Modeling the static and dynamic characteristics of a wind turbine airfoil and validation with experimental data

Galih Bangga\textsuperscript{1,\dagger}, Gerrit Kampers\textsuperscript{2}, Pascal Weihing\textsuperscript{1,3}, Matthias Arnold\textsuperscript{3}, Timo Kühn\textsuperscript{3}, Michael Hölling\textsuperscript{2}, Thorsten Lutz\textsuperscript{1}

\textsuperscript{1}Institute of Aerodynamics and Gas Dynamics (IAG), University of Stuttgart, 70569 Stuttgart, Germany
\textsuperscript{2}ForWind, Institute of Physics, University of Oldenburg, 26111 Oldenburg, Germany
\textsuperscript{3}Wobben Research and Development GmbH, 26607 Aurich, Germany

\dagger Corresponding author

E-mail: \{bangga,weihing,lutz\}@iag.uni-stuttgart.de, \{g.kampers,michael.hoelling\}@uni-oldenburg.de, \{matthias.arnold,timo.kuehn\}@enercon.de

Abstract. Dynamic stall modeling remains one of the most difficult topic in wind turbine aerodynamics despite its long research effort in the past. In the present studies, comprehensive investigations involving CFD, engineering models and experimental data were performed within the joint collaborative work DSWind. Both static and dynamic characteristics of a pitching wind turbine airfoil under a turbulent boundary layer flow were considered. The results indicate that optimized time-accurate CFD calculations can serve as reference data for verifying the engineering models, which can be potentially used for tuning the models under different air flow conditions.

1. Introduction

An accurate prediction of wind turbine blade loads is strongly influenced by many parameters including 3D and unsteady effects. The first mainly occurs in the root and tip areas of the blade due to radial flow and induced velocity influences, respectively [1]. The latter can occur due to variation of the inflow conditions caused by yaw misalignment, wind turbulence, shear & gusts and aeroelastic effects of the blade. It is already well known that dynamic loads acting on wind turbine blades are difficult to be predicted, despite their importance for wind turbine life time assessment. This is particularly true when the blade section operates at high angle of incidence near stall in combination with complex operating conditions like the changes of the wind speed, its direction and turbulence. As a result, the angle of attack seen by the local airfoil section changes over the time, which can manifest as the dynamic stall (DS) effect. Experimental studies [2–4] have indicated that the aerodynamic forces can differ significantly in comparison to the static condition [5]. The dynamic stall phenomenon involves flow separation and reattachment due to a rapid unsteady motion, causing a greater structural stress than the static stall condition. Despite its first long finding and research in rotor aerodynamics, the phenomenon is still not well understood for wind turbine applications [6]. DS is often initiated
by the generation of a leading edge vortex (LEV), which increases positive circulation effect on the airfoil suction side causing delayed stall. This intense leading edge vortex is convected downstream along the airfoil towards the trailing edge. Shortly afterwards, the trailing edge vortex (TEV) with opposite rotational direction than LEV is formed. TEV often occurs only within a very short period of time before it pushes the leading edge vortex towards the wake area. This onset may result in a significant drop of the lift coefficient ($C_L$) and needs to be considered in the structural design of the blade. Despite the long effort in investigating the phenomenon, a complete physical understanding and accurate predictions have not yet obtained to the date. One main aspect is the lack of reliable experimental data for adjusting the simplified models. This is particularly important for airfoils employed in a wind turbine blade. These airfoils are usually operating at much higher Reynolds numbers than the actual wind tunnel measurement and it is often too expensive to have enough measurement data for all sections along the blade radius, not to mention the interpolated geometry in between two adjacent airfoil sections. It has been shown that the prediction accuracy of blade element computations improves by providing a sufficient number of airfoil data along the blade [7].

