Experimental load measurement on a yawed wind turbine and comparison to FAST

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Abstract.
Current interest in unsteady aerodynamics of yawed turbines for wake redirection and cyclic load alleviation requires a clear understanding of turbine load fluctuation with azimuth position. To that end, an experimental 3.5 m diameter wind turbine rig was designed to measure rotor torque, flapwise/edgewise blade root bending moment, and normal force coefficient at r/R=0.66 and 0.82. The turbine was tested inside a large scale wind generation facility with a blockage ratio of 7%. Simultaneously and in time-resolved fashion, measurements were collected to produce phase-averaged performance parameters that are presented versus azimuth while the turbine is operating at different tip speed ratios and yaw angles. The NREL FAST code predictions were then compared to experimental data under the same conditions. It was found that in non-yawed conditions, FAST predictions were accurate but discrepancies start to emerge when the turbine is yawed and operating in dynamic stall conditions. In non-yawed cases, the discrepancy between experimental and FAST data is less than 7% when the flow is attached and increases to 22% when the flow is stalled. One of the main sources of discrepancy found is in the process of correcting the airfoil coefficients to account for 3D flow effects using AirfoilPrep.

1. Introduction
It is well understood that in real environmental conditions, wind turbines operate in a relatively unsteady flow environment due to yaw-misalignment, vertical shear or other factors. Also, in recent years, wind farm operators intentionally yaw turbines to redirect the wake away from downstream turbines to increase wind farm power output. These factors lead to unsteady and cyclic loading on the blades that are more problematic than static loads due to material fatigue that reduces the lifespan of the blades. In the recent “Grand Vision for Wind Energy” report by Dykes et al. [1], a group of experts identified that one of the challenges that must be addressed to realize the future of wind power is improving the accuracy and reducing the uncertainty in current design tools, models and simulations. By doing so, it allows turbine manufacturers to design blades and other components without using greater-than-optimal safety factors to account for the large inaccuracies in the current design tools. To improve these tools, it is imperative to fully validate and verify the models used to simulate wind turbines and to understand the limitations and uncertainty associated with each model based on experimental data.

The only two major notable large scale wind tunnel experimental studies on yawed wind turbines are the UAE Phase VI project reported in Hand et al. [2] and the MEXICO project reported in Schepers et al. [3]. This would indicate that experimental data at this scale are very
scarce. More experimental data is needed on a turbine operating in a controlled environment while operating under different conditions specially in yawed cases to understand the blade load response in unsteady conditions. The MEXICO project highlighted the need for surface pressure distribution along the blade and load measurements on a turbine operating in yawed conditions to capture the unsteady dynamic behavior. One of the main objectives of this study is to measure and analyze turbine loading at the rotor shaft, blade flapwise/edgewise direction and normal force coefficient at a blade segment while the turbine is operating at different tip speed ratios and yaw angles. The NREL FAST code was then used to predict and compare turbine loading to the experimental data for the same conditions.

2. Background and Theory

The NREL FAST code was first developed in the very early 2000s [4] but through the years it has been improved based on new aerodynamic models and additional experimental data that made it more accurate and reliable. This indicates that experimental data is essential to further develop and increase reliability of such models. Damiani et al. [5] recently developed a new unsteady airfoil aerodynamic model that could be used within the FAST platform to simulate dynamic stall on the turbine. The model first develops the unsteady behavior for a 2D airfoil and then extrapolates it for a 3D blade. Damiani et al. [5] compared the model to experimental data for various airfoil shapes, reduced frequencies, \( k \), and amplitudes of oscillation in a 2D setting. Even though they found good overall agreement between the model predictions and experimental data, some discrepancies were still present.

