A NOVEL AND COST-EFFECTIVE APPROACH TO SIMULATING DYNAMIC STALL ON ROTATING WIND TURBINE BLADES WITH A CHANGING ANGLE OF ATTACK

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ABSTRACT
The flow around wind turbine blades dynamically stalls when the local angle of attack temporarily rises above the angle of static separation. This introduces increased loads, which can lead to the destruction of the blade. The research reported here provides a computational fluid dynamics setup in OpenFOAM that solves the unsteady Reynolds-averaged Navier-Stokes equations to investigate dynamic stall on WT blades. The rotating and pitching motion of the blades is implemented via a novel combination of a dynamic and a sliding mesh approach. Simulations are carried out with different mesh resolutions and the results are compared with experimental data. It is shown that the usage of wall functions in the boundary layer is not suitable for investigating dynamic stall. When resolving the boundary layer instead, the results correctly predict the characteristics of a dynamic stall hysteresis with a maximum deviation of 8%. With the help of the developed setup, the computational effort of investigating dynamic stall on a large wind turbine (rated capacity 20 MW) can be reduced by 10% to approx. $\approx 2 \cdot 10^6$ CPUh when compared to similar setups in the literature.

INTRODUCTION
The power of a wind turbine (WT) increases quadratically with its rotor diameter, which drives the increase in size of future WTs. These WTs will reach rated capacities of approx. 20 MW. The long, slender, and flexible rotor blades of such megastructures will be more susceptible to deformations compared to today’s rotor blades leading to dynamic changes in the local angle of attack (AoA). Besides the deformation of the blade, the AoA is affected by fluctuations in wind speed and turbulence and an altitude-dependent wind speed distribution, which becomes more important for increasing WT diameters. An AoA above the angle of static separation causes the flow at the profile to enter the range of dynamic stall, which leads to transient loads that excite aeroelastic interactions between the flow and the blade (Leishman, 2002). This additional excitation may lead to mechanical fatigue and in the case of resonance leads to the destruction of the rotor blade. The consideration of these loads and the associated aeroelastic stability of the rotor blade is therefore a decisive factor in the design of future WT structures (Veers et al., 2019; Adema et al., 2020).

Dynamic stall has been a subject of research in the field of helicopter aerodynamics for many years (Leishman, 2006; Corke and Thomas, 2015). The influence of dynamic stall on the blades has been researched by the means of experimental investigations as in Merz et al. (2017) and Schwermer et al. (2019) and of computational fluid dynamics (CFD) (Letzgus et al., 2019). A comparison between 2D and 3D simulations conducted in Kaufmann et al. (2017) has shown the importance of analyzing dynamic stall as a three-dimensional phenomenon, because of span-wise vortices travelling along the blade. According to Guntur and Sørensen (2015), the rotation of the blade leads to the delay of the initiation of the separation of the flow and therefore to increased loads. This is why the rotation of the rotor blade should be considered when analyzing dynamic stall. Due to the size of wind turbines, experimental data for dynamic stall events of full rotors (rotating) is only available for smaller WT s as in Butterfield et al. (1991) and Hand et al. (2001). To investigate dynamic stall on WT
megastructures, either experiments of scaled WTs as in Berger and Kühn (2018), or CFD simulations have to be conducted. In contrast to helicopter blades, the large rotors (Radius $R = 180 m$) lead to high Reynolds numbers ($Re \approx 2 \cdot 10^7$) and low Mach numbers ($Ma < 0.3$). Together with the complex physics of a dynamic stall event, these high Reynolds numbers are associated with a high computational effort. Therefore, CFD simulations of large rotors have only been carried out for static AoAs (Bangga et al., 2017; Bangga, 2018) (rated capacity = 10 MW) and for small rotors when also simulating a changing AoA (Letzgus et al., 2019; Guntur et al., 2016). The combination of the rotating and pitching motion of the blade for the latter cases has been implemented via an overset mesh or a deformable mesh approach, respectively. State of the art reduced order models for predicting loads due to dynamic stall on WT blades rely on experimental data or CFD results from existing airfoil geometries and are thus semi-empirical (Adema et al., 2020; Rocchio et al., 2020; Mohamed and Wood, 2021). Larger rotor blades will lead to modified airfoil geometries (Zalkind et al., 2019) for which the reduced order models have not been tested. Further, to the best of the authors knowledge, none of these models have been validated for Reynolds numbers of $\approx 2 \cdot 10^7$.

