CFD Prediction of Tip Vortex Aging in the Wake of a Multi-MW Wind Turbine

Marion Cormier\textsuperscript{1}, Manuel B"uhler\textsuperscript{1}, Moritz Mauz\textsuperscript{2}, Thorsten Lutz\textsuperscript{1}, Jens Bange\textsuperscript{2}, Ewald Kr"amer\textsuperscript{1}

\textsuperscript{1}Institute of Aerodynamics and Gas Dynamics, University of Stuttgart, Pfaffenwaldring 21, 70569 Stuttgart, Germany.
\textsuperscript{2}Centre for Applied Geoscience, Eberhard Karls University of T"ubingen, H"olderlinstr. 12, 72074 T"ubingen, Germany.

E-mail: cormier@iag.uni-stuttgart.de

Abstract. In the present study, prediction from high-fidelity Computational Fluid Dynamics (CFD) simulations of the tip vortex aging in the near-wake of a multi-MW wind turbine is evaluated and compared to in-situ measurements as well as results of a semi-empirical model. Optimized tip vortex refinement is also introduced to investigate the influence of the grid topology on the vortex evolution. The grid refinement affects only the vortex core size and a reduction of the core radius by a factor of 3.4 was achieved with the chosen parameters. On the refined setup, vortex core sizes and strength are comparable with in-situ Unmanned Aircraft System (UAS) based measurements at 0.5 rotor radius downstream of the wind turbine. A comparison of the aging function with a semi-empirical vortex helix model shows a good agreement with the refined CFD results, but the core size predicted by the model is smaller than in simulations and experiments.

1. Introduction
With a constantly rising desire to increase the contribution of renewable energies in the global energy production, the existing and future wind parks should operate at steadily higher efficiency. A crucial point to increase the efficiency lays in a valuable management of the maintenance operations. In offshore windparks, the most time-efficient way to access the wind turbines is by helicopter. However, the strong velocity gradients, high turbulence intensity levels and zones of highly concentrated vorticity in the wake of wind turbines represent potential risks during the flight of maintenance helicopters. To assess the effects of wind turbine wakes on the flight dynamics of helicopters, previous studies have idealized the wind turbine tip vortices by a vortex helix [1, 2]. In these studies, a semi-empirical formulation, tuned with a large database of detailed experiments of the flow field around helicopter rotors, is applied to model the tip vortex helix.

However, the wakes of wind turbines operating in the turbulent atmospheric boundary layer (ABL) are more complex than in the idealized case of uniform inflow conditions. In the turbulent ABL, tip vortices do not form the idealized shape of a tip vortex helix but they break down after a few rotor diameters into small-scale turbulence due to interaction with the ambient flow [3, 4] or with neighbour tip vortices [5]. The instabilities that trigger the wake breakdown are enhanced in case of yaw misalignment [6, 7], thermal stability of the atmospheric boundary layer [8] or increased inflow turbulence due to complex orography [9]. Therefore, further studies...
considered the dynamics of the wind turbine wakes in their investigations of wake encounters. [10], [11] and [12] investigated the roll hazards of small aircrafts in highly resolved wind turbine wakes. Thereby, the wakes have been computed with help of large-eddy simulations (LES), combined with the actuator-disc and actuator-line approaches to model the wind turbine. In [13], turbulent wind turbine wakes have been simulated to investigate helicopter encounters.

The German research project HeliOW (Hubschrauber-Einsätze in Offshore-Windparks / Helicopter Operations in Offshore wind parks) aims to study the influence of wind turbine wakes on the flight dynamics of helicopters during maintenance operations within offshore wind parks. For this purpose, a simulation chain has been established: the 3D flow field resulting from highly resolved computational fluid dynamics (CFD) simulations of a modern wind turbine design is fed into a helicopter flight simulator [2, 14] to study the reaction of the helicopter and the pilot when encountering the perturbations. In this way, wind turbine wake breakdown and interactions with the ambient flow field are taken into account. A validation of the CFD numerical method is performed through comparisons of the flow fields with Unmanned Aircraft System (UAS) measurements [15] around a multi-MW wind turbine.