Different versions of FAST have been used to model the UAE Phase VI project by Jonkman [4], the MEXICO project by Schepers et al. [3] and the UAE project again by Damiani et al. [5, 6] using the newest version of FAST. They found that even with the new updated unsteady aerodynamic model, discrepancy was still observed but it has certainly improved over the years due to larger availability of experimental data. Based on the different studies mentioned, it was found that FAST was capable of accurately predicting blade loading on a wind turbine operating in steady conditions but in unsteady or yawed conditions the accuracy started to degrade. The discrepancy between the FAST prediction and the experimental data was mainly attributed to a weakness in modeling 3D flow effects, tip loss, stall delay, dynamic stall and unsteady aerodynamic behavior. These sources of errors are discussed in more detail next.

One of the main differences in aerodynamics between a 2D airfoil and a rotating blade is the 3D flow effect. Blade rotation develops a pressure gradient across the blade span that creates a spanwise velocity component on the blade delaying stall and increasing lift [4]. It was found that the magnitude of the 2D lift is significantly smaller than that of the 3D lift close to the root of the blade but as \( r/R \) increases to one, 2D and 3D lift magnitude converge [2, 3]. This highlights how the magnitude and flow behavior change on 3D blades. Schreck et al. [7] studied the difference between 2D and 3D aerodynamics by looking at the surface pressure and \( C_n \) from the UAE and MEXICO projects. They found that the choice of airfoil geometry has a strong influence on the strength and characteristics of the 3D stall effect. Another difference between 2D and 3D flow behavior is the tip loss caused by a leakage of flow from the pressure to the suction side. This introduces downwash which reduces the effective \( \alpha \) near the blade tip and results in a reduced lift and increased drag [4, 8]. When the turbine is yawed it causes unsteady flow conditions that could lead to dynamic stall. Pereira et al. [9] reported that there is a significant difference between 2D and 3D dynamic stall behavior and an empirical correction was used to improve their model predictions.

FAST attempts to correct for all these effects but due to the nature of these semi-empirical models the accuracy could be limited and is dependent on the input parameters chosen. The various effects mentioned could be approximated and predicted by FAST but they are a source of error when simulating wind turbines. Although the experimental data highlights the limitations
in FAST, it could also be used as opportunities to improve the models. These improvements in modeling will ultimately lead to a more cost-effective way of designing turbines and give the modeler more confidence in the results obtained. The experimental set of data presented in this paper provides an extra resource for modelers to further improve the models and achieve a higher accuracy.

3. Model and Experimental Setup

3.1. Experimental Setup

The experimental campaign was conducted at the Wind Generation Facility operated by the University of Waterloo. It is a large scale open circuit wind tunnel with a test area of 15.4 m wide and 7.8 m high. The maximum achievable wind speed is 13 m/s but more importantly the blockage ratio is around 7%. The fully instrumented upwind horizontal-axis wind turbine with a 3.5 m diameter, shown in Figure 1, was used to measure the loads at three different locations on the turbine. First, the torque sensor in the nacelle was used to measure the torque generated by the entire rotor. Second, strain gauges at the root of the blade were used to measure the flapwise ($M_{FW}$) and edgewise ($M_{EW}$) root bending moment. Finally, surface pressure measurements at $r/R=0.66$ and 0.82 were used to calculate and obtain the normal force coefficient ($C_n$). All these measurements were collected simultaneously and in time-resolved fashion so the data could be phase averaged and presented versus azimuth position. A custom built pitch control and trailing edge flap (TEF) control are used to mitigate turbine loads in unsteady conditions and will be presented in future publications. The rotor consists of one aerodynamic blade with a constant pitch of $\beta = 6^\circ$ and chord of 178 mm. More detailed information about the experimental setup could be found in Samara and Johnson [10, 11].

