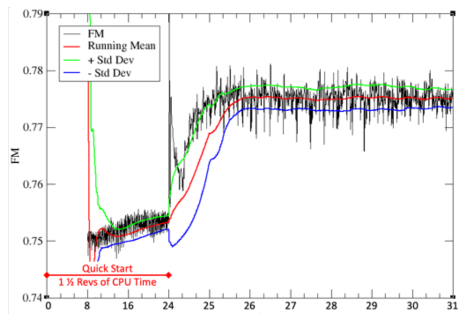

Figure 6 Convergence of FM, M_{tip} =0.625, θ=14°, Re=2.1x10^6.

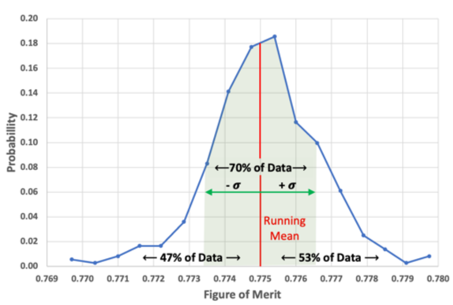

Figure 7 Probability distribution function of FM, M_{tip} =0.625, θ=14°, Re=2.1x10^6.

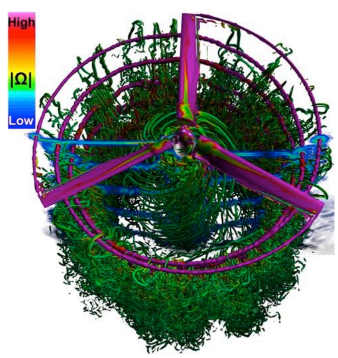

Figure 8 OVERFLOW AMR hover simulation, M_{tip} =0.625, Re=2.1x10^6.

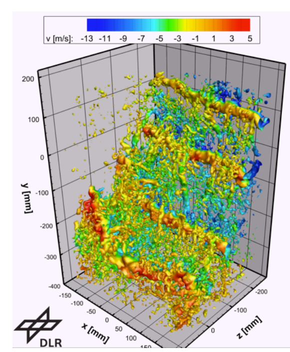

Figure 9 DLR tomo-PIV hover experiment.

References

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