In the present work, a CFD setup for the open-source flow solver OpenFOAM v2012 is developed for investigating dynamic stall on rotating rotor blades with a changing AoA. The setup is to be used for a parameter study that aims to find the correlation of basic airfoil design parameters of WT megastructures with dynamic stall. With the results of the parameter study a reduced order model for dynamic stall can be developed, which is valid for airfoil geometries of future WT megastructures at high Reynolds numbers. This is helpful for predicting the transient loads in the design process and for developing new airfoil geometries that are less susceptible to dynamic stall. Because of the immense computational resources of approx. $3.1 \cdot 10^9$ CPUh per simulation required for such a study (scaled computational effort of the simulations in Letzgus et al. (2019)), the secondary objective of this work is to develop a cost-effective setup by reducing the computational effort to a minimum. The setup is validated with the experimental data from Schwermer et al. (2019). A functional parameter study requires the setup to capture the following characteristics of the dynamic stall hysteresis: the dynamic load peak and the further increase of the lift coefficient when surpassing the angle of static separation. A novel combination of sliding and dynamic mesh approaches is implemented to capture the rotational and pitching motion of the blades. Symmetry conditions of the rotor are taken into account and the SST model (Menter, 1994) provides turbulence closure for solving the unsteady Reynolds-averaged Navier-Stokes (URANS) equations. In a second step, this standard SST model is extended with the $\gamma – Re_{\theta}$ transition model by Langtry and Menter (2009) and the results are compared with each other. A driving factor of the computational effort is the number of cells of the mesh. Therefore, the mesh resolution necessary for accurately calculating integral loads, such as the lift, is determined by comparing two meshes for simulations of a pitching blade section.

**METHODOLOGY**

**Modelling Description**

The overall objective of the underlying research project is to take into account the detachment processes in the design of WTs. This requires an accurate prediction of these detachment processes by means of CFD simulations. The most accurate simulation method currently applicable for technically relevant flows is the Large Eddy Simulation (LES), which is used by Schneider et al. (2011) to simulate turbulent separated flow with a Reynolds number of $Re \approx 1 \cdot 10^6$. According to Zießle et al. (2020), approx. $20 \cdot 10^9$ cells are sufficient to reproduce a separation-induced transition on an airfoil by LES with a chord length of $c = 0.1 m$ (height-to-chord ratio $h/c \approx 0.3$) and the velocity in the free stream $u_\infty \approx 98 m/s$. These dimensions are associated with a Reynolds number of $Re \approx 2 \cdot 10^5$ related to the airfoil chord and a computational effort of $\approx 0.4 \cdot 10^9$ CPUh. However, the wind turbines to be investigated later are to be simulated at Reynolds numbers of $Re \approx 2 \cdot 10^7$ (Schepers et al., 2018; Bangga et al., 2018). According to Pope (2000), the dimension of the smallest eddies of a flow is $\approx Re^{-\frac{1}{4}}$. To maintain the same relative mesh resolution, the cell width in each spatial direction and the time step size would have to be reduced by a factor of $Re^{-\frac{1}{2}}$. Assuming ideal parallelization, this would increase the computational effort for $Re \approx 2 \cdot 10^7$ by a factor of $\approx 1 \cdot 10^6$. Thus, according to the current status, no LES of a wind turbine is feasible with a realistic Reynolds number and sufficient mesh resolution. Nonetheless, hybrid methods also have too high demands on the computational resources for simulations of the full blade of the large WTs. Assuming linear scalability of the computational effort of the Detached-Eddy Simulations (DES) conducted in Letzgus et al. (2019), a fully resolved DES of a large WT requires $\approx 2.2 \cdot 10^{10}$ CPUh. Consequently, and with a view to the overall research objective, the subject of this work are URANS simulations of large WTs.

