CFD Simulations on Interference Effects between Offshore Wind Turbines

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Abstract. This paper presents results of detailed 3D CFD simulations of two 5MW wind turbines sited in the German wind farm Alpha Ventus which are located behind each other at half-wake conditions. The focus of interest in this study is put on wake-turbine interaction, in order to derive the main shadow effects and their influence on blade loads and power response of the downstream turbine. For this purpose, Detached Eddy Simulations (DES) were performed using the flow solver FLOWer from DLR (German Aerospace Center). To consider all relevant aerodynamic effects, the main turbine components are represented as direct model with resolved boundary layers. Measurement-based turbulent inflow conditions are prescribed to realistically account for the atmospheric boundary layer. In order to analyze the flow conditions in front of the downstream turbine, wake propagation and velocity spectra are evaluated and compared with the undisturbed atmospheric boundary layer. Their impact on loads and power production and their corresponding fluctuations is discussed by comparing these with the upstream turbine. It was found, that fatigue loads occurring at half-wake conditions are significantly higher for the downstream turbine, since blade load fluctuations are highly amplified by the unsteady wake of the upstream turbine.

1. Introduction

With the strive for clean, safe and economic energy production, the wind energy sector has become one of the biggest growth branches in the renewable energy sector. In the past three decades the energy production of a single turbine has increased by a factor of 500. This could be achieved by continuous technological progress leading to greater hub heights and rotor diameters of more than 120 m. Modern materials and manufacturing techniques allow for lower material input and cost-effective turbines. However, lightweight turbines and greatest possible reliability are only compatible objectives with the ability to accurately predict the loads acting on the blades during operation. In particular offshore, where maintenance is limited and their costs are high, this target is absolutely crucial for economic operation.

From flow-physical point of view the conditions inside an offshore wind farm are very complex. The operation within the atmospheric boundary layer which is unsteady by nature and characterized by turbulence, gusts and shear, results in a strong variation of the local velocity and angle of attack and hence leads to unsteady, nonlinear blade loads, even in the linear part of the airfoil polar [1]. Even greater complexity is induced to the flow in the wake of the wind turbines, where the tip region reveals large gradients and rotational motion due to the blades, whereas the core flow is characterized by reduced velocity, but enhanced turbulence intensity.
Regarding a shadowed turbine being immersed by the wake of an upstream turbine, the velocity deficit results in reduced power production. On the other hand, the increase in turbulence intensity directly leads to an increase in the dynamic loads, especially for half-wake conditions.

To accurately predict these loads, severe challenges are posed on the CFD process chain. The simplest approximation of modeling the impact of wind turbines on the flow field is the Actuator Disc Method (ACD) [2]. For the latter, different methods exist for distributing tabulated airfoil data on a permeable disc which are then introduced as body forces into the Navier-Stokes equations. A more sophisticated method of this approach is the Actuator Line Method (ACL) ([3, 4]), where the body forces are non-uniformly distributed on rotating lines representing the turbine blades. In order to obtain the most detailed view into the effects dominating the load response of the blades, the most sophisticated simulation technique – which is applied for the presented study – is that of directly modeling the entire wind turbine ([5, 6, 7, 8]). Therefore, the surfaces of the main turbine components such as the blades, hub, nacelle and the tower are meshed with resolved boundary layers. The benefit of this approach is that all unsteady, three-dimensional, viscous and non-linear effects are taken into account, without the need for further modeling. These include, for example, dynamic stall phenomena or interference effects from other turbine components like the tower shadow. However, it is also to be noted that compared to the previous simulation techniques the latter demands for the highest computational effort.

An overview of the applied turbulence modeling technique is given in the next section. In section 3, computational details are provided, followed in section 4 with presentation and discussion of the results. The conclusions are presented in Section 5.

