Wake Breakdown in High-Fidelity CFD Simulations of Rotor-in-Hover: New Tools & Insights

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Abstract: Wake breakdown is a well-documented computational phenomenon associated with highly resolved computational hover predictions. As the computational state-of-the-art for hover predictions has progressed, allowing for higher resolution of the rotor wake, the formation of secondary braids in computed helical wake systems has manifested in various forms. The formation of 3D secondary braids between two parallel convecting vortex filaments, under the right conditions, is physical. Recent hi-definition rotor-hover experiments do confirm their presence. However, computed wake breakdown is more pervasive, and the question of whether high-fidelity methods exaggerate the extent of the secondary vortex production has been a topic of research in the past decade. In this paper, we survey the computational ingredients that make up a high-fidelity hover solver, highlight interesting recent developments, and try to summarize what we know (and what we do not know) about computed wake breakdown. Recent advances in direct volume rendering to visualize the vortical content of the helical wake and the insights they provide into the wake breakdown vortical interplay are also highlighted. Future directions for unsteady, high-fidelity hover simulation wake breakdown research are speculated to emphasize temporal fidelity/convergence.

Keywords: Vortex Dynamics, Hover vortex wake, Helical vortex system, 3D vortex breakdown, rotor hover

1. Introduction:

The helicopter is a versatile aircraft that covers a wide range of flight conditions ranging from level to vertical flight and conditions in between. The hover condition, in particular, plays a crucial role in helicopter design. However, it also represents one of the most difficult aerodynamic conditions to predict accurately. The self-induced flow field coupled with the closely interacting tip-vortex wake has, historically, complicated numerical simulation of hover. In the past, the issue was primarily an overly diffusive prediction where the under-resolved tip vortices would rapidly disappear as the wake age increased. As computational resources increased, more grid resolution was thrown at the problem, mitigating but not solving the issue. Current state-of-the-art hover [1] computing platforms such as OVERFLOW and HPCMP CREATE^{TM}-AV HELIOS use adaptive mesh refinement (AMR) and high-order numerical strategies to compute several revolutions of the rotor wake accurately. Figure 1 illustrates this technological shift. As the computational power and methodological capabilities became sufficient to capture a large proportion of the helical wake structure, a new problem emerged, especially for hover computations.

As the high-order/AMR solutions are computed for more time steps, secondary vortex structures began appearing when the pitch of the helical structure (distance between two successive helical vortex strands) became small enough relative to the vortex core size. The evolution of the secondary vortical structures is dramatically shown in Figure 2a-g for the computation of a 4-bladed UH-60A rotor in hover [2] as it progresses through multiple revolutions. At the computation's outset, instabilities are associated with the starting vortex (Figure 2a-b), but these are removed from the solution as the calculation progresses (Figure 2c). Once the starting vortex is shed off of the computational domain, a relatively clean wake exists briefly (Figure 2c), before secondary instability braids eventually return en masse (Figure 2d-h). The secondary vortex braid instabilities also appear in forward-flight cases [3] and maneuvering cases. However, since the overall vortex system is stabilized by an external flow (non-self-induced by the vortex system as in hover), the presence of secondary braids does not substantially affect the overall computation.

2. Instabilities & Dynamics of 3D Helical Vortex System:

A closer look at the secondary braids reveals their structure. Figure 3 focuses on the vorticity iso-surfaces around the braids bridging successive helical-vortex strands of the central wake. The alternating positive/negative braids hooking around the main helical strands transferring energy from large to small is a classic mixing mechanism in shear-layers. Figure 4 reproduces the picture of LES employing Smagorinski sub-scale model simulations from evolving spatial shear-layers [4]. A well-known phenomenon is the axial braids that bridge the primary spanwise oriented shear-layer roll-up structures.

Thus, given the physical/numerical foundations of what is being solved (i.e., helical vortex systems with small vortical pitch) the appearance of the instability braids between closely convecting vortical strands seems correct. However, the appearance of braids with strength/prevalence entirely overwhelming the stability of the main-helical-wake structure, as seen in most of the finely-resolved S-76 (or similar planforms such as the UH-60/TRAM) computations, is difficult to explain. Further examples of such wake breakdown in refined hover calculations [5][6] are shown in Figure 5.