2. Objectives
In the present work static and dynamic characteristics of a wind turbine airfoil will be investigated. More importantly the paper is aimed at looking for possibilities to replace experimental data by computational fluid dynamics (CFD) computations. The results of the simulations will be compared with experimental data and widely used semi empirical models. Weaknesses of existing dynamic stall modeling shall be identified, and possible corrections to those limitations will be described along with calculation examples. Furthermore, the studies also attempt to investigate the sensitivity of engineering models to changes in the static polar data and the challenges in dynamic stall modeling at a very high reduced frequency.

3. Methodology
The present studies were carried out within the joint research work (DSWind) at the University of Stuttgart in collaboration with ENERCON and the University of Oldenburg. High fidelity simulations (URANS & DDES) of wind turbine airfoils were carried out in the work as reliable database. The eddy resolving scale DDES simulations are employed in the present studies especially for reference data at the full scale Reynolds number ($Re$) where experimental data is missing and to cover for the weakness of URANS with regards to post stall predictions. The results serve as a basis for validating but also for improving dynamic stall models available in literature.

3.1. Experimental Setup
To validate the results, the well known low $Re$ experimental data from the measurement campaign conducted at the Ohio State University (OSU) [9] will mainly be used for comparison. Leading edge grit (turbulator) was applied in this measurement campaign to force flow transition. Furthermore, an additional measurement campaign to support the study at low $Re$ for the static polar data was carried out in a closed-loop wind tunnel at the University of Oldenburg. The tunnel features a 1m x 0.8m x 2.7m closed test section at a maximum Reynolds number of 1000K. The wind tunnel is sketched in Figure 1. The airfoil is mounted vertically in the middle of the test section 1.1 m downstream from the nozzle and its suction side is pointing towards the observer. The measured airfoil has a chord length of 0.3 m and is fixed to two rotating plates at its ends. The lift and drag forces as well as the pitching moment around a quarter chord position were measured. This later experimental dataset is used to highlight the impact of the wind tunnel effects for the static force measurement at high angles of attack ($\alpha$).
3.2. Numerical Setup

The CFD simulations were carried out using the compressible code FLOWer from the German Aerospace Center (DLR) [10]. The code has been extended for wind turbine applications at IAG - University of Stuttgart intensively in the last years [11, 12]. CFD simulations were performed for the National Renewable Energy Laboratory (NREL) S801 airfoil (13.5 % relative thickness) at two low and one full scale $Re$ of 510K, 1000K and 5300K, respectively. Both the static and dynamic conditions were simulated assuming a fully turbulent boundary layer. In the absence of measurement data at the full scale Reynolds number ($Re = 5300K$), the dynamic stall modeling will be compared only with the CFD simulations.

| Grid Cells/Name                | Mesh-A | Mesh-B | Mesh-C | Mesh-D |
|--------------------------------|--------|--------|--------|--------|
| Circumferential                | 256    | 256    | 544    | 544    |
| Boundary Layer                 | 64     | 64     | 64     | 64     |
| Normal                         | 128    | 128    | 128    | 128    |
| Spanwise                       | 1      | 1      | 224    | 1      |
| Total                          | 0.048M | 0.046M | 42M    | 0.233M |
| $y^+$                          | < 1.0  | < 1.0  | < 1.0  | < 1.0  |
| Span                           | -      | -      | 2.7    | -      |
| Farfield distance              | 150c   | wind tunnel size | 123c | 123c |
| Topology                       | O-mesh | O-mesh | O-mesh | O-mesh |
| Outer domain                   | Circular | Wind tunnel | Square | Square |
| Inner-Outer connection         | Joined | Chimera | Chimera | Chimera |
| $\Delta t$ Static             | $t_c/100$ | $t_c/100$ | -      | -      |
| $\Delta t$ Dynamic            | $T/8000$ | $T/8000$ | $T/4000$ | $T/4000$ |

Four different meshes were applied in the study, namely a 2D standard URANS mesh (Mesh-A), mesh incorporating the tunnel wall (Mesh-B) to incorporate the tunnel effects, DES-dedicated mesh (Mesh-C) and a 2D version of the DES-Mesh by applying only 1 grid cell in

Figure 1: Sketch of the closed test section setup for the airfoil characterization (side view). The airfoil model is mounted vertically on two axes with attached force sensors [8].
the spanwise direction (Mesh-D) which runs in URANS mode, see Table 1 and Figure 2. All CFD calculations employ Mesh-A except stated otherwise. Grid independency studies have been done in advance for each grid before the simulations were carried out. The SST [13] and SA [14] models were applied in the 2D URANS simulations to close for the turbulence equations. The DES simulations utilize the Delayed-DES version based on the SST background turbulence model.