2. Turbulence Modeling

In this study, turbulence shall be treated by applying the Delayed Detached Eddy Simulation approach (DDES) developed by Spalart [9]. The idea of this hybrid RANS/LES technique is to design a turbulence model such that it works as a RANS model within the surface boundary layer, in order to save computational time, while working in the outer flow regime as a sub-grid-scale model to resolve the dominant turbulent structures in LES mode. By such means, atmospheric turbulence is treated in LES mode to adequately model its propagation downstream. In contrast to the original DES97 formulation [10], DDES remedies grid-induced separation by modification of the DES length scale \( \bar{d} \). The turbulence model to which the DDES method is applied is the Spalart-Allmaras model with Edwards modification [11] that solves a transport equation for the quantity \( \hat{\nu} \) which is closely related to the turbulent eddy-viscosity \( \mu_t \) (Eq. 4):

\[
\frac{D\hat{\nu}}{Dt} = c_b, \bar{S}\hat{\nu} - c_{w1} f_w \left( \frac{\hat{\nu}}{\bar{d}} \right)^2 + \frac{1}{\sigma} \left[ \frac{\partial}{\partial x_j} (\nu + \hat{\nu}) \frac{\partial \hat{\nu}}{\partial x_j} + c_{b2} \frac{\partial^2 \hat{\nu}}{\partial x_i^2} \right],
\]

(1)

where the strain-rate norm \( \bar{S} \) and its auxiliary variables are defined as

\[
\bar{S} = \bar{S}^{1/2} \left[ \frac{1}{\chi} + f_{v1} \right]; \quad \bar{S} = \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \frac{U_i}{U_j} - \frac{2}{3} \left( \frac{\partial U_k}{\partial x_k} \right)^2; \quad f_{v1} = \frac{\chi^3}{\chi^3 + c_{v1}^3}; \quad \chi = \frac{\hat{\nu}}{\nu}.
\]

(2)

The wall term \( f_w \) and its corresponding auxiliary variables are defined as follows:

\[
f_w = g \left[ \frac{1 + c_{w3}^6}{g^6 + c_{w3}^6} \right]^{1/2}; \quad g = r + c_{w3} (r^6 - r); \quad r = \frac{\tanh \left[ \hat{\nu}/\bar{S} \kappa \bar{d}^2 \right]}{\tanh 1.0}.
\]

(3)

The model constants can be retrieved from Table 1. Finally, the turbulent eddy-viscosity \( \mu_t \) is calculated from

\[
\mu_t = \rho \hat{\nu} f_{v1}.
\]

(4)
Table 1: Coefficients of the Spalart-Allmaras turbulence model

| $c_{b1}$ | $σ$ | $c_{b2}$ | $κ$ | $c_{w2}$ | $c_{w3}$ | $c_{w1}$ | $C_{DES}$ |
|----------|-----|----------|-----|----------|----------|----------|----------|
| 0.1355   | 2/3 | 0.622    | 0.41| 0.3      | 2        | 7.1      | 0.65     |

The model’s behavior, whether it works as a sub-grid-scale, or as a classical RANS model occurs by the DES length scale $\tilde{d}$:

$$\tilde{d} = d - f_d \max(0, d - C_{DES} \Delta),$$

where the blending function $f_d$ is defined as

$$f_d = 1 - \tanh([8r_d]^3); \quad r_d = \frac{\nu_t + \nu}{(U_{ij}U_{ij})^{1/2} \kappa d^2}.\quad (6)$$

The closest wall distance is given by $d$, whereas $U_{ij}$ denotes the velocity gradient and $\nu_t$ and $\nu$ are the turbulent and molecular kinematic viscosity, respectively. In order to prevent from switching to LES mode within the surface boundary layer – this may happen for thick boundary layers and ambiguous grids – the blending function $f_d$ is close to zero to favor RANS mode. For $f_d = 1$ the original DES97 [10] formulation is obtained which uses the minimum of the wall distance $d$ and the constant $C_{DES}$ times the largest cell edge $\Delta$ as switch between RANS and LES.

3. Computational Details

3.1. The Wind Turbine

Both turbines considered in this study are Senvion 5M wind turbines which are sited behind each other in the German research wind farm Alpha Ventus. The 5M is a 5 MW offshore wind turbine with a rotor diameter of 126 m and a hub height of 95 m. The rotor is tilted by an angle of 6° and preconed by 4°. Both turbines operate at 12 rpm and all blades provide the same pitch settings of 11.2°. Although, the shaded turbine does not work in its design point, these constant settings seem appropriate to analyze the load response of the downstream turbine with respect to effects mainly attributed to shadowing. Therefore, in a first glance, also aeroelastic effects are excluded by considering rigid blades. This study presents also local blade loads at three different radial positions with the purpose to cover different regimes of reduced frequency $k = \frac{\omega c}{V}$, where $V$ is the resulting velocity in the airfoil reference system and $c/2$ the semi chord of the airfoil. The considered slices are located inboard at $r/R = 0.15$, where $k = 0.131$, mid at $r/R = 0.5$, where $k = 0.0482$ and outboard at $r/R = 0.9$, where $k = 0.0118$ (Fig. 2). According to Leishman [1], only for $k < 0.01$ the flow can be assumed steady or quasi-steady. Hence, unsteady aerodynamics can be expected for the inner half of the blade.