The discretization of the governing system of equations is based on a 2nd order finite volume approach in space and time. The spatial discretization is a 2nd order upwind method according to Warming and Beam (1976) and the temporal discretization corresponds to the implicit three-point backward Euler scheme. The additional terms resulting from the turbulence are modelled by means of the SST (Menter, 1994). For comparison, a simulation with the $\gamma – Re_{\theta}$ transition model by Langtry and Menter (2009) is conducted. The influence of the mesh movement is taken into account by correcting the predominant fluxes in the affected cells. This is done by replacing the velocity with a relative velocity in all convection
Table 1 Non-dimensional cell sizes of the coarse mesh of test case A. The values for the fine mesh are half the size.

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The non-dimensional cells sizes normal to the wall are determined with the phase-averaged wall shear stresses $\tau_w$, the density $\rho$, the kinematic viscosity $\nu$ and the distance between the cell center and the wall $y$. Non-dimensional cell sizes perpendicular to the wall are calculated accordingly but with the chord-wise and span-wise cell sizes $\Delta x$ and $\Delta z$:

\[ y^+ = \frac{y \cdot \sqrt{\tau_w/\rho}}{\nu} \]  
\[ \Delta x^+ = \frac{\Delta x \cdot \sqrt{\tau_w/\rho}}{\nu} \]

Because of the applied pitch motion, the wall shear stresses and therefore the non-dimensional cell sizes are unsteady. The presented values are the maximum values in the respective areas for all RPAs. The cells of the surrounding domain are created with a constant growth factor of 1.2.

Test Cases

In this work, two cases are defined to investigate flow separation around a rotor blade with the DSA-9A airfoil shape. The radius of the blade considered is $R = 0.65$ m and the chord length is $c = 0.072$ m with a height-to-chord ratio of $\frac{h}{c} = 0.14$. In test case A, a section of the blade at $r = 0.77R$ is used with a span-wise length of $0.02m = 0.03R$ to simulate dynamic stall while ignoring the rotational motion of the blade. Simulating this case with two different mesh resolutions serves to test the setup and verify the necessary mesh resolutions for resolving integral loads. The computational domain of this test case A is shown in Fig. 1.

A fixed velocity of $u = 74.1$ m/s is specified at the inlet using a Dirichlet boundary condition resulting in a Reynolds number of $Re = 4.4 \times 10^5$. The inlet velocity corresponds to the resulting angular velocity at $r = 0.77R$ of the rotating blade. The flow is assumed incompressible and a constant static pressure is imposed at the outlet. A no-slip boundary condition is set on the blade itself and the boundary layers are assumed fully turbulent. A periodicity condition is applied at the span-wise edges of the blade section. All other boundary conditions correspond to a Neumann boundary condition with $\frac{\partial \phi}{\partial n} = 0$. Furthermore, a periodic pitching of the blade is imposed with a root pitch angle (RPA)

\[ \Theta(t) = 23.8^\circ - 6.2^\circ \sin(2\pi f_{rot} t) \]

and $f_{rot} = 23.6$Hz. The pitch axis lies at $c/4$ of the blade in the direction of axis Z. The angle of static separation is reached at an RPA of $\Theta_s = 26.5^\circ$ (Schwermer et al., 2019). The mesh resolution for the coarser mesh is given in Tab. 1. The non-dimensional cell sizes normal to the wall are determined with the phase averaged wall shear stresses $\tau_w$, the density $\rho$, the kinematic viscosity $\nu$ and the distance between the cell center and the wall $y$. Non-dimensional cell sizes perpendicular to the wall are calculated accordingly but with the chord-wise and span-wise cell sizes $\Delta x$ and $\Delta z$:

\[ y^+ = \frac{y \cdot \sqrt{\tau_w/\rho}}{\nu} \]  
\[ \Delta x^+ = \frac{\Delta x \cdot \sqrt{\tau_w/\rho}}{\nu} \]

Because of the applied pitch motion, the wall shear stresses and therefore the non-dimensional cell sizes are unsteady. The presented values are the maximum values in the respective areas for all RPAs. The cells of the surrounding domain are created with a constant growth factor of 1.2. The finer mesh resolution is created by cutting every cell in half for every spatial direction, increasing the overall cell count by factor 8. Thereby, the increased mesh resolution does not change the geometrical discretization.