Analytical work done in the early 70s on inviscid helical vortex instabilities by Widnall [7] remains to date the definitive word on the subject of helical vortex instabilities. Widnall had identified three modes of helical vortex instability, long-wave instability, mutual-inductance instability, and shortwave instability. More recently, Walther et al. [8] used vortex methods to simulate the different helical vortex instabilities identified by Widnall numerically. Walther's work uses a single-blade generated single-strand helical system, but the results are instructive as guidance for multi-strand helical systems. The kind of instability seen in S-76 (and similar) simulations is indicative of a combination of mutual-inductance and shortwave instabilities. Typically, these instabilities are known to grow if the ratio of the separation distance between successive helical vortex strands to the vortex core size becomes smaller than a specific cut-off value. The numerical computations may trigger these instabilities in the near-field for several reasons (i.e., computed core size is too large, other numerical errors, etc.). It was also interesting to observe that numerical hover solutions in earlier cylindrical/axially stretched grids (Figure 6) tend not to breakdown the near-blade helical system [9]. Once again, there could be several reasons: damped wake, grid stretching damping out instabilities, etc.

Recent experimental evidence shows that these structures exist in a rotor wake [10]. Figure 7 illustrates one result from this experiment. The "shake-the-box" technique, a time-resolved particle tracking method, captured secondary braids similar to what is seen in the numerical predictions. However, while these measurements have shown the existence of these secondary structures, the degree to which these structures should develop in a hovering rotor wake still needs further analysis. It is generally accepted that the development of vortex soup is incorrect, but the existence of wake breakdown in some form is considered a real phenomenon. It is hoped that advanced experimental techniques such as the shake-the-box method will help guide where this line lies.

3. Conclusions & Future Directions:

The current paper covers an overview of more recent wake breakdown research results, an in-depth analysis of the more significant collected results, and some new insights gained using more advanced visualization techniques (figure 8).

The full paper will address key questions such as:

1. When does the wake break down?
2. What is the dynamics of the 3D vortical breakdown?
3. Do solver, algorithmic and turbulence treatments affect breakdown?
4. Do gridding strategies affect wake breakdown?
5. Does geometric-treatment strategies such as root-cut out have any impact?
6. Do computational and convergence strategies have any impact?
7. What is the best method to visualize 3D dynamics of computed helical wake?
8. Does volume rendering provide better insights?
9. What are the engineering impacts of simulations that exhibit vortex breakdown?
10. Spatial-temporal convergence and its effect on breakdown.

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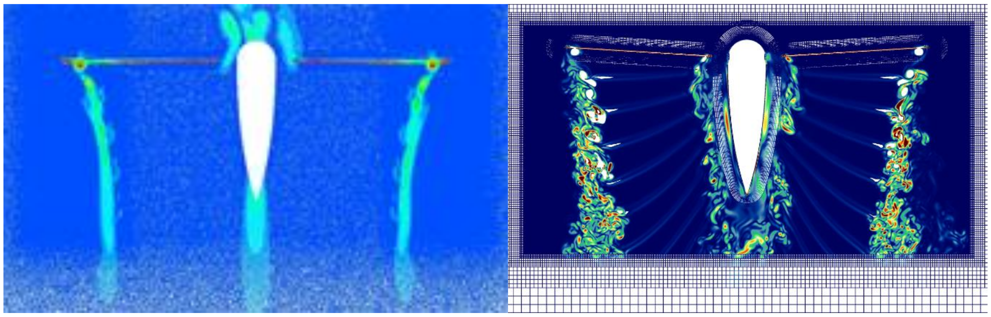

Fully-Unstructured Overset **Structured/Cartesian Overset**

Figure 1. Impact of fully-unstructured vs. higher-order structured computations.

