Actuator Line Method Simulations for the Analysis of Wind Turbine Wakes Acting on Helicopters

Manuel Bühler, Pascal Weiheing, Levin Klein, Thorsten Lutz and Ewald Krämer

Institute for Aerodynamics and Gas Dynamics, University of Stuttgart, Pfaffenwaldring 21, 70569 Stuttgart, Germany

E-mail: {buehler, weiheing, klein, lutz, kraemer}@iag.uni-stuttgart.de

Abstract. In the present study the actuator line method is used to simulate the wake of a wind turbine and ways to characterize its impact on the flight of a helicopter model through the wake are evaluated. The helicopter within the simulation setup is represented by a dynamic actuator line which was implemented into the flow solver FLOWer. In order to evaluate the loads on the helicopter the thrust force distribution is compared in different areas of the wake. For further improvement of the actuator line implementation different methods to evaluate the angle of attack are compared. This was examined as the angle of attack is a highly important parameter for the actuator line and helps to optimise the accuracy and performance of the actuator line method. As there is no experimental data available and the model of the helicopter comes with distinct simplifications the loads are compared to values without the wake of the wind turbine, thus in free flight.

1. Introduction

In the last years there is a strong desire to move the production of electricity towards renewable energy sources especially with the Paris agreement from 2016 in force the pressure rises also from politics to have larger portions of renewable energy in the grids. One crucial part of the transfer is the expansion of wind energy. Referred to Germany the available locations for onshore wind turbines are limited. This is one of the reasons why offshore wind energy became more and more relevant within the last years.

Considering offshore wind parks there are certain aspects that become significantly more difficult compared to onshore wind parks. Apart from the setup of the turbines, the maintenance becomes far more challenging. There are mainly two possibilities to send maintenance personnel to the wind turbines. The first one is to go by boat and the more flexible and faster option is to go by helicopter. But to approach the wind turbines within larger wind parks the helicopter will have to fly through the wakes of other turbines in service within the park. The impact of the wakes on the flight physics of the helicopter accompanied by a possible increase in workload for the pilot or a potentially dangerous decrease in controllability is so far not thoroughly studied and understood. One possible cause for these effects is a change in lift across the helicopter rotor due to changing inflow velocity or angle of attack at the rotor blades.

Within the research project "HeliOW" the goal is to investigate the potential impact of the wake and turbulent structures of offshore wind farms on the flight behaviour and flight physics of the helicopter. This is performed in two ways. On the one hand temporal and spatially
highly resolved simulations of the unsteady flow fields will be performed and used in helicopter flight simulators of project partners to perform flight tests. On the other hand the helicopter is modelled in a simplified way using the actuator line method to represent its main rotor within the computational domain to capture the impact of the wake. In this study progress of the second way is presented using the actuator line method for helicopter and wind turbine in two implementations.

The actuator line method is a commonly used method for the simulation of wind turbine wakes nowadays [1]. There have been numerous studies analysing different numerical parameters for the simulation with the method [2], [3], [4]. Furthermore studies have been conducted to analyse the impact of wind turbines located in the wake of other turbines [5]. These studies seek a better understanding of wind park effects and a more reasonable positioning as well as an optimized control system of wind turbines standing in wind parks. Apart from the research on the impact of the turbines on each other only one study is known to the author that covers the analysis of the impact of wind turbine wakes on helicopters and fixed-wing aircraft. The study of van der Wall et al. among other things discusses the impact of isolated vortices on the rotor disc of a helicopter and the resulting influence on the flight physics [6].

2. Methodology

The wind turbine is represented by the actuator line method within this study. This simulation technique is used within the flow solver FLOWer which was originally developed by the German Aerospace Center (DLR) [7] and is constantly extended at the Institute of Aerodynamics and Gas Dynamics (IAG). The implementation of the actuator line method is performed according to [8],[9]. In previous work the wake structure of the actuator line method was compared to simulations with full resolution CFD methods [10].