3.2. Computational Domain, Grids and Boundary Conditions

The computational domain represents part of the German research wind park Alpha Ventus and spans a volume of $1216 \times 560 \times 404 m^3$ including the wind turbines AV4 and AV5 (see Fig. 1). The turbines are aligned to the wind direction, which offers an inflow angle to the $x$-axis of $\gamma = 8°$, and positioned half-wave with a lateral offset of 63 m and a distance of 845 m ($\approx 6.7$ rotor diameters). Since regarding the wake development the directions of interest are parallel and perpendicular to the inflow wind direction $\gamma$, a wind direction aligned coordinate system $x, y, z$ and $y, z$, is introduced, having its origin in the hub of the AV4 (see Fig. 1).

The domain is composed of block-structured component meshes for tower and nacelle, spinner and the blades. Furthermore, several auxiliary meshes are required to provide an appropriate link between the components. All meshes are embedded into a background mesh being assembled within FLOWer using the overset grid technique [12]. As the turbulence model allows integration through the viscous sublayer, all meshes were created such to provide a fully resolved boundary...
layer with a wall normal first cell height of $y^+ \approx 1$. The meshes for the blades were created using an automated grid generation tool which has been developed at IAG [13]. The tool works on the meshing software Gridgen and creates c-type blade meshes based on the .iges geometry and several user specified parameters such as mesh size, dimensions, growth rates or point distributions, etc. Overall, one blade was discretized by approx. 3.5 million cells. The other meshes were created manually using the software Pointwise. In order to adequately represent the atmospheric boundary layer, the resolution of the background mesh is mainly $2 \times 2 \times 2 \text{ m}^3$. It is refined towards the wall to better resolve wall shear, whereas above a height of 280 m the cell sizes are gradually increased to save grid points. Since particular focus is put on preservation of the tip vortices over a long distance, an annular refinement mesh is introduced between both rotors and behind the downstream turbine. The used meshes and their sizes are summarized in Tab. 2. In total, the domain consists of approximately 110 mio. cells.

The boundary conditions of the domain are given in Fig. 1. At the inlet, a Dirichlet boundary condition prescribes the turbulent velocity profile. At the outlet and the upper plane, farfield conditions are applied, whereas both side planes imply periodic boundaries. All surfaces are treated as no-slip walls.

![Figure 1: Schematic view of the computational domain and the boundary conditions](image1.png)

![Figure 2: half-wake conditions and evaluation points $r/R$ for both turbines](image2.png)

| Name                  | Cells ($\times 10^9$) | No. | Motion | Description                                      |
|-----------------------|-----------------------|-----|--------|-------------------------------------------------|
| Tower+Nacelle         | 3.46                  | 1   | steady | Covers tower and nacelle, BL                     |
| Spinner               | 1.66                  | 2   | rotation | BL                                              |
| Joint                 | 0.78                  | 6   | rotation | Connects spinner and blade, BL                    |
| Blade                 | 3.62                  | 6   | rotation | BL                                              |
| Tip Vortex 1          | 9.98                  | 1   | steady | Tip refinement mesh of the wake of AV4           |
| Tip Vortex 2          | 2.73                  | 1   | steady | Tip refinement mesh of the wake of AV5           |
| Background            | 57.01                 | 1   | steady | Covers the surrounding of AV4 and AV5            |

3.3. Turbulent Inflow
The turbulent inflow data are obtained from a precursor LES simulation, performed at ForWind, Oldenburg, Germany, using the solver PALM [14]. The boundary conditions for the LES incorporate information from a WRF model which, in turn, is fed by measurements of the mast FINO1 that is located upstream of the AV4. The measurements were conducted at almost neutral conditions. In order to limit computational costs and with the purpose to check for converged loads, a signal of 60s was extracted from the resulting LES solution and made periodic [5].
Within FLOWer, the data are then interpolated at each timestep in space and time to the inlet plane of the background mesh [15]. Spatial interpolation is performed bilinear, whereas time interpolation was further developed using the FFT pack of [16]. The time averaged profiles of the velocity magnitude $V_{mag} = \sqrt{u^2 + v^2 + w^2}$, at the inlet and the virtual turbine position are plotted in Fig. 3.3. These results were obtained from a simulation without turbines. The sheared profile is characterized by anisotropic, non-homogeneous turbulence. However, as can be seen from streamwise turbulence intensity, dissipation occurs. An issue which is subject of current research.