In test case B, the full rotor with a combined rotational and pitching motion is analyzed. Two meshes for the full rotor blade are created in Pointwise©:

1. A coarse mesh with $\Delta x_{max}^+$ and $\Delta z_{max}^+$ shown in Fig. 2 but with the initial cell center height: $30 < y^+ < 50$. The boundary layer is modelled utilizing wall functions. Total number of cells = $5.5 \cdot 10^6$.

2. A finer mesh with cell sizes as shown in Tab. 2. The boundary layer is fully resolved. Total number of cells = $10.8 \cdot 10^6$. 

Figure 1 2D view of the computational domain of test case A

Pitch Axis

Flow Direction

x

y

$\Theta$
Figure 2 Computational domain of test case B (left) and detailed view of the blade and blade envelope (right)

<table>
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<th>Name</th>
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Table 2 Cell sizes of the mesh resolving the boundary layer (test case B)

A hyperbolic extrusion is applied to the structured surface mesh of the blade resulting in the boundary layer meshes consisting of quad cells. As in test case A, the cell sizes increase with a growth factor of 1.2 away from the wall. The same growth factor is used to create the cells in the surrounding domain. The blade hub is not considered in the mesh generation. In the direction of rotation, the periodicity of the geometry is used so that only one blade is simulated. While test case A has no rotational motion, test case B has two mesh movements. The complete computational domain is rotated along the rotation axis $Y$ (see Fig. 2) with a constant speed of $\omega = 2\pi f_{\text{rot}}$. According to the experiment, the pitch frequency is chosen to be identical to the rotor frequency $f_{\text{rot}}$, so that one rotor revolution corresponds to one pitch period. To simulate this complex superimposed mesh motion, a sliding mesh approach (cyclicAMI) is used on the edge between the mesh of the blade envelope and the outer computational domain (see Fig. 3). The cells at the blade envelope and the outer computational domain are not connected so that they can slide off of each other when the blade pitches. The face values of these two interfaces are computed via linear interpolation between neighboring cell values. A fixed velocity of $u = 2.4149$ m/s is specified at the inlet and a constant static pressure is imposed at the outlet. The flow is assumed incompressible. These conditions correspond to the experimental studies from Schwermer et al. (2019), which are used to validate the setup with test case B. A detailed description of the experimental setup at the German Aerospace Center (DLR) in Goettingen is provided in Schwermer et al. (2016).

The maximum Courant-Friedrichs-Lewy number (CFL number) for which the simulations converge is CFL $< 15$ for test case A and for test case B CFL $< 80$. This results in an azimuthal time step for test case B of $\Delta \psi \approx 1/13^\circ$, which corresponds to the pressure sensor sampling frequency of the experiment. To reduce the computational cost to a minimum, the maximum time steps are chosen for the simulations. The initial transient is determined by applying the approach in Ries et al. (2018) for scale-resolving simulations to the conducted URANS simulations. The instantaneous lift coefficient hysteresis are computed for the last 12 simulated revolutions (24 in total for test case B). With the help of an autocorrelation function, confidence intervals with a 95%-confidence level are determined for every time step. Stationarity (end of initial transient) is assumed when 95% of the lift coefficients for every time step fall within the estimated confidence intervals. The same procedure is applied for test case A by computing the confidence intervals with the last 11 pitch cycles. Thereby, in
Maximum Deviation

Figure 4 Phase averaged sectional lift coefficients for the coarse and fine mesh resolutions of test case A. The maximum sampling error for the phase averaged URANS values is $\pm 5.2 \cdot 10^{-5}$.