The current study focuses on the CFD simulations conducted within this project, where efforts have been made to increase the tip vortex resolution in the near-wake region. The resulting flow fields are compared with both in-situ measurements and the semi-empirical model that has been used to approximate the vortex helix in some previous studies [2]. The purpose of the present paper is to assess, on the one hand, the ability of the numerical setup to reproduce the vortex aging process of the tip vortices by highly resolved CFD and, on the other hand, the transferability of the semi-empirical model to wind turbine wakes. The methods used, including not only the numerical methods and setup but also the experimental database and the semi-empirical model, are presented in the next section. In section 3, the flow fields resulting from the CFD simulations are analyzed and compared to the other approaches, followed by a discussion in section 4. Finally, the conclusions are presented in section 5.

2. Methodology
In this section, the numerical methods and setup for the fully-resolved unsteady Reynolds-averaged Navier-Stokes (URANS) simulations are described. Then, the experimental database and the semi-empirical model used for comparison are shortly described.

2.1. Wind turbine and inflow conditions
The simulated wind turbine is a generic recreation of the commercial Enercon E-112 model, based on open-access airfoil data and provided by the manufacturer. The recreation presents the same macro data as the original wind turbine and mimics its induction distribution. The rotational speed and the pitch angle of the blades during the measurement window have been provided by the operator of the wind park.

The inflow characteristics were derived from measurements of a E-112 wind turbine located in Wilhelmshaven, North of Germany, in July 2018 [15]. An UAS of type MASC-3 (Multi-Purpose Airborne Sensor Carrier) equipped with a multi-hole probe is used for the highly time-resolved measurement of the wind field [16, 17, 18]. The wind measurements of the inflow and the wake, which contain the trace of tip vortices, belong to the same UAS flight. It is assumed that the inflow conditions do not significantly vary during the measurement time. The experimental database for the measured tip vortices is described in more details in section 2.5. The inflow velocity at hub height $z_{ref}$ is $u_{ref} = 8.8 \text{ m/s}$ with 5% turbulence intensity [15]. As represented in Fig. 1, the mean wind profile was reconstructed from UAS measurements and approximated with a power law with an exponent $\alpha = 0.4$. Despite the availability of highly time-resolved UAS measurements of the inflow wind vector around a multi-MW wind turbine, the inflow profile of Fig. 1 was determined with only two measurements points in the rotor area. However, the inflow
of the E-112 wind turbine in the Jade wind park is complex when the wind direction is North, as it was the case during the measurement window. It is mainly dominated by a maritime boundary layer combined with an internal boundary layer due to the land area between the wind turbine and the shore which features a dike, trees and several buildings. Nonetheless, the approximation of the inflow by a power law was considered to be sufficient for the present study in order to perform comparisons of the near-wake properties with unique measurements of the trace of tip vortices in the wake of a multi-MW wind turbine. Moreover, the relatively low turbulence intensity for the value of the power law exponent can be explained by the stable thermal stratification present on the measurement day [15].

Figure 1. Mean wind profile fitted on measurement data

Figure 2. Refined mesh around the blade tip vortices. For more clarity, only 12.5% of all mesh lines are shown.

2.2. Numerical methods
The highly-resolved CFD simulations have been conducted with the flow solver FLOWer. FLOWer is a compressible, finite-volume and block-structured Reynolds-averaged Navier-Stokes solver [19], developed by the German Aerospace Center (DLR). It is the central link in the process chain for wind turbine simulations that has been established at the Institute of Aerodynamics and Gas Dynamics (IAG) of the University of Stuttgart [20]. In the structured meshes of the turbine components, the 2nd order Jameson-Turkel-Schmitt central spatial scheme is used [21], while, in the background and tip vortex meshes, the 5th order WENO scheme is applied in order to reduce numerical dissipation of the vortical structures. The time integration is performed with a Runge-Kutta scheme and a dual time-stepping scheme is utilized to accelerate the convergence. To close the turbulence problem, the Menter-SST $\kappa-\omega$ turbulence model is used [22]. To enhance vortex conservation, a vortical flow correction model for two-equation turbulence models is applied [23]. At the inlet of the computational domain, the mean wind profile of the shear layer is imposed as a Dirichlet boundary condition. To recreate the turbulent atmospheric boundary layer, synthetic turbulence, which is generated with the Mann model, is added as source terms in the flow field downstream the inlet [24].