3.4. Numerical Parameters
The convective fluxes are discretized by the second order central differencing scheme $JST$. For time discretization, an implicit algorithm is used with a timestep of 0.0416 s which is equivalent to 3° blade azimuth movement. For each timestep 30 inner iterations are performed. The long distance between the turbines requires very long simulation time for the wake of the $AV4$ to develop and finally interact with the $AV5$. In order to do so, a pre-calculation of 36 revolutions was performed before data was extracted for another 12 revolutions corresponding to one 60 s inflow period.

4. Results and Discussion
In the following, interference effects between the turbines $AV4$ and $AV5$ are presented. These cover both results of flow field and wake development, as well as the impact of those on power, rotor and blade loads. Due to confidential clauses the latter are normalized using appropriate mean values. Note that all mean values are computed over the evaluation period of 60 s. For the presented FFT results the Hann-window is applied.

4.1. Flow Field and Wake Development
A general overview of the flow field of the interacting wind turbines is conducted by visualizing the dominant vortex structures by means of an appropriate $\lambda_2$ iso-surface (Fig. 4). The contour showing the relative Mach number indicates local velocity changes with respect to $U_\infty = 15.27$ m/s (time- and spanwise averaged streamwise velocity at hub height). The near wake of the $AV4$ is characterized by regularly formed tip vortices which finally break down approx. 2.5 D downstream. Large part of the wake seems to degenerate, until it interacts with the $AV5$. In the core of the wake, the root vortices start moving three-dimensionally as the wake is getting unstable. An effect, which could be an indication for wake meandering.

More details regarding the horizontal wake development can be traced from an instantaneous contour of the relative velocity magnitude $V_{mag}/U_\infty$ at hub height (Fig. 5). As mentioned before, the break down and movement of the entire wake can be identified. This particularly influences the root region of the shadowed rotor which is affected by significantly changing velocity magnitudes. Moreover, it can be observed that the wake of the $AV5$ is asymmetric as one side is immersed by the wake of the upstream turbine, whereas the unshaded side depends on almost undisturbed atmospheric freestream conditions. Further downstream, due to mixing, this asymmetry tends to diminish.
A more quantitative analysis of the wake development and its unsteadiness is provided by time-averaged horizontal wake deficits and streamwise turbulence intensity profiles $T_i\gamma$ plotted in Fig. 6 for various downstream positions $x_\gamma$. The errorbars indicate the standard deviation of the fluctuations of $U_\gamma/U_\infty$.
of $U_\gamma/U_\infty$. The subscript $\gamma$ denotes properties in the $\gamma$-coordinate system. The plane upstream of the AV4 is characterized by a slightly asymmetric profile, featuring smaller velocities, but higher fluctuations for $y/D > 0$. Overall, ambient streamwise turbulence intensity is relatively low ($2-4\%$). When looking at the near wake of the AV4, the mean streamwise velocity falls to approx. $80\%$ of $U_\infty$ in the wake’s center. For $y/D < 0$ the shear layer is distinct and almost linear and fluctuations are small, whereas on the opposite side the ambient conditions result the shear layer to be more rounded, revealing significantly higher fluctuations. Due to the relatively low ambient turbulence intensity, recovery of the wake is fairly low. Hence, particularly the lower shear layer is very stable. Directly upstream of AV5 ($x_\gamma = -0.5$) the increasing turbulence intensity, only present between $0 < y/D < -0.5 D$, suggests the turbine to trigger fluctuations upstream. Downstream of the AV5, both wakes merge resulting in a local decrease of the velocity below $70\%$ of $U_\infty$. Interestingly, the increase in turbulence intensity is significantly higher behind the AV5, compared to the increase due to the AV4.