2.1. Calculation method for angle of attack

In order to improve the accuracy and performance of the actuator line implementation different methods for the calculation of the angle of attack are investigated as the calculation of the angle of attack is a major influence quantity on the resulting flow field of the actuator line. This is because from the angle of attack the resulting forces and thereby the induction of the actuator line on the flow field are calculated. As the formation of the tip vortices is also directly influenced by that it is a goal to thereby reproduce them with higher precision for the following investigation of this study. Therefore two commonly used methods to calculate the angle of attack are compared to a newly presented approach.

Usually the angle of attack for the actuator line is calculated in reference to a monitor point (MP). The commonly used method is rather simple and uses the velocity components in the quarter chord point which at the same time serves as modelling point for the actuator line. Here the flow angle $\phi$ is calculated regarding all possible angles appearing when looking at a wind turbine (pitch, yaw, tilt, azimuth). The angle of attack $\alpha$ is finally calculated by subtracting the local twist $\epsilon$ and the pitch angle $\theta$ from the flow angle of the blade.

The drawback of this method is that there is no shed or bound circulation of the blade considered in the calculation which can bring in uncertainties. Though theoretically the induced velocity is zero in the actuator line point [11].

As corrections for the calculation of the angle of attack two additional methods will be described in the following. The first method is called point circulation method (SHS1). It was first suggested by Shen et al. [12]. For this method a monitor point upstream of the blade is taken for every single blade section (see Fig.1a). The angle of attack is subsequently calculated by using the law of Biot-Savart. There are mainly two parameters that can be changed for the calculation within this method which is the distance of the monitor point from the quarter chord point according to the definition and the stop criterion for the angle of attack calculation.
as the calculation is performed in an iteration loop. Thus there tends to be an influence of these input parameters on the resulting angles of attack and subsequently the forces of the actuator line.

The second method is called line average method (LineAve) and is first presented in [13]. It was developed at the IAG and is in the context of the work in [13] used to calculate the angle of attack of fully resolved wind turbine rotors as a post-processing tool. This shall be adopted in the present study to the actuator line method to calculate angles of attack during the simulation. Within this method a closed line of points around the rotor blade or actuator line modelling point is taken to evaluate the angles of attack. Thus, there is not a single monitor point but an arbitrary number of monitor points on a closed line (see Fig.1b). By averaging the tangential and radial velocity components of all points along the closed circle around the modelling points the resulting velocity components are calculated and the angle of attack is extracted.

The numerical simulations for the comparison of the angle of attack methods is performed using

(a) SHS1 calculation method
(b) LineAve calculation method

Figure 1: Monitor point placement for angle of attack calculation (modified from [13])

a slightly modified version of the NREL 5MW turbine [14]. It has a diameter of $D = 126 \, m$ and a tower height of $H = 90 \, m$. The rotor is fitted with a precone angle of $\alpha_c = -2.5^\circ$ and a tilt angle of $\alpha_t = 5^\circ$. The considered operation point is at $11.3 \, m/s$ uniform inflow velocity and a rotational speed of $11.7 \, RPM$. As a reference for the calculation with the actuator line a fully resolved simulation is used. This simulation was performed on the same background mesh including body fitted meshes for the turbine components. These are fitted with chimera boundary conditions as this is necessary to compute the rotating parts within the background mesh.

2.2. Helicopter model testcase

The investigations on the helicopter model are performed using a dynamic actuator line implementation. This implementation of the dynamic actuator line for FLOWer was first presented in [15]. The actuator line is in this case able to move freely along a predefined path within the computational domain according to the specified speed and time step of the time accurate simulation. The flight path can be defined using an arbitrary number of way points within the computational domain. In order to make the helicopter model more realistic a cyclic pitch was additionally implemented. This was so far not necessary for simulations of wind turbines.