2.3. Numerical setup
In the present computational setup, only the fully turbulent rotor is simulated and the components are considered as rigid. All structures of the wind turbine rotor are meshed separately and placed relatively to each other with the Chimera overset technique [25].
all components, the non-dimensional wall distance of the first mesh layer is set to $y^+ \approx 1$, ensuring fully-resolved boundary layers. The blade mesh was created automatically using the IAG script `Automesh` and presents a C-H mesh topology with 256 and 120 cells in circumferential and spanwise directions, respectively. The connectors located between nacelle and blades as well as the nacelle have been manually meshed with the commercial tool `Pointwise`. The cartesian background mesh was created with an automated script and the smallest cell size is $0.5m$ in the rotor and tip vortex regions, similar to [26]. A cell size of $1m$ has been chosen from the inlet up to $3.5R$ downstream the rotor for turbulence propagation and wake dynamics. This region extends laterally and vertically from $-2R$ to $2R$ and from the ground to $4R$. Further away from those regions, grid coarsening with hanging grid nodes is introduced in order to reduce the number of grid cells - and thus computational costs. According to the guidelines of the International Electrotechnical Commission (IEC) [27], an integral length scale of $42m$ was used in the Mann model for the generation of the turbulent fluctuations. The boundary conditions of the computational box are Dirichlet at the inlet, Navier-Stokes wall at the ground and far-field at lateral sides, top and outlet.

**Figure 3.** Mesh components of the fully-resolved wind turbine. For more clarity, only 12.5% of all mesh lines are shown.

A preliminary computation with only the mean wind profile but without synthetic turbulence at the inlet has been performed in order to determine the position of the blade tip vortices for the studied operating point. Based on the resulting tip vortex trajectory, a refined cylindrical mesh for the tip vortex helix has been created, as presented in Fig. 2. It was assumed that, for this purpose, the effects of the inflow turbulence on the position of the blade tip vortices can be neglected. The cell size in the cross-section of the tip vortices was set to 0.1 m. In radial direction, hanging grid nodes are used to quickly reach to the cell size of the background mesh for the Chimera overlapping zone. As the velocity gradients in the rotor azimuth direction are much smaller than in streamwise direction, a larger cell size corresponding to 1° azimuth is used for that direction in order to reduce the total number of grid cells. The refined tip vortex mesh extends up to $0.7R$ downstream of the rotor and has a thickness of 10 m, so that tip vortices stay in the fine mesh even with small deviations of their trajectory due to the inflow turbulence.
The whole resulting setup, as represented in Fig. 3, consists of about 120 Mio cells while the setup for the preliminary analysis, also referred to as baseline setup in the following, has 67 Mio cells. The refined tip mesh accounts for 23 Mio. cells and the refinement with $\Delta x = 1$ m for the turbulence propagation adds 30 Mio. cells.

2.4. Evaluation of tip vortex properties

Horizontal slices of the CFD flow field at hub height are analyzed with an automated script developed at the IAG of University of Stuttgart [28] in order to extract the tip vortex position, their core radius and their vortex strength. Local minima of the $\lambda_2$ vortex criterion are identified to determine the vortex center. To determine the core radius, the extreme values of the tangential velocity are identified in streamwise and spanwise directions and the distance of the extrema from the core center is averaged. The vortex strength is given as the integral of the normal component of the vorticity over the vortex core area.

2.5. Experimental and analytical databases

In-situ measurements of wind fluctuations in the wake of a E-112 wind turbine, attributed to blade tip vortices, are compared to the simulation results. The wind flow is measured using UAS of type MASC-3, as described in 2.1. A detailed description of the experimental data and the analysis method to extract the tip vortex strength and core size can be found in [15]. The CFD results are also compared to the prediction of tip vortex properties from the semi-empirical model presented in [1], which has been used in previous helicopter wake encounter studies. It assumes an initial core radius $r_0$ of 5% of the chord length at the radial position $0.93R$ and an initial circulation of the vortex, based on the lifting line theory,

$$\Gamma_0 = \frac{\pi u_{\text{ref}}^2}{N_b \Omega} c_T$$

(1)

with $N_b$ the number of blades, $\Omega$ the rotational speed and $c_T$ the thrust coefficient of the rotor. A time-dependant decay function models the natural diffusion of the vortices, where $\psi$ denotes the vortex age as azimuth angle [1]:

$$r_c(\psi) = r_0 \sqrt{1 + \left( \frac{R}{r_0} \right)^2 a \frac{\Omega}{\psi}}$$