The spectra of the velocity fluctuations of $U_\gamma/U_\infty$ are shown in Fig. 7 and 8 for various evaluation points along $y/D = -0.15 R$ and $y/D = -0.9 R$, respectively. The former are representative for a streamline in the wake’s center, whereas the latter are located in the region of the border. The dashed lines indicate the rotor frequency $3P$ and higher harmonics. In both cases, it is seen from the higher harmonics of the $3P$-frequency, that the turbines induce high-frequency fluctuations upstream of the rotor. When looking at the wake’s center at $x_\gamma = 1D_{AV4}$, there is only a small amplification around the $3P$-frequency, since disturbances from the rotor are damped by the tower. Upstream of the AV5, axial velocity fluctuations are only slightly higher compared to the situation in front of AV4. In the region of the wake border, at $x_\gamma = 1D_{AV5}$, the frequency band around $3P$ is highly amplified. However, due to mixing with the surrounding flow, these amplitudes strongly decay towards the downstream turbine, yielding higher fluctuations only in the high frequency regime. The high amplitudes at low frequencies seen at $x_\gamma = -0.5 D_{AV5}$, indicate large scale lateral motion of the wake, traced from the periodic change in velocity at the evaluation point located in the shear layer of the wake.

![Figure 7](image1.png)  
**Figure 7:** Fluctuations of $U_\gamma/U_\infty$ along $y/D = -0.15 R$ at various downstream positions

![Figure 8](image2.png)  
**Figure 8:** Fluctuations of $U_\gamma/U_\infty$ along $y/D = -0.9 R$ at various downstream positions

4.2. **Power and Loads**

The normalized power output of the rotor is compared for both turbines vs. the azimuthal position of blade 1 in Fig. 9 over 12 revolutions. To compare the mean power reduction of the AV5, both predictions are normalized with the mean power of the AV4. Note that by using this
normalization, no conclusion can be drawn on the relative fluctuations. Regarding the general
trend, power has a local minimum as one of the blades passes the tower (i.e. at 60°, 180° and
300°). Fluctuations of up to 30% observed for the AV4 solely arise from atmospheric turbulence.
Mean power output of the shadowed turbine is reduced by 15% compared to the upstream
turbine. In spite of half-wake conditions, the shape of the power polar remains symmetric. This
behavior dramatically changes when looking at the polar diagram of the normalized axial force
of a single blade (Fig. 10). While for the non-shaded rotor area of AV5, the axial force remains
almost unaltered, it remarkably diminishes as the blade is more and more immersed in the wake
of the AV4. It is interesting to note, that the minimum load does not occur when the blade
passes the tower, but at around 240°. At that position the blade is completely immersed in that
part of the wake which offers an exceptional vertical and horizontal deficit. It is obvious, that
this asymmetric trust behaviour leads to oscillating (dynamic) loading on a variety of structural
parts and finally needs to be transferred into the foundation structure.

In order to assess the shadow effects with regard to fluctuations of power and loads, the
respective mean value, the properties are normalized in this case by the mean value of the
corresponding turbine. Moreover, to easily compare the fluctuations of both turbines, a third
curve is included which denotes the ratio of the amplitudes of AV5 and AV4. In Fig. 11 is plotted
the spectrum of the rotor power. Clearly visible, the peaks at the 3P-frequency and higher
harmonics point out the tower impact on power fluctuations. Relative to the corresponding
mean power, the fluctuations of the AV5 are 50% higher compared to the AV4. Also, the
frequency regime between 1-6 Hz is notably amplified. Considerably greater differences between
the signals are seen to occur when evaluating the spectrum of the axial force (Fig. 12). As
already notable from the large asymmetry in the polar diagram, the load fluctuations of the
AV5 peak at the blade passing frequency 1P, exhibiting 2.5 times higher amplitudes compared
to the AV4. Except for frequencies between 3-4 Hz again, the high frequency regime ranging
1-10 Hz is enhanced, revealing amplification factors of up to 10.

Lastly, spectra of the normalized normal coefficient at the radial positions defined in Fig. 2
shall render detailed information on local blade load fluctuations (Fig. 13). Normal force
The normalized power output of the rotor coefficient is normalized by the mean value obtained from each turbine at the corresponding radial position. When comparing the distributions obtained in the hub region at $r/R = 0.15$ with those gathered in the mid and outer portion of the blade (at $r/R = 0.5$ and $r/R = 0.9$), fundamental differences can be identified. When considering the innermost slice, both turbines underly practically the same load amplitudes at the $1P$-frequency and higher harmonics, but reveal significant amplification rates at lower frequencies. This is due to the fact that the inner part of the blade does not dive deep into the wake center, which would yield a distinct $1P$ dependency, but rather is imposed by the large scale motion of the wake discussed in Fig. 8, which induces the observed amplifications at low frequencies. By contrast to the hub region, the mid and outer portion of the blade shows a strong $1P$ dependency, as these parts reach the wake center of the $AV4$. It can be concluded that all slices considered here, are exposed to enhanced load fluctuations at high frequencies. This frequency regime of several $Hz$ is of great relevance regarding fatigue life of the composite blade structures [17] and therefore is important to be considered in the design process.