Within the study a small helicopter model was set up which was also already presented in [15]. It is based on an EC-135 helicopter while maintaining the macro data like the diameter of $d = 10.2 \, m$, the rotational speed of $n = 395 \, RPM$ and a generic cyclic and collective pitch which was estimated using data from [16]. At this stage of the research the simplification is adopted that the collective pitch is kept constant. In real flight conditions the collective pitch would have to be adapted to the local flow conditions to maintain the flight altitude. As the blade data of the helicopter is also confidential NACA0012 profiles without twist have been used for
the blade. The actuator line has 10 modelling points along the radius of the blade. In order to investigate the influence of the actuator line movement on the resulting flow field two different test cases were conducted. In the first test case (Case 1) the actuator line remains stationary and a uniform inflow velocity of $u_{\infty,1} = 30 \text{ m/s}$ is used. For the second testcase (Case 2) no inflow velocity is used but the actuator line moves with the full velocity of $u_{ACL,2} = 30 \text{ m/s}$. For these calculations a Cartesian grid with a finest grid resolution in the proximity of the actuator line rotor of $\Delta X = \Delta Y = \Delta Z = 0.25 \text{ m}$ is used. Further away from the rotor the grid is gradually coarsened by the usage of hanging grid nodes.

2.3. Helicopter model flight in wind turbine wake

For the final numerical computation of this study the small helicopter model was included into a numerical setup of the modified NREL 5MW research wind turbine represented by the actuator line method. The mesh setup is built rather different for this case. As the tip vortices are of crucial importance for the investigation a vortex ring of refined grid cells is introduced into the wake of the wind turbine. Additionally the area of interest for the helicopter is refined further to maintain the same resolution as used for the previous computations ($\Delta X = \Delta Y = \Delta Z = 0.25 \text{ m}$). This is also the finest resolution used within this mesh. The coarsening of the grid is also in this case realised with hanging grid nodes.

The helicopter model is positioned at $x = 63 \text{ m}$ downstream the turbine which equals half the diameter of the modified NREL 5MW turbine ($D/2$). At this downstream position the helicopter is put in two different areas of the wake. The first one is at hub height ($H = 90 \text{ m}$) where the actuator line dives into the vertically oriented tip vortices. The second position is on top height of the wake ($160 \text{ m}$) where the actuator line crosses the horizontally oriented tip vortices of the modified NREL 5MW turbine. In Fig. 2 the mesh structure for this downstream position and the flight paths can be seen in two different cuts. The computation is run at the same operating point like before and first with a stationary helicopter model in the starting point of the path outside the turbine wake to be able to develop the wake of the modified NREL 5MW turbine. After a sufficient simulation period where the time step is set according to $1.5^\circ$ of azimuth of the wind turbine, the movement of the helicopter model is started and the time step is reduced to a value which equals to $1.5^\circ$ of azimuth of the helicopter model. Due to the highly different rotational speeds this is a strong decrease in time step.

![Mesh structure of wake of the modified NREL 5MW research turbine with local refinement for dynamic actuator line](image)

Figure 2: Mesh structure of wake of the modified NREL 5MW research turbine with local refinement for dynamic actuator line
For all the presented simulations in this study the same boundary conditions have been used. For all wind turbine components Navier-Stokes walls have been applied and the ground is simulated as an Euler wall. All remaining boundaries of the domains have been fitted with far field boundary conditions.

3. Results
The calculation of the angle of attack for the actuator line was first investigated in order to improve the performance of the implemented method. Therefore the two different correction methods for the calculation of the angle of attack previously described shall be discussed in the following.

For a comparison of the SHS1 method and the LineAve method the same setup was used and compared to a fully resolved computation on the same background mesh. This procedure was already described in the previous section.

For the correct calculation of the angle of attack over the whole blade the tip area is of great importance. As the tip vortex convecting downstream of the blade has an influence on the flow of the tip area of the blade it is important to consider this in the calculation of the angle of attack. With the SHS1 method there is only one monitor point used upstream of the modelling point of the actuator line. But with the LineAve method there are in this case eight points used on a circle around the modelling points. In Fig. 3 the angle of attack and thrust force distribution are plotted over the radius of the blade.