(2)

$$\Gamma(\psi) = \Gamma_0 e^{b\psi}$$

(3)

with $a = 5.10^{-6}$ rad/s and $b = -0.001932$ rad$^{-1}$ two empirical parameters. The semi-empirical parameters are taken from [1], where they have been fitted with a large database of detailed Particle Image Velocimetry (PIV) measurements of the flow field around helicopter rotors [29]. For more details about this formulation of a simplified vortex helix, the reader is referred to [1].

3. Results

In this section, the effects of the grid topology on the CFD prediction of tip vortex aging are assessed. First, the tip vortex aging in the CFD simulations is analyzed, with a focus on the effects of specific grid refinement on the spatial structures in the near-wake. Then, the vortex properties at $x/R = 0.5$ are compared to first experimental measurements of tip vortices behind a multi-MW wind turbine in the same conditions. Finally, the numerical and experimental core size and strength are compared to the semi-empirical vortex helix model.
3.1. CFD prediction of tip vortex aging in the near-wake

The simulated flow fields in the near-wake of the wind turbine are analyzed with the method described in section 2.4. Figure 4 compares the trajectory of the tip vortex cores in the simulation with and without refined tip vortex mesh. In the setup with finer grid resolution, some small fluctuations of the tip vortex position are observed around the trajectory of the baseline setup. They can be attributed to effects of the inflow turbulence, which is taken into account only in the finely resolved setup. Figure 5 shows the downstream evolution of the core radius, for both setups again. In the baseline setup, the core size increases slowly, with two plateaus for the radius values $r_c = 2.05$ m and $r_c = 2.3$ m. The grid resolution of $\Delta x = 0.5$ m limits the growth of the vortex core, which in turn results in a precision of 0.25 m in the radius values and the observed plateaus. In the refined setup, the core size increases slowly until the core suddenly expands at $x = 0.6R$, shortly before the end of the refined tip grid at $x = 0.7R$, which is marked by the vertical dashed line. The vortex tube widens as it enters the coarser grid, which also has an influence upstream due to flow field continuity.

**Figure 4.** Normalized core trajectory with and without refined tip vortex mesh. The vertical dashed line marks the end of the refined tip grid.

**Figure 5.** Core radius with and without refined tip vortex mesh. The vertical dashed line marks the end of the refined tip grid.

**Figure 6.** $\lambda_2$-Isosurface at the blade tip to highlight the influence of the variation in mesh resolution on the vortex structure and contours of the normalized streamwise velocity component. From left to right: baseline setup, baseline setup zoomed in the blade tip region, close view of the tip vortex in the baseline setup, close view of the tip vortex in the refined setup.
To understand the large differences in core size between the two grid resolutions, the vortex structure in the blade tip area is analyzed, too. Figure 6 shows the $\lambda_2$-isosurface for the blade at the horizontal position and the mesh close to the blade tip in a vertical cut, for the cases without (1st to 3rd plots from left to right) and with (4th plot) refined tip vortex ring. In both figures, the same $\lambda_2$ value is set to the isosurfaces. A thin vortex sheet in the wake of the blade is visible in the background of both figures. It quickly vanishes at the transition from the blade mesh to the background mesh due to higher numerical dissipation on the coarser grid. The shed vortex sheet rolls up to form the detached tip vortex at the tip as the blade rotates downwards. The gap in the $\lambda_2$-isosurface in the Chimera overlap region between the blade and background meshes in the 3rd plot of Fig. 6 is due to the sudden change of the grid resolution with a factor 1 to 10. Due to viscous forces, the velocity distribution adjusts to the new cell size and the vortex core widens as it enters the background mesh. In the last plot of Fig. 6, the tip vortex extends from the blade mesh to the refined tip mesh. A small gap is observed in the $\lambda_2$-isosurface, as the cell size increases with a factor 1 to 2 between the two mesh structures. The widening of the vortex tube is smoother in the refined setup compared to the baseline setup.