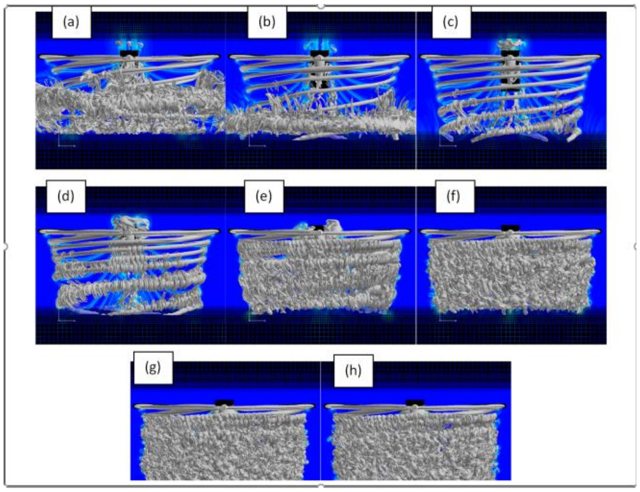

Figure 2. Early manifestations of computed wake instabilities in high-fidelity solutions, from 2011. Computed wake instabilities as the wake evolves for an UH60 blade using Euler off-body solutions, from Reference [2].

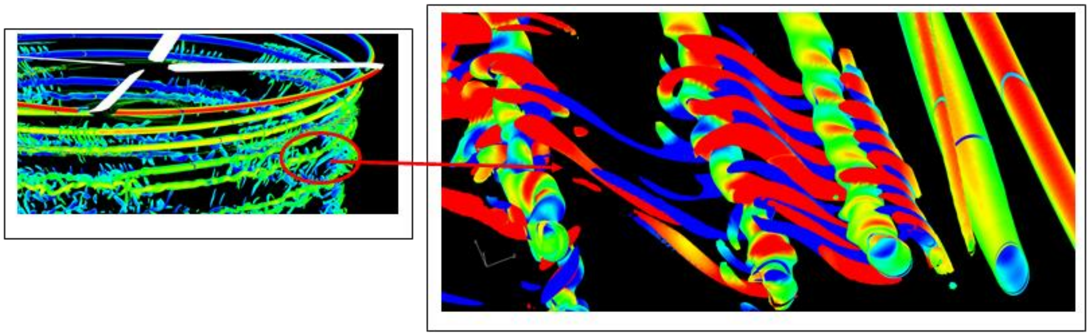

Figure 3. Directional iso-vorticity contours explaining the structure of the secondary vortex generation, similar to shear-layer streamwise hairpin vortex pair generation of alternating rotational orientation.

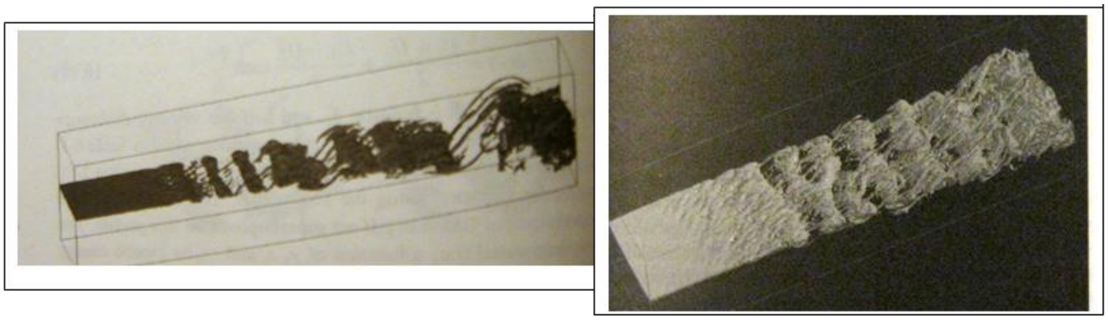

Figure 4. Large eddy simulation of jet shear layer capturing streamwise braids (from Comte et al. [4]).

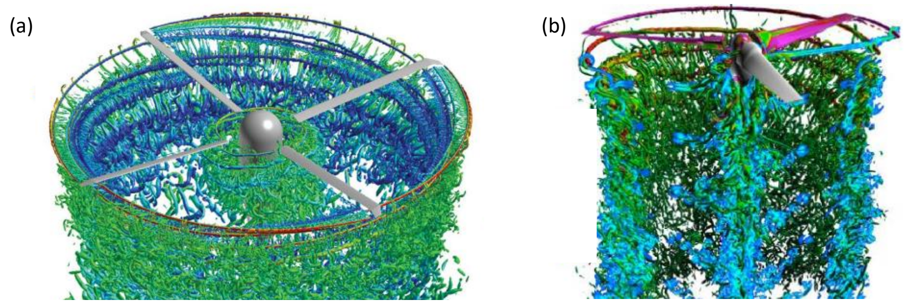

Figure 5. Highly-resolved wake hover simulations (a) 4-bladed S-76 HELIOS simulation with near-body OVERFLOW option (Jain [5]), (b) 3-bladed TRAM OVERFLOW simulation (Chaderjian [6]).