It becomes obvious that on the one hand the overall thrust of the actuator line simulations matches over a wide range of the radius but is too low compared to the analysis of the fully resolved calculation. With the SHS1 method there is additionally a triangle like shape of the thrust force distribution visible. Typically this behaviour is alleviated using tip correction models [17] but for the calculations presented in this study no tip correction models have been applied to be able to highlight the effect of the calculation method of the angle of attack. A better accordance can be seen for the fully resolved calculation and the actuator line simulation with the LineAve method especially in the tip region which justifies the omitting of a tip correction model. This becomes apparent in the distribution of the angle of attack and the thrust force similarly as the forces are calculated on the basis of the angles of attack. The reason for that is a better consideration of the tip vortices and their induction on the flow around the blade tip.

![Figure 3: Load distribution of the modified NREL 5MW blade for actuator line and fully resolved calculations](image)
The angles of attack for the fully resolved calculation are also evaluated with the LineAve method. The overall deviation of the actuator line simulations from the fully resolved one is currently further investigated with a special attention on the smearing parameter $\epsilon$ which is another important parameter for the accuracy of the actuator line method [9]. This parameter $\epsilon$ controls the spatial extent over which the discrete force of the actuator line modelling point is smeared.

In order to validate the implementation of the dynamic actuator line and to show the independence of the movement on the wake structure of the actuator line, two different motion and inflow configurations were investigated. In Fig. 4 the vortex structures with the $\lambda_2$-criterion of Case.1 and Case.2 are plotted. It can be seen that these structures are similar. For Case.1 a thin vortex sheet covers the central wake of the helicopter but does not change its basic structure. An additional comparison is given in Fig. 5 where the dimensionless thrust force is given over one revolution for the dynamic and the static actuator line. The values are extracted at a radial position of 4.5 m ($x/r = 0.88$). The plot is given in non dimensional values due to the strong simplifications that have been made for the helicopter and to be able to compare the results better with the subsequent flights in the wake of the wind turbine. The normalization is performed with the highest thrust force value over the revolution of the dynamic actuator line. It shows that there is a perfect agreement for both setups and it can be stated that there is almost no influence of the movement of the actuator line on the development of the wake and the loads on the rotor.

On the basis of these testcases, flights through the wake of the modified NREL 5MW wind

![Figure 4: Testcases with visualisation of the $\lambda_2$-criterion and u-velocity component](image)

(a) Case.1 ($u_{\infty,1} = 30 \text{ m/s}$)  
(b) Case.2 ($u_{ACL,2} = 30 \text{ m/s}$)

Figure 4: Testcases with visualisation of the $\lambda_2$-criterion and u-velocity component

![Figure 5: Dim.less thrust force over one rotor revolution (4.5 m of radius ($x/r = 0.88$))](image)
turbine are performed considering different paths including two flight altitudes. The subsequent variation of the flight path results in a change of the relative position of the helicopter model to the tip vortices of the wind turbine. This will be compared with the previous results from the calculations without the wind turbine wake thus in free flight.

The tip vortices of the wind turbine induce different velocity components due to their position in space. Vertical oriented tip vortices on the left and right side of the wake on hub height induce horizontal velocity components. Whereas the horizontally oriented tip vortices on the upper and lower side of the wake induce vertical velocity components. This is the reason why it is important to look at different locations within the wake when dealing with the question of influences of the wake structures of the wind turbine on the flight of a helicopter.

The first flight of the helicopter with a speed of \( u_{ACL} = 30 \, \text{m/s} \) on hub height can be seen in Fig. 6. In the figure the wakes of both, the wind turbine and the helicopter model are visualized with the \( \lambda_2 \)-criterion. In this figure it seems that the helicopter 'eliminates' the tip vortices in the proximity of the helicopter. Apart from this qualitative view on the flight the vorticity can be considered. In Fig. 7 the vorticity in \( z \)-direction is plotted in a horizontal cut through the flow field on hub height. Here the clear influence of the helicopter model can be seen within the plot.