### 3.2. Comparison with measured data

The numerical results at $x = 0.5R$ downstream of the rotor are compared to the in-situ UAS wake measurements described in section 2.5. Table 1 compares the core sizes and strengths from the two computational setups and the two measured tip vortices, whereby the vortex strength $\Gamma$ is normalized by the highest value $\Gamma_{\text{CFD}}$ extracted from the CFD flow fields at this position. For consistency with the experimental data, the values of the normalized vortex strength are given with a precision of 0.01$[-]$.  

|                | $r_c$ [m] | $\Gamma/\Gamma_{\text{CFD}}$ [-] |                | $r_c$ [m] | $\Gamma/\Gamma_{\text{CFD}}$ [-] |
|----------------|----------|---------------------------------|----------------|----------|---------------------------------|
| CFD - baseline setup | 2.06     | 1.00                            | CFD - with tip mesh     | 0.60     | 0.95                            |
| in-situ measurement 1 | 0.66     | 1.09                            | in-situ measurement 2   | 0.55     | 0.90                            |

Table 1. Core radius and normalized vortex strength from CFD simulations and UAS measurements [15] 0.5$R$ downstream the wind turbine

In the measurement plane, the core sizes evaluated from the analysis of the UAS velocity signal [15] show the same magnitude as the ones simulated on the refined mesh. The deviation between numerical and experimental data amounts $\pm 8 - 10\%$. With regard to the uncertainties from experimental data and the determination of the same inflow conditions for the numerical simulation, it shows a decent agreement between the experimental and numerical results. As analyzed in the previous section, the baseline CFD setup produces tip vortices that are 2.5 time larger than on the refined setup and, thus, than the measured ones, too. A comparison of the normalized vortex strength shows more consistent results between the different approaches. A difference of 5% is observed between the two numerical setups. Again, the vortex strength evaluated from the measurements is in a range of $\pm 10\%$ relative to the numerical results, which is an acceptable agreement.

### 3.3. Comparison with the semi-empirical model

Figure 7 compares core sizes resulting from the UAS measurement flight, the vortex aging from the CFD simulations and the semi-empirical model. The black solid line represents the vortex
Figure 7. Core radius from semi-empirical model, from UAS measurements and from the CFD simulation, with and without refined tip vortex mesh. The vertical dashed line marks the end of the refined tip grid.

The aging function from equation (2). In the near wake, the model prediction lays about 11.5 and 2.5 times below the CFD prediction without and with tip mesh, respectively. A CFD simulation with finer grid resolution could help verify, if the simulated core radius size converges to the same size as the semi-empirical model. However, it was not possible in the present study due to the significantly increasing computational costs. To compare the tip vortex aging independently from the discrepancy in initial core size, the model prediction is shifted up with an offset. The offset is chosen such that the new aging function crosses the first tip vortices of the CFD simulations and the resulting curves are represented in Fig. 7 with the dashed blue lines. It appears that, on the coarser mesh, the vortex decay is larger than the natural diffusion modelled in equation (2). On the finer mesh, the evolution of the core size fits the aging function of the model. Thus, the semi-empirical parameter used in the aging function seems appropriate to the present case. A higher numerical dissipation of the vortical structures on the coarser mesh could explain the higher growth rate of the core radius in the baseline setup.