![Figure 1: 3D model of the wind turbine assembly showing the main components](image)

3.2. FAST Setup

It is crucial to set the FAST input parameters to resemble the physical model because the accuracy of the predicted output is as good as the input parameters used. Through meticulous analysis, the physical properties of the turbine were found and imported into the FAST model. The 2D airfoil coefficients at the appropriate Re were experimentally obtained from Samara and Johnson [10]. Before the coefficients were loaded in FAST, AirfoilPrep by NREL [12] was used to modify the coefficients independent of airfoil geometry to account for the 3D flow effects that the blades experience on a rotating system. Depending on the $r/R$ location, AirfoilPrep increases $C_L$ and delays stall. All the blade properties from twist/chord distribution to blade mass density and stiffness were imported to FAST. A lot of care and effort were taken to ensure that all aspects of the wind turbine geometry were properly modeled. The wind turbine was
simulated with no degrees of freedom (DOF) because the blade deflection is insignificant due to the short length of the blades (1.4 m) and the natural frequency of the blades does not coincide with the excitation of the turbine. To confirm this, two cases were simulated one with DOF and the other is completely rigid. The results were identical indicating no impact from enabling DOF.

As mentioned, Damiani et al. [5] suggested that to better simulate dynamic stall or unsteady aerodynamics, a few important parameters must be tuned based on 2D dynamic stall hysteresis loops for the same airfoil. To this end, the 2D dynamic stall experimental measurements from Samara and Johnson [13] were used to tune the FAST parameters responsible for simulating dynamic stall. The airfoil lift, $C_L$, and moment, $C_M$, coefficients results from this unsteady dynamic model (dotted line) were then compared to 2D experimental data (solid line) and are presented in Figure 2. The mean pitch sinusoidal oscillation, $\alpha_{mean}$, was set to 10° to simulate dynamic stall and 20° to simulate deep dynamic stall. In both cases the reduced frequency was set to 0.1 and the oscillation amplitude was set to 10°.

For $\alpha_{mean} = 10^\circ$ in Figures 2a and 2c, the model predicted the $C_L$ cycle within 13% uncertainty while for the $C_M$ cycle within 12% to 26% uncertainty. The location of the leading edge vortex (LEV) peaks are within ±1°. The peaks in the model are not as sharply defined as the experimental data. The model $C_M$ cycle also predicted a clockwise loop indicating the occurrence of stall flutter similar to what was found in experimental data. Moving on to the more challenging cases to simulate for $\alpha_{mean} = 20^\circ$ in Figures 2b and 2b, there are more discrepancies. The uncertainty values for $C_L$ and $C_M$ are within 15%-18% and 14%-33% respectively. Although the model was capable of predicting multiple LEV, they are not as sharply defined as the experimental results and the peaks are within ±3°. It is possible to tune the model parameters further to reduce discrepancy in the magnitude and location of the LEV but for the purposes of this study the results are acceptable. The parameters could be tuned for every case separately but that is unreasonable since there is only one airfoil input file. The parameters were tuned to satisfy all tested cases equally.

All the conditions that are presented so far are rather challenging because the airfoil is operating in the deep stall region. Even so, the model was capable of predicting the multiple LEV in the cycle and the uncertainty in magnitude is within 12% to 33%. Damiani et al. [5] also compared the model to different experimental results for different airfoils and conditions. The discrepancies they noted match and resemble the discrepancies mentioned. They argued that the discrepancy between experimental and model predictions could be due to the limitations of the code especially in deep stall. They concluded that the accuracy of the model is heavily dependent on the availability of experimental data and better tuning of the unsteady aerodynamic parameters. The experimental data presented here provides validation data to the model and possible limitations.

3.3. Test Cases

to test the influence of wind turbine loading under yawed conditions, a test matrix was conducted with three tip speed ratios ($\lambda$) and two yaw angles ($\gamma$). The three $\lambda$ values correspond to a free stream velocity of 7.3, 8.7 and 10.5 m/s while the rotor is rotating at 200 rpm. The test matrix is shown in Table 1. Case 1 and 2 correspond to $\gamma = 0^\circ$ and $30^\circ$ respectively. A more comprehensive test matrix was conducted where the blade pitch angle did vary but is not presented here due to space constraints. These results will be included in future publications.