4. Results
In this section, the results of the studies are evaluated and discussed. The detailed analyses will be performed firstly for the static airfoil characteristics for two different Reynolds number in Section 4.1. Then, the obtained knowledge will be transferred for simulating the dynamic characteristics of the airfoil in Section 4.2

4.1. Static Characteristics
Figure 3 shows the static lift data of the S801 airfoil at \( Re \) of 510K (3a), 1000K (3b), and 510K incorporating the tunnel wall effects (3c). It can be seen in Figure 3a that OSU data has a smaller stall angle and maximum \( C_L \) than the present experimental data which can be attributed to differences on the boundary layer tripping influence. Figure 3a shows that CFD predictions agree fairly well for most \( \alpha \) ranges. The static stall angle can even be predicted accurately though little deviation is observed on the predicted maximum \( C_L \). In Figure 3b, both turbulence models are consistent for the negative stall predictions but deviate in the positive stall regime. Here the SST model has a better accuracy in stall prediction than the SA model. A similar prediction result for the DU 96-W-180 airfoil at \( Re = 1300K \) was documented in [15]. Interestingly, CFD predictions and the reference data from OSU slightly differ with the present experimental data at large \( \alpha \) above 30°, not only in terms of the magnitude but also the gradient. To investigate the cause, the CFD simulation incorporating the wind tunnel wall is included in Figure 3c using Mesh-B. It can be seen that the gradient of lift is now fairly comparable with the present experimental data, though the magnitude is larger. The occurrence of the wind tunnel wall creates a blockage effect which accelerates the flow locally especially on the suction side of the airfoil, as the wake expands and the area between the tunnel wall and the wake edge becomes smaller. This causes a further reduction in pressure level and creates an additional lift component.

In Figure 4, the static drag data is presented for the investigated cases. The OSU data has smaller drag value in the stall regime than the present measurement data for \( Re = 510K \). The present data also shows stronger stall gradient at \( \alpha \approx 20^\circ \), in contrast to the OSU data that progresses more gradually. The CFD prediction for the SA model is closer to the present experiment, but for the SST model it is closer to the OSU experiment. Having a look at the effect of the tunnel wall, Figure 4c shows that modeling the tunnel wall causes the SST prediction to be closer to the present experimental data at this low \( Re \) value. The tunnel wall model also improves the stall prediction in the negative stall regime. Increasing the Reynolds number to 1000K reduces the gap between the present experiment with the OSU data. Both turbulence
models also have a good performance at this $Re$, except for the fact that the negative stall angle is not correctly predicted as has been seen already for the $Re510K$ case.

The static pitching moment data about the quarter chord point is presented in Figure 5. Similar with $C_D$, $C_M$ drops stronger in the present experiment than the OSU data at $\alpha \approx 20^\circ$. The present data also shows more negative $C_M$ in the post-stall regime. The characteristics are not observed for the larger Reynolds number. This indicates that the type and position of turbulator used have a strong influence on the stall characteristics especially at low $Re$ where transition is more pronounced. The employed leading edge grit may cause the OSU data to drop much earlier by approximately $3^\circ$. Similar to above observation, one can notice as well that the wind tunnel wall influence the CFD results.
4.2. Dynamic Characteristics

In this section, the dynamic characteristics of the airfoil at several mean angles of attack \( \alpha \) of 8\(^\circ\), 14\(^\circ\) and 20\(^\circ\) shall be investigated. CFD predictions are compared with the experimental data and the widely used Leishman-Beddoes (LB) model [5] with the constants derived from [16] (some literature mentions it as Beddoes-Leishman model, e.g. [16]) and the 2nd order Snel model [17]. The static polar data from OSU measurement was used for the polar reconstruction except stated otherwise. The SA turbulence model is applied for most cases according to preliminary studies conducted for the S809 airfoil at the same Reynolds number in [6]. These results are still relevant for the present airfoil as shown in Figure 6. In contrast, the SST model is applied for the higher \( Re \) value since it delivers better static stall prediction at higher \( Re \) as already shown in Section 4.1.

