CFD ANALYSIS OF HELICOPTER WAKES IN GROUND EFFECT

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Abstract

The paper presents CFD results for the wake of a helicopter flying a low altitude at different advance ratios. The wakes are assessed in terms of topology and velocity magnitudes. The structure of the wake near ground changes rapidly with the advance ratio and its decay appears to be faster than what is suggested by theoretical analyses. The results show clear the potential of modern CFD for use in helicopter safety and highlights the need for detailed surveys of helicopter wakes using full-scale physical experiments.

1. INTRODUCTION

Helicopter wakes are of very complex structure, composed by large coherent vortical structures, inside a flow of smaller turbulent scales [1]. In classic helicopter research works, the wakes are represented by vortical filaments that can be of prescribed shape or computed in a dynamic fashion. The filaments are carriers of vorticity and are used for computing an induced flow field superimposed to a stream of air or, near ground, to an atmospheric boundary layer. This approach is adequate for initial evaluations of helicopter performance, but it lacks fidelity when it comes to delivering data necessary for safety operations where one helicopter encounters the wake of another. Predicting the details of the helicopter wake with high fidelity is a considerable task. Not only the employed method must be able to delivery accurate data, and do so efficient for routine use, but it must also be flexible enough to account for the effects of the atmosphere, ground, presence of multiple rotors etc. Wakes are a feature of all flying machines, and there are clear separation criteria between fixed wing aircraft from the International Civil Aviation Organization (ICAO), while the situation for helicopters is different, and specific, helicopter separation criteria have not been established yet. For hover-taxi, there is an existing guidance from Civil Aviation Authority (CAA) [2], which suggests respecting a minimum distance of three rotor diameters. However more detailed guidelines are needed, considering the size and weight of the helicopters and even the specific nature of some near-ground operations.

2. CFD SOLVER

The CFD solver HMB3 of University of Glasgow [3,4] has been employed in this work as a high-fidelity method.

3. RESULTS AND DISCUSSION

Firstly, simple rotor wake test cases are used to show the level of agreement between numerical predictions and test data. It should be made clear that the vast majority of rotor wake surveys cover the near-rotor flow region extending one or two rotor diameters downstream of the centre of rotation. Such studies are performed inside wind tunnels and although the thrust settings of the rotors are usually of the correct scale, when presented as a rotor thrust coefficients, the Reynolds number of these flows tends to be very low. This is not an ideal situation since the decay rates of turbulent wakes depend on Reynold's number. There are of course additional complications with the use of the tunnels due to the constrains of test sections and their small size. This is not ideal since studies of wake encounters typically consider distances of the order of 50 to 70 times the rotor diameter (provided ICAO guidelines are followed). Figure 1 shows the size of the employed computational domain for some of the cases considered in this paper. The domain covers 10 rotor diameters in the lateral direction and some 35 diameters downstream.

Table 1 provides a summary of experimental works related to detailed helicopter wake surveys. Again, most of the listed works correspond to wind tunnel measurements. The most comprehensive work cited in the literature is by Köpp [5] who measured full-scale wake using LiDAR. His study covered different helicopter weights and speeds and the measured wake strength is the main source of data in the open literature. More recent works include the studies of JAXA [6] again using a full-scale helicopter. The work of JAXA captures the helicopter wake but there are no explicit data published in the open literature, to guide the extraction of wake decay rates.

Table 2 shows the most promising methods for the

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simulation of the far-wake region of the helicopter. The table divides the methods in low and higher fidelity groups and provides indications of the ability of the methods to predict the wake decay, account for the effect of the grounds, and even couple the method with other techniques or models such as flight simulation tools, or models of atmospheric turbulence.

Table 3 describes the rotors used to model the wake of an approximate EC145 aircraft put together to simulate the experiments of JAXA. In this work the rotors were modelled as actuator disks [7] to reduce the overall computational costs. In this work an aircraft flying at various speeds at 30 ft of altitude is simulated and for a main rotor thrust coefficient of 0.022. The results of Figure 2 show clearly the ability of the method to capture the change of the wake topology. At hover and low-speeds, a large ground vortex is visible. The flow is dominated by strong downwash and the wake of the rotor appears to be dominant for a radius covering 3 main rotor diameters before almost un-disturbed flow is reached. As the speed increases, the main ground vortex appears to be partially under the front of the main rotor disk while some 4 diameters around the aircraft appear to be influenced by its spatial development. The situation changes very rapidly as the speed reached 40kts with no ground vortex present ahead of the helicopter. Instead, a trailed wake is formed resembling that of a fixed wing aircraft. The wake is trailed behind the main rotor disk and reaches the ground at a distance of about 5 main rotor diameters behind the helicopter. It is interesting that at this speed the wake is mainly affecting the region immediately downstream of the helicopter and the extent of its influence in the lateral direction is significantly reduced reaching 1.5 rotor diameters only. Given the employed mesh density and the use of the Chimera [8] technique, the wake was well-resolved for up to 4 main rotor diameters downstream the rotor.