test case A 12 profile overflows are initially simulated for the transient of the flow, and 19 rotor revolutions for test case B. After the transient, 10 more profile overflows are simulated for test case A and 5 rotor revolutions for test case B to conduct phase averaged values of the flow. The statistical convergence of the phase averaged values is verified by determining sampling error intervals as in Ries et al. (2018). The intervals are visualized with error bars in the respective figures and 95% of the instantaneous values that are used for phase averaging fall within these intervals. The computational cost for test case B with the boundary layer resolving mesh resolution is $\approx 8 \cdot 10^4$ CPUh. Assuming linear scalability, a simulation of a large WT with a rated power of approx. 20 MW using this CFD setup requires $\approx 2.8 \cdot 10^6$ CPUh.

RESULTS

Test Case A

In test case A, a section of the blade at $0.77R$ is used to verify the necessary mesh resolution for resolving integral loads during a dynamic stall event. For the future research of large WTs, the parameters to be investigated are the lift and the drag, which depend on the pressure distribution on the airfoil. According to Clancy (1975), the sectional lift coefficient is calculated with the velocity $u$, the lift force per unit span $l$, and the chord length $c$:

$$c_l = \frac{l}{\rho u^2 c} \quad (4)$$

In Fig. 4, the sectional lift coefficients for the two mesh resolutions of test case A are visualized as a function of the RPA $\Theta(t)$. In both cases the minimum lift occurs at $\Theta(t)_{\text{min}} = 17.6^\circ$. With an increasing RPA, the lift increases and a maximum is reached at $\approx 29.7^\circ$. Inversely, the lift decreases when the RPA decreases. The characteristic lift hysteresis loop of a dynamic stall event as described in Butterfield et al. (1991) is captured for both mesh resolutions and the lift for a decreasing RPA is lower than for an increasing one. There is no dynamic load peak (lift overshoot) at $\Theta(t)_{\text{max}} = 30^\circ$, which would be characteristic for a dynamic stall event. However, this is in accordance with the results from Guntur et al. (2016) and is due to the missing influence of the rotation of the blade. The maximum deviation between the two simulations occurs at $\Theta = 29^\circ$ during the downstroke and amounts to 0.85%. These results indicate that $\Delta x^+ < 700$ and $\Delta z^+ < 2800$ are sufficient for investigating the lift hysteresis of a dynamic stall event. It should be noted that refining the mesh even further and thereby increasing the cell count by factor 8 could decrease the maximum deviation. However, a simulation of a large WT with such a mesh would require $\approx 70 \cdot 10^6$ CPUh which is unfeasible for a parameter study.

Test Case B

In test case B, the full rotor with a combined rotational and pitching motion is simulated and the results are validated with the experimental data from Schwermer et al. (2019). The phase averaged values are calculated with 4557 data points per rotor revolution. The resulting sectional lift coefficients of test case B are visualized in Fig. 5. The error bars for the experimental data from Schwermer et al. (2019) are visualized for every 440 data points.