In Figure 7a, it can be seen that 2D URANS CFD, LB-model and Snel-model provide very similar predictions except in the downstroke regime. The CFD prediction has a much larger lift level than the experimental data and the models. Despite that, it can be seen that the pitching amplitude \( \Delta \alpha \) in the experiment is actually larger than the specified 10\(^\circ\), where it already reaches the stall regime. Turbulator effects can also be the reason of the discrepancy as shown already for the static polar data in Figure 3a. Note that the OSU polar data is the one used for reconstructing the dynamic polar in the engineering models. By replacing the static OSU data with the static CFD Polar (SA-model) for the reconstruction process in Figure 8a, the predictions of the simplified models change considerably. The dynamic lift value is now becoming closer to the CFD data.

In the second assessment in Figure 7b, \( \Delta \alpha \) in the experiment is equal with the intended 10\(^\circ\), which yields a good agreement with CFD. The LB and Snel models also deliver good agreement with the measured values. A slight discrepancy is shown for the Snel model, where it predicts earlier stall and earlier lift recovery in the downstroke regime. By replacing the static OSU data to the static CFD data for the reconstruction, Figure 8b indicates a strong deviation between the engineering models in comparison with CFD and experiment. This observation is in contrary with the above observation for \( \alpha = 8^\circ \). This already indicates that the dynamic CFD simulations are sensitive to turbulator effects in the near stall regime, but is less sensitive as the degree of separation becomes stronger. In fact, flow separates from the leading edge directly when stall occurs, which makes the turbulator effect less pronounced. This also indicates a dependency upon the stall characteristics of the airfoil, i.e., dependent on the airfoil thickness and leading edge radius.

Figure 7c shows the most complicated case, where the airfoil is fully operating within the stall regime. Unfortunately the actual pitching angle deviates from the intended 10\(^\circ\) in the experiment. It can be observed that CFD indicates delayed lift stall of \( \approx 3^\circ \). This might be partly caused by the inaccurate pitching description, but also indicates the the difference between the static OSU data with the present static CFD and experimental data in Figure 3. Furthermore, shedding effects within the downstroke regime are overestimated as well due to the coherent vortices of the URANS predictions. It has been shown in [18] that standard URANS turbulence modelling are fairly dissipative that attenuates the instabilities and the vortex structures related to the dynamic stall. The dynamic lift in the engineering models is underestimated, causing deviations with the CFD and experimental data. Similar to the previous observation, changing the static polar data to the CFD data causes differences mainly in the lift build up in the flow reattachment regime, see Figure 8c.
Figure 7: Dynamic lift data predicted by CFD simulations in comparison with experimental data and engineering models for three different mean angles of attack $\bar{\alpha}$ of $8^\circ$, $14^\circ$ and $20^\circ$ with $k = 0.073$ and $\Delta \alpha = 10^\circ$.

Figure 8: Dynamic lift data predicted by CFD simulations in comparison with experimental data and engineering models (constructed using static CFD polar) for three different mean angles of attack $\bar{\alpha}$ of $8^\circ$, $14^\circ$ and $20^\circ$ with $k = 0.073$ and $\Delta \alpha = 10^\circ$.

To assess the reason for the strong deviation when the polar data is replaced and the sensitivity of engineering model responses to changes in the static data, Figure 9 presents the relationship between those datasets. One can clearly see that the difference between the static polar data $5^\circ < \alpha < 20^\circ$ causes the shift of the dynamic polar in a comparable amount with the static polar difference. Interestingly, the mean gradient of the dynamic polar also follows the static polar itself, though the general trend of the dynamic polar of both predictions is comparable. Learning from this experience, the source of the static polar data is a very important aspect for accurate prediction in practice. This is especially true when the intended model will be applied for wind turbine simulations that involve 3D effects [1]. A small difference in the near stall regime can cause some discrepancy with the target/expected results.