To further look at the simulation data, the velocity magnitude (with the aircraft speed subtracted) was computed at several azimuth angles around the aircraft and at several distances from the main rotor hub. The results are shown in Figures 3-6 corresponding to hover, and forward speeds of 10,20 and 40 kts. As can be seen, for the hover and to some extent for the 10kts forward speed case, the flow appears to have a certain degree of symmetry around the aircraft. Especially for the hover case, there is very little variation in the azimuthal direction. At 10kts the symmetry is still there but there is a small degree of asymmetry looking at 0 degrees of azimuth. Since the aircraft speed is subtracted the ground velocity appears to be zero in these plots. Moving to the plots for 20kts on Figure 5, there is now a clear directionality in the flow. Although the ground vortex is now closer to the aircraft, the main feature in the plot is the distortion of the wake downstream of the aircraft. Especially near the rotor, it is now visible that at zero degrees of azimuth the velocity peak is not near the ground as the rotor wake changes from a toroidal shape of a trailed wake. At 40 kts the situation is now different with peak velocities appearing higher above the ground. It is this change of wake configuration between the toroidal and trailed forms that makes the use of simple rules for aircraft separation somehow more complicated for this case.

The results so far show good predictions of velocities and of the overall flow topology and are perhaps suitable for a first estimate of the separation distances required between helicopters. Nevertheless the prediction of the wake decay is still difficult. To investigate the ability of the employed method in delivering estimates of decay the work of Kopp [5] was used. In this work the actuator disk method of HMB was employed to simulate the measurements of a Puma aircraft wake. The case corresponds to an advance ratio of 0.16 and a thrust coefficient of 0.017. Due to the limitations of the employed CFD mesh and its loss of resolution after about 5 rotor diameters, it is not possible to compare the results with the experiments. Nevertheless, the swirl velocity of the CFD was extracted and is compared in Figure 7 with measurements. The results show an overall fair agreement. Given that the employed mesh resolution is not very high, the comparison can be seen as encouraging.

4. SUMMARY OF FINDINGS AND FUTURE WORK

The obtained results suggest that using averaged Navier Stokes equations, an actuator disk model and moderate CFD grids can be a pragmatic way to simulate helicopter wakes for the purposes of investigating helicopter wake encounters. Using moderate speed computers to calculate a set of advance ratios and thrust coefficients at distances of up to 5 rotor diameters behind a rotor is not too expensive and can be carried out over a period of 1-2 weeks. Using more advanced CFD techniques like adaptive meshing can bring this cost further down. The use of the data from studies like JAXA suggests that comparisons with full-scale helicopters is feasible and is perhaps a good way to avoid some of the complexities of wind tunnel data. Where wind tunnel measurements, however, can be invaluable is in measuring at least the early decay rate of the wake. This is a difficult quantity to predict well since it requires adequate density of

CFD grids to avoid effects of numerical dissipation and detailed modelling of the wake turbulence. It is expected that combining measurements with high fidelity CFD methods coupled with flight mechanics tools [9] can provide a robust framework to quantify the effect of wake encounters and could contribute to the development of more specific separation distances beyond what is currently employed.

5. NOTATION

C_T	Rotor thrust coefficient (C_T = 0.022)
R	Rotor radius (R = 0.8 m)

6. ACKNOWLEDGEMENTS

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Author	Year	Theme	Method
Heyson [10]	1956	Full scale wind tunnel wake measurement	Dynamic pressure rakes
Caradonna and Tung [11]	1981	Pressure and wake strength in hover	Pressure probes and hot-wire
Curtiss [12]	1985	Wake measurements in ground effect	Hot-wire
Teager et al. [13]	1996	Wake measurement in forward flight	LiDAR
Köpp [5]	1999	Helicopter wake decay	LiDAR
Sjöholm et al. [14]	2014	Helicopter wake on large scale	LiDAR
Herges [15]	2017	Wind turbine wake geometry	LiDAR
Sugiura et al. [16]	2016	Helicopter ground effect	LiDAR. Ultrasonic anemometer
Bauknecht et al. [17]	2015	Helicopter tip vortex measurements	Back Oriented Schilren

Table 1: Summary of test cases with corresponding references. Measured data can be used for wake decay studies.