In order to enable the comparison with the conditions in free flight without the influence of the wake and cross flow of the wind turbine, the thrust force distribution of the previous test case is compared to the forces occurring in this flight condition which is plotted in Fig. 8 for six revolutions. The values in Fig. 8a are taken from the radial position of \( 4.5 \, \text{m} \, (x/r = 0.88) \) of the helicopter rotor blade and the plot is non-dimensionalized with the maximal thrust force value on the blade from the previous test case. Fig. 8b shows the thrust force of the whole rotor of the helicopter model non-dimensionalized with the maximal thrust force value of the rotor from
the previous test case. It becomes obvious that in both analyses the loads are higher by a factor of around two in this flight condition which seems to be a result of the combined influence of the wake with tip vortices and the cross flow of the wind turbine inflow. It can be seen on the dimensionless $y$-axis of Fig. 8a that the range of load fluctuation during one revolution of the blade is higher than in the test case. Additionally Fig. 8b shows a transient rise in thrust force over the considered azimuth range that indicates an influence by the tip vortices and the wake itself independent from the cross flow.

In Fig. 9 and 10 the $\lambda_2$-distribution and the vorticity in $y$-direction of the second flight case on a height of 160 $m$ are plotted. In this flight condition the helicopter model hits the tip vortices almost tangentially with the same velocity of $u_{ACL} = 30 m/s$. In Fig. 9 there is the same phenomena observable that the helicopter model strongly influences the tip vortices of the wind turbine and seems to 'eliminate' them in its vicinity. In Fig. 10 for this condition the vorticity in $y$-direction was taken as the rotational axis of the tip vortices is different due to the location of the vortices in space. Therefore the vorticity structure of the helicopter model looks different to Fig. 7 on hub height and the tip vortices of the wind turbine can be recognized as cylindrical wake structures.

In Fig. 11 the dimensionless thrust force over eight revolutions is plotted along the flight though the tip vortices on the flight altitude of 160 $m$. The values in Fig. 11a are again taken from...
the radial position of $4.5 \text{ m} \ (x/r = 0.88)$ and the plot is non-dimensionalized with the maximal thrust force value on the blade from the previous test case. Fig. 11b shows the thrust force of the whole rotor of the helicopter model non-dimensionalized with the maximal thrust force value of the rotor from the previous test case. Fig. 11a looks similar to Fig. 8a from the first flight case. Also the loads are higher by a factor of around two, however Fig. 11b shows a different behaviour to the first flight case. The transient behaviour in this case shows an oscillation which indicates a different influence by the tip vortices and the wake as the helicopter model tangentially enters the wake. It has to be stated that the plot of eight revolutions of the helicopter rotor in this case equals only half the flight through the wake from the outer position to a $y$-position of $y = 0$. But as the wake is symmetrical this consideration is sufficient.

4. Conclusions
In order to further improve the accuracy and performance of the actuator line implementation different methods for the calculation of the angle of attack are compared in this study. Therefore a new calculation method called line average (LineAve) method is implemented and compared to the SHS1 method. A simulation with the modified NREL 5MW research wind turbine showed that the calculation of the angle of attack with the LineAve method provides better results in the tip area of the blade compared to the actuator line evaluation with the SHS1 method with respect to a fully resolved calculation.
Subsequently a newly developed dynamic actuator line was successfully implemented into the flow solver FLOWer. This actuator line is able to move freely within the computational domain. This gives the opportunity to build up a small test setup of a helicopter which is based on the macro data of a EC-135 helicopter. The small test setup was validated with the comparison to a non-moving actuator line method calculation. This setup is then applied to fly through the wake of the modified NREL 5MW research wind turbine and gives a first analysis of the influence of two different flight conditions on the model. For the first flight the helicopter model crosses the tip vortices of the wind turbine on hub height and for the second flight the helicopter flies tangentially into the tip vortices on the upper surface of the wake tube. For the analysis $\lambda_2$ iso surfaces, the vorticity in the relevant coordinates and the thrust force output by the actuator line are compared. The $\lambda_2$ and vorticity plots show promising figures for the functionality of the method and the plots of the thrust force on blades and the whole rotor show different transient behaviour that indicate a different influence by the tip vortices and the wake. The collected data will serve as a foundation for further analyses with different flight conditions including more flight altitudes and a variation of the flight velocity as well as the distance from the wind turbine of the helicopter. With a broader database it is also intended to separate the effect of the wake deficit, the tip vortices with the vortex degradation and the cross flow more clearly.

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