Figure 10 displays the dynamic drag response due to pitching motion. The prediction of $C_D$ is often more challenging to predict than of $C_L$. For the lowest investigated mean angle of attack, $\bar{\alpha} = 8^\circ$, drag does not change dramatically in comparison with the static data. The prediction of the LB-model is not accurate for this case and should be improved in this regard. On the other hand, the Snel-model is unable to predict $C_D$ in its formulation, therefore it shows only the static drag values. Increasing $\bar{\alpha}$, a noticeable hysteresis effect is shown above stall starting from $\alpha > 17^\circ$. A similar behavior is observed at the largest $\bar{\alpha}$. One may conclude that strong drag fluctuation/hysteresis takes place only in the post stall regime, while for the smaller angles of attack the prediction by the static polar data is sufficient. This effect is actually represented...
fairly well in the CFD calculations. The discrepancy in the results at around $20^\circ$ is similar to what has been observed in the static case.

In Figure 11, the unsteady pitching moment response over the angle of attack is presented. The engineering models fail to correctly reconstruct the moment coefficient accurately. Note
that the Snel-model includes only lift in the formulation, thus it yields exactly the static polar data itself. The LB-model is actually able to predict the hysteresis effect, but the trend looks inaccurate. This can influence the damping value when one includes the model for aeroelastic wind turbine simulations. On the other hand, CFD performs fairly well for $\alpha$ of $8^\circ$ and $14^\circ$. Further increasing $\alpha$ to $20^\circ$ causes strong shedding effects in the CFD data, which is not the case in the measurement. The minimum peak moment coefficient is also overestimated.

![Figure 12: Dynamic polar data predicted by CFD simulations at $Re = 5300K$, $\bar{\alpha} = 18^\circ$, $\Delta \alpha = 5^\circ$ and $k = 0.2$.](image)

Figure 12 shows the assessment for the largest $Re$ of 5300K. No experimental data is available for this case, thus high fidelity 3D DDES and URANS simulations were performed as the reference basis. The plot is presented as a cycle not as polar for clarity. One can see that 3D and 2D results show some discrepancies especially after stall occurs at cycle $\approx 0.2$. However, the general trend of all curves obtained from CFD simulations are very similar and consistent. Furthermore, it is noticeable that the employed Leishman-Beddoes dynamic stall model hardly predicts the deep stall characteristics and the increased drag as well all the drop of the pitching moment, and it requires further improvements in the future. It is also worthwhile to mention that the Snel model has a severe convergence issue at this large reduced frequency value. Therefore, the data for this model is not included in this comparison.

5. Conclusions

Comprehensive studies on the static and dynamic characteristics of a wind turbine airfoil have been conducted. Several main conclusions can be drawn from the work.

- Form the analyses it can be concluded that CFD can serve as a reliable database in some cases where experimental data is not available, providing suitable numerical setup is applied.
- The CFD results can be used for tuning the dynamic stall models according to the intended airfoils without the need for exhaustive experimental data at high Reynolds numbers. This will be of importance and beneficial for wind turbine load calculations employing engineering models.
- URANS may induce some discrepancy in the near maximum lift regime. However, the global performance of optimized 2D URANS calculations is of comparable accuracy as the 3D expensive calculations.
- The widely used LB-model and Snel-model predict faster flow reattachment in the downstroke regime causing overestimation of $C_L$ with a weaker hysteresis effect when the static polar data differs with the reference data. Thus a careful selection of the viscous polar source is very important especially when the model will be used for wind turbine simulations involving 3D effect in the root area of the blade.
• A better shedding prediction needs to be developed for engineering models.
• An improved modeling for $C_D$ and $C_M$ remains challenging and shall be developed in the future work.
• Dynamic stall models are sensitive to changes in the static polar data especially when separation starts to develop with the reduced polar gradient.
• Semi-empirical modeling at high reduced frequency regimes remains a huge task despite its importance for flutter analyses. This aspect shall be taken into account in future studies because the topic is particularly relevant for flutter analyses or when the blade is influenced by vortex induced vibration effects.