	Low Computational Cost			**High Computational Cost**		
	Dynamic Inflow	**Prescribed Models**	**Free Wake**	**Actuator Disk**	**Grid Based**	**Grid Free**
Vortex Decay	Y	N	N	Y	Y	Y
Ground Effect	Y	N	Y	Y	Y	Y
Coupling	N	N	N	Y	Y	Y

Table 2: Comparison of candidate methods for simulation of helicopter wakes.

	Main Rotor	**Tail Rotor**
Number of blades, b	4	2
Rotor radius [m], R	5.5	0.978
Non dimensional rotor radius, R*	13.415	2.385
Chord length [m], c	0.41	0.22
Non dimensional chord length, c*	1.0	0.537
Cutout (radius) [m]	0.725	0.225
Non dimensional cutout	1.7685	0.45
Solidity	0.095	0.1432
Number of revolution [rpm], N	200	2170
Angular velocity, [1/s]	20.94	227.2
Period of revolution, [s]	0.3	0.027
Thrust coefficient	0.022	0.003

Table 3: Details of the employed rotor model for the simulation of the JAXA wake survey.

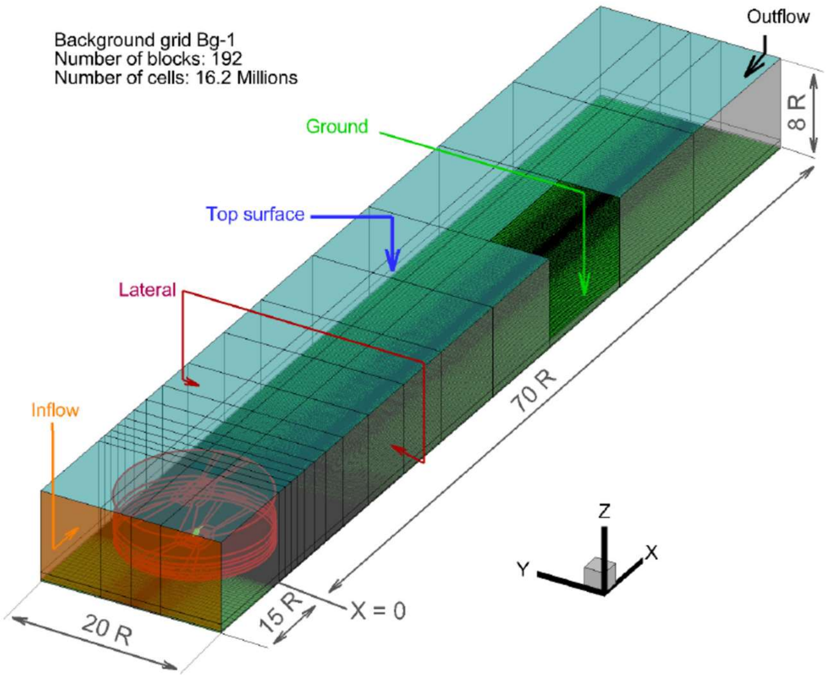
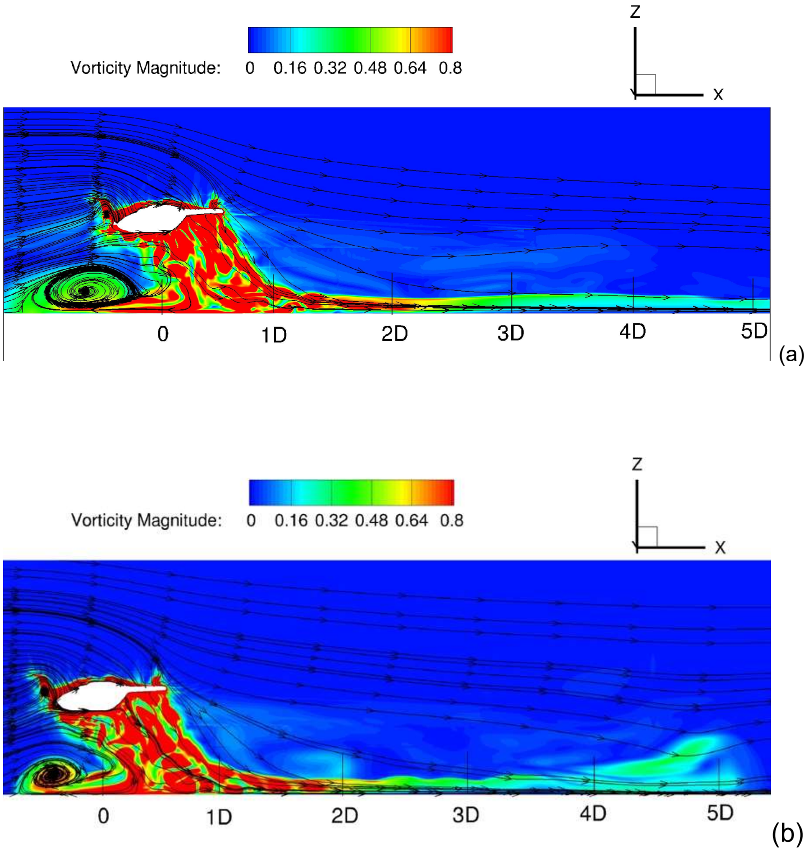