The results of the simulation utilizing wall functions underpredict the minimum lift at $\Theta = 17.6^\circ$ by $\approx 10.5\%$. Increasing the RPA leads to an increase of the lift until $\Theta \approx 27.8^\circ$. The dynamic lift peak happens $2.4^\circ$ earlier than in the experiment and is overpredicted by $2.7\%$. Exceeding this RPA, the lift decreases which is a non-physical behavior compared to the experiment. During the downstroke motion, the lift is underpredicted by up to 40%. The simulation with the standard SST
model and resolved boundary layer predicts the lift within the experimental uncertainties during the upstroke motion of the blade for $18.6^\circ < \Theta < 27^\circ$. For $17.6^\circ < \Theta < 18.6^\circ$, the maximum deviation is 2.7%. When exceeding $\Theta = 27^\circ$ the lift curve flattens as in the experiment and the dynamic lift peak at $\Theta_{\text{max}} = 30^\circ$ is predicted within the experimental uncertainties. The maximum deviation during the upstroke motion of approx. 6.7% occurs for $\Theta = 28.67^\circ$. In analogy to test case A, the lift is lower during the downstroke than during the upstroke motion. The lift during the downstroke is captured within the experimental uncertainties for $30^\circ > \Theta > 21.4^\circ$. Between $21.4^\circ > \Theta > 17.6^\circ$ the maximum deviation is 8.2%. As in the experiments, the sampling error increases for $\Theta > 27^\circ$ during the upstroke and for $\Theta > 21^\circ$ during the downstroke motion, which is due to the unsteadiness of a dynamic stall event. For the SST model extended with the $\gamma$-Re$_\theta$ transition model, the upstroke motion is captured within the experimental uncertainties for $23.5^\circ < \Theta < 28.5^\circ$. The maximum deviation between $17.6^\circ < \Theta < 23.5^\circ$ is 3.7%. The results show a similar flattening of the lift curve as the results from the standard SST model but the maximum deviation is reduced to 5.4% for $27^\circ < \Theta < 30^\circ$. The largest difference between the two
A comparison between the two meshes shows that the results are highly dependent on the treatment of the boundary layer. It is evident that modeling the boundary layer with wall functions is not suitable for investigating dynamic stall because the flow detaches prematurely and the characteristic lift hysteresis is not captured. By contrast, the mesh resolving the boundary layer captures the distinct dynamic stall hysteresis for both turbulence models. The $\gamma$-$Re_\theta$ transition model improves the results during the upstroke motion when the AoA exceeds the angle of static separation. However, the downstroke motion and the reattachment of the flow is predicted more accurately by the standard SST model. An explanation for this behavior can be found in the mesh resolution of the boundary layer. For the mesh resolving the boundary layer, both $\Delta x^+$ and $\Delta z^+$ correspond to the cell sizes of the coarse mesh of test case A while $y^+$ exceeds the recommended limits. The cell sizes at the wall are therefore examined to analyze the deviations of the two turbulence models. The $y^+$ values of the standard SST model for the maximum deviation during the upstroke motion at $\Theta = 28.67^\circ$ are visualized in Fig. 6. The graphs show that the highest $y^+$ values occur at the leading edge ($y^+ < 4$), which is in accordance with the high wall shear stresses to be expected in this region. The $y^+ < 1$ recommendation is not met for 2 pressure probes which are used to calculate the lift coefficients. It could be the case that the pressure values at these probes are causing the deviation from the experiment. To locally compare the experimental and URANS pressure distributions on the blade, the non-dimensional pressure coefficients are calculated as

$$c_p = \frac{p - p_{\infty}}{0.5 \rho u^2}$$

with the pressure on the blade $p$ and the pressure in the freestream $p_{\infty}$. Surprisingly, Fig. 7 shows that for the standard SST model, the probe close to the leading edge ($x/c = 0.028$) predicts the pressure coefficient within the experimental uncertainties, despite $y^+ \approx 2.5$. The maximum deviation for probes with $y^+ > 1$ is 4.1%. This is consistent with the good results from test case A where $y^+ > 1$ at the leading edge of the coarse mesh. Instead, the highest deviations of up to 101.3% occur between $0.6 < x/c < 0.85$ on the suction side of the blade for two probes with $y^+ < 1$. In Fig. 6, it can be seen that $y^+$ reaches a minimum for $x/c = 0.39$, which is equivalent to the wall shear stress and therefore the velocity gradient reaching a minimum (see Eq. 2). This is an indication of a separation point of the flow and thus, the two pressure probes being located in an area of separated flow. Since the flow is assumed fully turbulent with the standard SST model, the transition of the boundary layer is not considered, which can lead to errors in predicting the lift (Michna et al., 2021) and the location of the separation point (Dong et al., 2019). Extending the SST model with the $\gamma - Re_\theta$ transition model improves the prediction of the pressure between $0.6 < x/c < 0.85$ to a maximum deviation of 35%. However, the transition model overpredicts the pressure at the leading edge ($x/c = 0.109$) by 30%. The pressure coefficients on the suction side of the blade are identical for both models. This leads to the conclusion that the $\gamma - Re_\theta$ model is able to improve the simulation results when $y^+ < 1$ while the standard SST model proves to be less sensitive to $y^+ > 1$. 