Acknowledgment
The authors gratefully acknowledge the Wobben Research and Development GmbH for providing the funding through the collaborative joint research DSWind. The measurement data provided from the Ohio State University is highly appreciated.

References
[1] G Bangga. Three-Dimensional Flow in the Root Region of Wind Turbine Rotors. Kassel University Press GmbH, 2018.
[2] J Martin, R Empey, W McCroskey, and F Caradonna. An experimental analysis of dynamic stall on an oscillating airfoil. Journal of the American Helicopter Society, 19(1):26–32, 1974.
[3] L W Carr, K W McAlister, and W McCroskey. Analysis of the development of dynamic stall based on oscillating airfoil experiments. 1977.
[4] K McAlister, L Carr, and W McCroskey. Dynamic stall experiments on the naca 0012 airfoil. 1978.
[5] J Leishman and T Beddoes. A semi-empirical model for dynamic stall. Journal of the American Helicopter Society, 34(3):3–17, 1989.
[6] G Bangga. Numerical studies on dynamic stall characteristics of a wind turbine airfoil. Journal of Mechanical Science and Technology, 33(3):1257–1262, 2019.
[7] Galih Bangga. Comparison of blade element method and cfd simulations of a 10 mw wind turbine. Fluids, 3(4):73, 2018.
[8] Hendrik HeißeImann, Joachim Peinke, and Michael Hölling. Experimental airfoil characterization under tailored turbulent conditions. In Journal of Physics: Conference Series, volume 753, page 072020. IOP Publishing, 2016.
[9] R Ramsay, M Hoffmann, and G Gregorek. Effects of grit roughness and pitch oscillations on the s801 airfoil. Technical report, National Renewable Energy Lab., Golden, CO (US), 1996.
[10] N Kroll, C Rosso, K Becker, and F Thiele. The megaflow project. Aerospace Science and Technology, 4(4):223–237, 2000.
[11] P Weihing, J Letzgus, G Bangga, T Lutz, and E Krämer. Hybrid rans/les capabilities of the flow solver flower—application to flow around wind turbines. In Symposium on hybrid RANS-LES methods, pages 369–380. Springer, 2016.
[12] Johannes Letzgus, Anthony D Gardner, Till Schwermer, Manuel Keßler, and Ewald Krämer. Numerical investigations of dynamic stall on a rotor with cyclic pitch control. Journal of the American Helicopter Society, 64(1):1–14, 2019.
[13] F Menter. Two-equation eddy-viscosity turbulence models for engineering applications. AIAA journal, 32(8):1598–1605, 1994.
[14] P Spalart and S Allmaras. A one-equation turbulence model for aerodynamic flows. In 30th aerospace sciences meeting and exhibit, page 439, 1992.
[15] William T Kirk, VR Capece, G Pechlinanoglou, CN Nayeri, and CO Paschereit. Comparative study of cfd solver models for modeling of flow over wind turbine airfoils. In ASME Turbo Expo 2014: Turbine Technical Conference and Exposition. American Society of Mechanical Engineers Digital Collection, 2014.
[16] R Pereira. Validating the Beddoes-Leishman Dynamic Stall Model in the Horizontal Axis Wind Turbine Environment. PhD thesis, 2010.
[17] H Snel. Heuristic modelling of dynamic stall characteristics. In In proceedings of the EWEC conference, pages 429–433, 1997.
[18] Guillaume Martinat, Marianna Braza, Y Hoarau, and Gilles Haran. Turbulence modelling of the flow past a pitching naca0012 airfoil at 105 and 106 reynolds numbers. Journal of Fluids and Structures, 24(8):1294–1303, 2008.