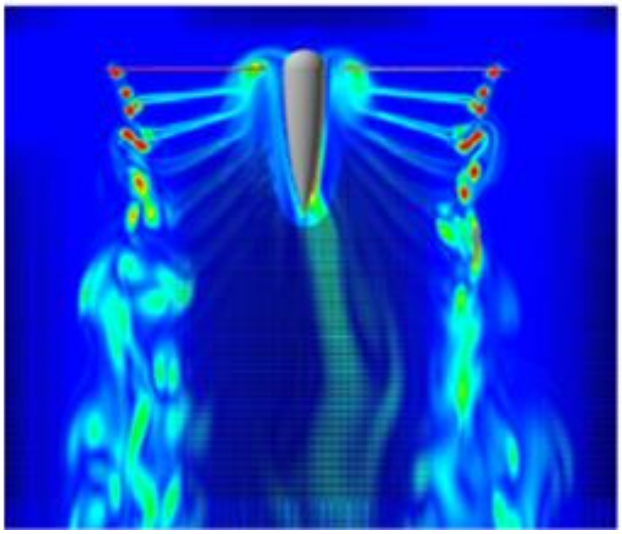

Figure 6. (a) Fig. 6 S-76 OVERFLOW simulation using cylindrical/axially stretched grids, from Narducci [9].

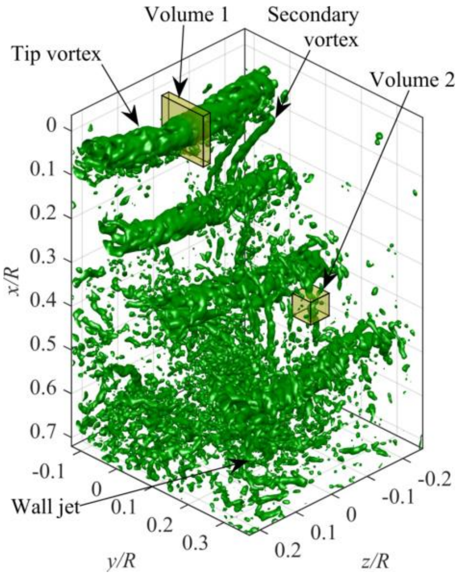

Figure 7. Experimental evidence of secondary vortex structures in a rotor wake, from Wolf et al [10].

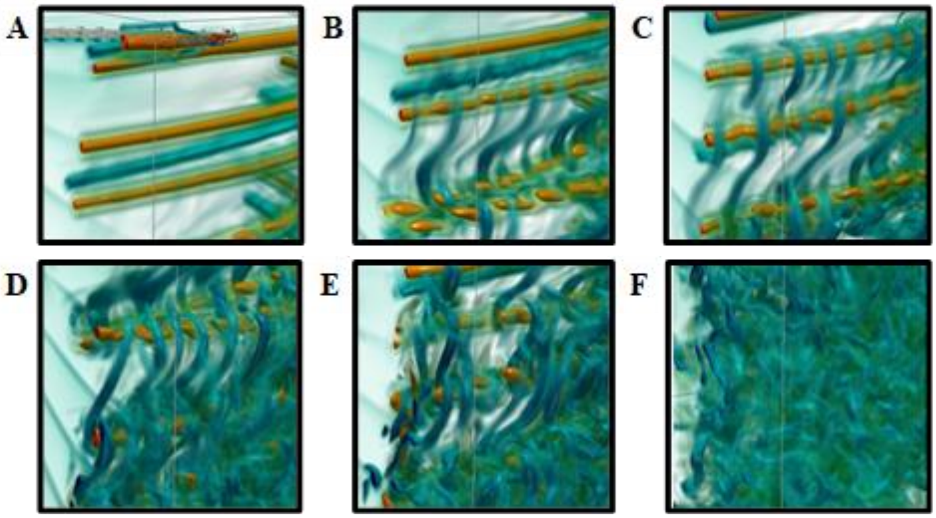

Figure 8. Direct Volume Rendering of computed wake vortex dynamics