Figure 7 Phase averaged pressure distributions of URANS and experiment at $\Theta = 28.67^\circ$ during upstroke. The triangles are the pressure values from the experiment with the color corresponding to the respective cell sizes at these positions in the simulation (green: $y^+ < 1$; red: $y^+ > 1$).
CONCLUSIONS

A cost-effective CFD setup for simulating dynamic stall on rotating rotor blades with a time-variable angle of attack was developed. The novel combination of sliding and dynamic mesh approaches captures the superimposed rotational and pitching motion of the blade. The setup solves the URANS equations with the SST turbulence model by Menter (1994), which can be extended with the $\gamma$-Re$_\theta$ transition model by Langtry and Menter (2009).

The computational effort of simulating a large WT (rated capacity 20 MW) was estimated to be approx. $\approx 3.1 \cdot 10^6$ CPUh. With the help of this setup the computational effort was reduced by 10% to approx. $\approx 2.8 \cdot 10^6$ CPUh. Accurate prediction of integral loads during a dynamic stall event limits cell sizes perpendicular to the wall to $\Delta x^+_{\text{max}} < 700$ and $\Delta z^+_{\text{max}} < 2800$. A comparison with the experimental data from Schwermer et al. (2019) showed that the results are dependent on the treatment of the boundary layer. Wall functions have proven to be unsuitable, as the lift decreases in a non-physical way after exceeding the angle of static separation. The maximum deviation between the lift coefficients of the experiment and the simulation is 40% and occurs during the downstroke motion of the blade. By contrast, when resolving the boundary layer instead of using wall functions, the simulation captures the distinct dynamic stall hysteresis for both turbulence models. During the upstroke until the angle of static separation, the maximum deviation for the standard SST model is 2.5% and 3.7% for the SST $\gamma$-Re$_\theta$ model. When exceeding this angle, a further increase in lift can be observed which is characteristic for a dynamic stall event. For angles of attack higher than the angle of static separation during the upstroke motion, the $\gamma$-Re$_\theta$ model improves the results by reducing the maximum deviation from 6.7% to 5.4%. The dynamic load peak is predicted within the experimental uncertainties for both models. The reattachment of the flow is captured within the experimental uncertainties for the standard SST model while being underpredicted by up to 39.7% by the $\gamma$-Re$_\theta$ model. An analysis of the local pressure coefficient distribution showed that the $\gamma$-Re$_\theta$ model can reduce the deviation from 101.3% to 35% in areas of separated flow when the non-dimensional cell sizes at the wall meet $y^+ < 1$. However, in areas of the blade where $y^+ > 1$, the deviation is increased from 4.1% to 30%. It can be said that the standard SST model is less sensitive to local coarse mesh resolutions while the $\gamma$-Re$_\theta$ model depends upon $y^+ < 1$ for the whole airfoil. Therefore, the results could be improved by refining the mesh in the vicinity of the leading edge for the $\gamma$-Re$_\theta$ model, which would increase the computational effort.
**NOMENCLATURE**

**List Of Symbols**

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<tr>
<td>$\Phi$</td>
<td>-</td>
<td>Transformed Quantity</td>
</tr>
<tr>
<td>$\psi$</td>
<td>(^1/\circ)</td>
<td>Azimuthal time step</td>
</tr>
<tr>
<td>$\omega$</td>
<td>rad(\cdot)s(^{-1})</td>
<td>Angular velocity</td>
</tr>
</tbody>
</table>

**Subscripts**

- max: Maximum
- min: Minimum
- rot: Rotor
- s: static separation
- $\infty$: Infinity

**Operators**

- $\Delta$: Delta - Difference
- $\partial$: Partial
Abbreviations
AoA Angle of attack
CFD Computational Fluid Dynamics
CFL Courant-Friedrichs-Lewy
DES Detached-Eddy Simulation
LES Large-Eddy Simulation
RPA Root pitch angle
URANS Unsteady Reynolds-Averaged Navier-Stokes
WT Wind turbine

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