4. Discussion

The influence of the mesh topology on the tip vortex core size and evolution is described in section 3.1. Although the number of computational cells increased by one third due to the introduction of the refined tip vortex mesh, the resulting increase in computational costs was not only limited by the size of the computational setup. In order to ensure a Courant-Friedrichs-Lewy number lower than 1 for stability and convergence in all regions of the computational domain [30], the time step needs to be reduced, too. A physical time step corresponding to 0.25° azimuth was applied for the evaluated part of the simulations on the finely resolved setup, while it corresponds to 1.5° azimuth for the simulations on the baseline setup. At the end, the time step reduction by a factor of 6 had a higher impact on the computational costs of the refined setup than the
spatial resolution itself. The comparison of the tip vortex aging between the finely resolved numerical simulations and the semi-empirical model from [1], presented in section 3.3, shows a good agreement of the core size growth. However, a discrepancy is observed for the initial core size between the two approaches. The empirical formula introduced in [1] to estimate the initial core radius, based on the chord length at 93% of the rotor radius, predicts smaller core sizes than both CFD simulations and UAS measurements. Here, it should be noted that only two blade tip vortices could be evaluated from the UAS-measured wind signals and more measurements are needed to increase the value of this comparison. In the present study, the grid resolution for the tip mesh was determined by the size of the measured tip vortices, under assumption that at least 12 grid points are required through the vortex core to satisfactorily resolve and propagate it through the flow field. A local grid convergence study at the blade tip could nonetheless help to determine, how fine the tip vortices are for the considered wind turbine at the given operating point.

5. Conclusions
In the present paper, high-fidelity URANS simulations of the near wake of a multi-MW wind turbine are presented and the resulting flow fields are analyzed and compared to experimental and analytical data.

In order to compare the simulations with the in-situ UAS measurements in the wake of the real wind turbine, the inflow of the CFD simulations is determined based on the measured wind field. Two different computational setups are introduced in order to address the effects of the grid topology on the tip vortex aging in the near wake. The inflow turbulence is taken into account only in the refined simulation. To enhance the tip vortex conservation, an efficient local meshing strategy is adopted for the new grid topology along with the utilization of higher order numerical schemes. A novel cylindrical grid is introduced, which fits the tip vortex trajectory. To reduce total number of cells, coarsening with hanging grid nodes and larger cells in azimuth direction is applied in this structured mesh. The tip vortex trajectory remains unchanged with the new grid topology, but a reduction of tip vortex core size by a factor 3.4 was achieved in the refined setup. An analysis of the vortex structure in the tip region shows how the vortex tube widens in the baseline setup as it enters the coarser background mesh. The velocity distribution adjusts to the new cell size due to viscous forces. In the optimized setup, the finer resolution of the tip mesh limits the widening of the vortex tube. Although the tip vortex mesh contributes to only one third more cells in the computational setup, the computational costs are considerably increased due to the smaller time-step corresponding to 0.25° blade azimuth, as a consequence to maintain numerical stability in the small grid cells.

A comparison with the two evaluated tip vortices from UAS measurements shows good agreement with the fine CFD solution, as the simulated core radius equals the mean value of the experimental ones. The vortex strength is also compared and shows an acceptable agreement between the different approaches. Then, the aging process is compared to the semi-empirical model from [1]. The model predicts tip vortices which are 2.5 to 11.5 time smaller than the CFD simulations or the UAS measurements. It seems that the empirical relation used to determine the initial vortex core, fitted on helicopter data, predicts smaller core sizes for wind turbine wakes than numerical and experimental data. Nonetheless, the aging function of the models presents a good agreement with the refined simulations in the near-wake. On the coarser mesh, higher numerical dissipation leads to a more rapid widening of the tip vortices. Further numerical studies will be dedicated to the investigation of the initial core size of tip vortices with a grid convergence study, dedicated to the tip region only.
6. Acknowledgements
This research is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) within the framework of the German joint research project HeliOW (Grant number: 0324121). The authors gratefully acknowledge WRD GmbH for providing a generic recreation of the E-112 wind turbine and of SCADA data and the HLRS Stuttgart for providing computational resources.