Figure 1: Computational domain relative to rotor disk radius, R.



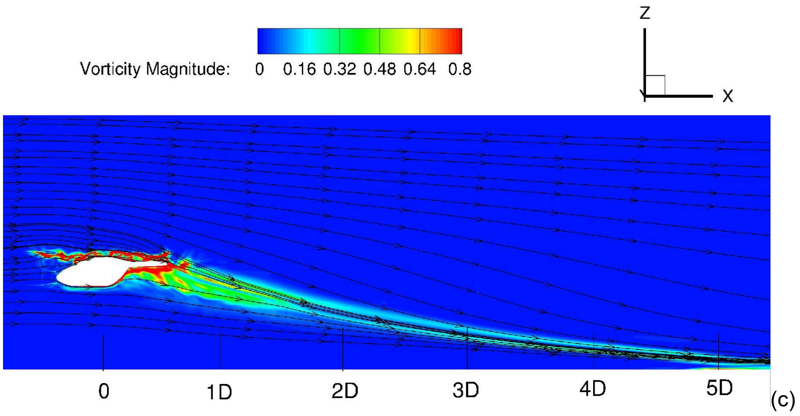
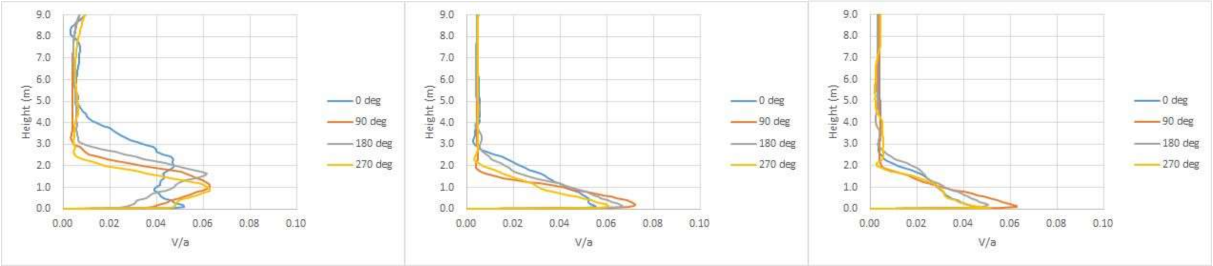
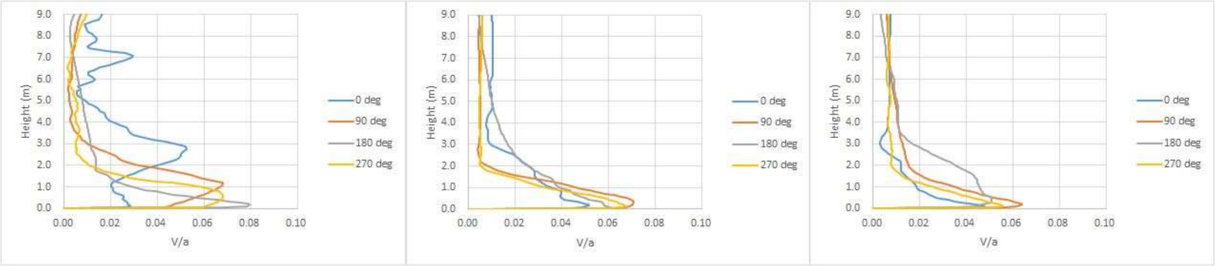


Figure 2: Comparison of the wake geometry, for three different values of flight speed: 1(a) 15kt, 1(b) 20kt, 1(c) 40kt. The ground effect is simulated for an altitude of 30ft.