Figure 11: Fluctuations of the normalized power output of the rotor

Figure 12: Fluctuations of the normalized axial blade force of blade 1

Figure 13: Fluctuations of the local normalized normal force coefficient of blade 1 at $r/R = 0.15$ (left), $r/R = 0.5$ (middle) and $r/R = 0.9$ (right) : (…) $AV4$, (—) $AV5$, (—) $\frac{AV5}{AV4}$
5. Conclusions
In this paper detailed numerical simulations have been performed to investigate interference effects between wind turbines. The turbines were positioned originally as the turbines AV4 and AV5 in the German research offshore wind farm Alpha Ventus. A direct CFD model of the turbines was used. Pitch and rotational speed of both turbines were the same. The simulations were performed in DDES-mode using measurement-based LES inflow data of the maritime turbulent boundary layer. Regarding the wake development, the relatively low ambient turbulence intensity resulted in an exceptional preservation of the wake deficit in streamwise direction. In the far wake a break down of the wake could be observed and convincing evidence has been found in the velocity spectra that the wake undergoes large scale motion. This phenomenon and its relation to wake meandering will be part of future investigation. Further, it could be shown that particularly the downstream turbine triggers turbulence, both, upstream in the high frequency regime and downstream. In terms of power output the mean production of the downstream turbine is reduced by 15% compared to the upstream turbine. Due to the half-wake conditions, a strongly asymmetric load response in the axial blade force could be observed, resulting in more than 2.5 times higher load fluctuations at the 1P-frequency. The evaluation of spectra of the local normal force coefficient showed that the 1P-frequency is highly amplified for the downstream turbine in the mid- and outer portion of the blade, whereas in the root region both turbines exhibit the same fluctuations. The presented power and load evaluations showed that the presence of the wake of an upstream turbine significantly induces high frequency loads on a downstream turbine. A fact that is particularly important in terms of fatigue.

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References
[1] Leishman J G 2002 Wind energy 5 85–132
[2] Mikkelsen R 2003 Actuator Disc Methods Applied to Wind Turbines Ph.D. thesis Technical University of Denmark
[3] Troldborg N, Sørensen J N and Mikkelsen R 2007 Journal of Physics 75
[4] Troldborg N 2008 Actuator Line Modeling of Wind Turbine Wakes Ph.D. thesis Technical University of Denmark
[5] Meister K, Lutz T and Krämer E Journal of Physics (To be published)
[6] Meister K, Lutz T and Krämer E 2012 EUROMECH [528]
[7] Bekiropoulos D, Rieß R, Lutz T, Krämer E, Matha D, Werner M and Cheng P W 2012 DEWEK
[8] Johansen J, Sørensen N N, Michelsen J and Schreck S 2002 Wind Energy 5 185–197
[9] Spalart P R, Deck S, Shur M, Squires K, Strelets M K and Travin A 2006 Theoretical and Computational Fluid Dynamics 20 181–195
[10] Spalart P, Jou W, Strelets M and Allmaras S 1997
[11] Edwards J R and Chandra S 1996 AIAA journal 34 756–763
[12] Beneke J A, Steger J L, Dougherty F C and Buning P G 1986 Chimera. A Grid-Embedding Technique.
[13] Meister K, Lutz T and Krämer E 2009 EUROMECH [508]
[14] Raasch S and Schröter M 2001 Meteorologische Zeitschrift 10 363–372
[15] Troldborg N, Sørensen J N, Mikkelsen R and Sørensen N N 2013 Wind Energy
[16] Swarztrauber P 1982 Academic Press
[17] Mandell J F, Samborsky D, Combs D, Scott M and Cairns D 1998 Fatigue of composite material beam elements representative of wind turbine blade substructure Tech. rep. National Renewable Energy Lab., Golden, CO (US)