References
[1] van der Wall B, Fischenberg D, Lehmann P and van der Wall L 2016 Impact of wind energy rotor wakes on fixed-wing aircraft and helicopters Proceedings of the 42nd European Rotorcraft Forum, Lille, France, 5–8 Sept. 2016 pp 1–28
[2] Strbac A, Martini T, Greiwe D, Hoffmann F and Jones M 2019 Analysis of rotorcraft wind turbine wake encounters using piloted simulation Proceedings of the 45th European Rotorcraft Forum, Warsaw, Poland, 17–20 Sept. 2019
[3] Wu Y T and Porté-Agel F 2012 energies 5 5340–5362
[4] Sørensen J N, Mikkelsen R, Sarmast S, Ivanell S and Henningson D 2014 Determination of wind turbine near-wake length based on stability analysis Journal of Physics: Conference Series vol 524 (IOP Publishing) p 012155
[5] Sarmast S, Dadfar R, Mikkelsen R F, Schlatter P, Ivanell S, Sørensen J N and Henningson D S 2014 Journal of Fluid Mechanics 755 705–731
[6] Schulz C, Letzgus P, Lutz T and Krämer E 2017 Wind Energy 20 253–268
[7] Lin M and Porté-Agel F 2019 Energies 12 4574
[8] Abkar M and Porté-Agel F 2015 Physics of Fluids 27 035104
[9] Schulz C, Letzgus P, Weihe P, Lutz T and Krämer E 2018 Numerical simulation of the impact of atmospheric turbulence on a wind turbine in complex terrain Journal of Physics: Conference Series vol 1037 (IOP Publishing) p 072016
[10] Tomaszewski J M, Lundquist J K, Churchfield M J and Moriarty P J 2018 Wind Energy Science (Online) 3
[11] Varriale C, De Marco A, Daniele E, Schmidt J and Stoevesandt B 2018 Aerospace 5 42
[12] Glabeke G 2011 The influence of wind turbine induced turbulence on ultralight aircraft, a cfd analysis Katholische Hogeschool VIVES, Oostende vol 99
[13] Bakker R, Visingardt A, Van Der Wall B G, Voutsinas S, Basset P M, Campagnolo P, Pavel M, Barakos G and White M 2018 Wind turbine wakes and helicopter operations: An overview of the gartuer hc-ag23 activities Proceedings of the 14th European Rotorcraft Forum, Delft, Netherlands, 18-21 Sept. 2018
[14] Horvat B, Hajek M and Rauleder J 2020 Analysing rotorcraft vortex encounter methods with a lattice-boltzmann method based gpu framework AIAA Scitech 2020 Forum p 0539
[15] Mauz M, Rautenberg A, Platis A, Cormier M and Bange J 2019 Wind Energy Science 4 451–463
[16] Rautenberg A, Schön M, zum Berge K, Mauz M, Manz P, Platis A, van Kesteren B, Suomi I, Kral S T and Bange J 2019 Sensors 19 2292
[17] Wildmann N, Bernard S and Bange J 2017 Renewable Energy 103 613–619
[18] Wildmann N, Ravi S and Bange J 2014 Meas. Tech 7 1027–1041
[19] Kroll N and Faßbender J 2005 MEGAFL ow - Numerical Flow Simulation for Aircraft Design
[20] Meister K, Lutz T and Krämer E 2009 Development of a process chain for detailed wake simulation of horizontal axis wind turbines
[21] Jameson A 1991 AIAA paper 1596 1991
[22] Menter F R 1994 AIAA journal 32 1598–1605
[23] Dol H, Kok J and Oskam B 2002 Turbulence modelling for leading-edge vortex flows 40th AIAA Aerospace Sciences Meeting & Exhibit, January 2002
[24] Schulz C 2018 Numerische Untersuchung des Verhaltens von Windenergieanlagen in komplexem Gelände unter turbulenter atmosphärischer Zuströmung (Shaker Verlag)
[25] Beneck J, Steger J, Doughearty F and Buning P 1986 Chimera. a grid-embedding technique Tech. rep. ARNOLD ENGINEERING DEVELOPMENT CENTER ARNOLD AFB TN
[26] Bühler M, Weihe P, Klein L, Lutz T and Krämer E 2018 Actuator line method simulations for the analysis of wind turbine wakes acting on helicopters Journal of Physics: Conference Series vol 1037 (IOP Publishing) p 062004
[27] 61400-1 I 2005 Wind turbines – part 1: Design requirements IEC 2005 International Electrotechnical Commission Geneva, Switzerland
[28] Lutz T, Meister K and Krämer E 2011 Near wake studies of the mexico rotor In proceedings of the EWEC conference pp 161–165
[29] van der Wall B and Richard H 2006 *Experiments in Fluids* **40** 798–812

[30] Blazek J 2015 *Computational fluid dynamics: principles and applications* (Butterworth-Heinemann)