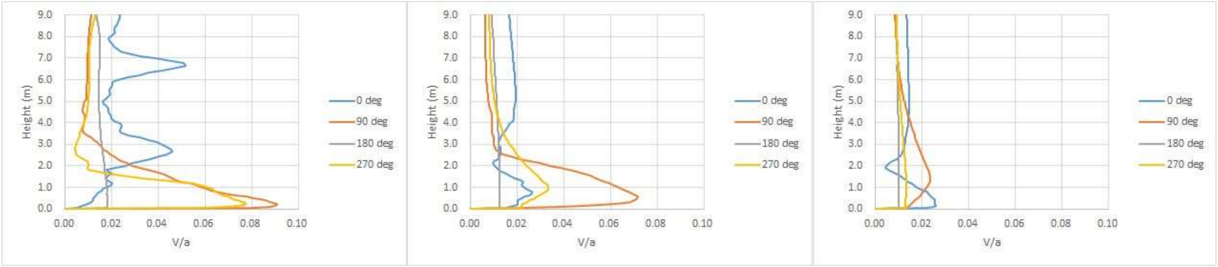
1.25R 2.0R 3.0R

Figure 3: Velocity profiles (0kt).



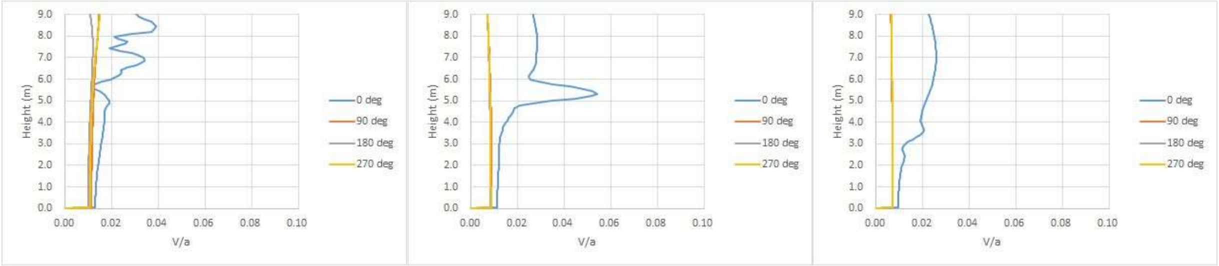
1.25R 2.0R 3.0R

Figure 4: Velocity profiles (10kts)



1.25R 2.0R 3.0R

Figure 5: Velocity profiles (20kt).



1.25R 2.0R 3.0R

Figure 6: Velocity profiles (40kt).

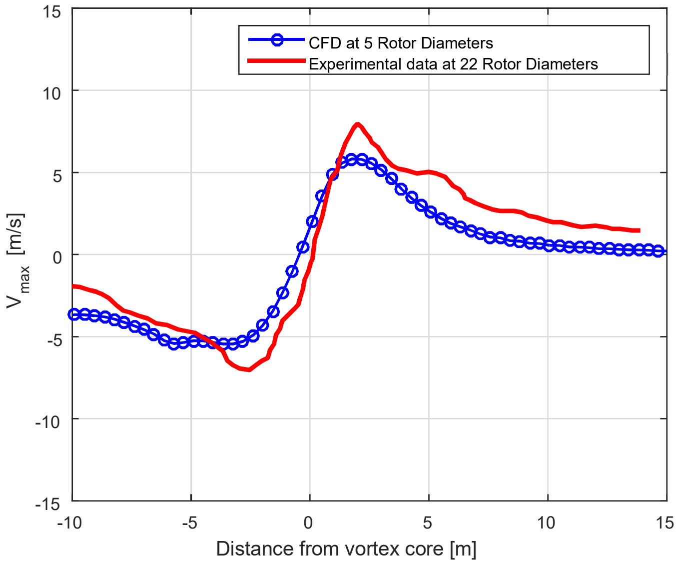


Figure 7: CFD and measured velocities for Kopp's case. The CFD was extracted at 5 rotor diameters behind the rotor and is compared with data gathered at 22 rotor diameters.