4. Results
4.1. Non-Yawed Turbine
The incoming wind speed is one of the most important parameters when studying the aerodynamics of a wind turbine. It influences the geometric blade angle of attack ($\alpha$), tip
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Figure 2: Comparing the coefficient of lift ($C_L$) and moment ($C_M$) dynamic stall cycle between experimental results obtained from Samara and Johnson [13] and the FAST unsteady aerodynamic model where $k=0.1$, $\alpha_{\text{mean}}=10^\circ$ or $20^\circ$ and $\alpha_{\text{amp}}=10^\circ$. The static airfoil coefficients are shown in ⋆ for reference.

Table 1: Experimental test matrix along with the variables presented

| Case | $\lambda$ | $\beta (^\circ)$ | $\alpha_F (^\circ)$ | $\gamma (^\circ)$ | Variables Presented |
|------|-----------|-----------------|-------------------|-----------------|-------------------|
| 1    | [3.5, 4.2, 5] | 6               | 0                 | 0               | Torque, $M_{FW}$, $C_n$ at r/R=0.82 and 0.66 |
| 2    | [3.5, 4.2, 5] | 6               | 0                 | 30              | Torque, $M_{FW}$, $C_n$ at r/R=0.82 and 0.66 |

speed ratio, power output and most importantly in this study, the magnitude of blade loading. Thus it is important to study how the change in wind speed (change in $\lambda$) influences the turbine performance parameters: $\Delta$Torque, $M_{FW}$ and $C_n$. These variables are plotted against azimuth, $\psi$, for $\lambda=3.5$, 4.2 and 5 as per Table 1. The same test matrix discussed was simulated in the FAST model (dotted lines) and compared to the experimental data (solid lines). Focusing on the non-yawed case in Figure 3, it is noted that for all the $\lambda$ cases the pattern in the performance variables does not change with wind speed but only the magnitude is altered. The pattern in the data is the same even though each data set was taken on different dates. This shows repeatability in the measurements and increases confidence in the results. As the wind speed increases or $\lambda$ decreases, the turbine loads become higher as indicated by the three plotted variables but the increase is not linear. This is because as the incoming velocity vector ($U_\infty$) increases, the geometric angle of attack ($\alpha$) also increases according to the relative velocity triangle. The $\alpha$ increase is also seen in the FAST results and the values are shown in the legend of Figures 3c and 3d. The variation in $\alpha$ versus azimuth is constant as expected because $\gamma = 0^\circ$. 
The torque measurement is presented first in Figure 3a as it is a measure of performance of the entire rotor. The measurements are phase averaged from 1000 cycles into bins of 5°. The \( \Delta \text{Torque} \) measurement presented here is the difference between the torque generated with no incoming wind speed and the torque generated when the wind speed is set to the desired speed while the turbine rotation is fixed. This approach was done to the experimental and model data alike to highlight the torque generated by the single blade and eliminate the drag generated by the counterweight cylinders. The torque generated with no incoming wind speed was measured to be 29 Nm while FAST prediction was 28.9 Nm. This means that if \( \Delta \text{Torque} \) is higher than 29 Nm then the rotor torque is positive but if its lower than 29 Nm then the rotor torque is negative and the motor in the nacelle is driving the rotor. Since \( \Delta \text{Torque} \) in all the cases presented is lower than 29 Nm, this indicates that the single bladed rotor is not capable of providing sufficient rotational force to overcome drag at the operated rotational speed. This argument is also seen in FAST as both experimental and model results are very similar. At \( \lambda = 5 \), \( \Delta \text{Torque} \) from FAST and experimental data match but when \( \lambda \) increased to 3.5, FAST under-predicted by 5%. This difference is acceptable and could be due to uncertainty in experimental results, model input parameters and FAST model predictions. The small variations in \( \Delta \text{Torque} \) are mainly due to the wind tunnel non-uniformity.

Focusing on the \( M_{FW} \) plots in Figure 3b, there is a slight increase in bending moment for the three \( \lambda \) cases at \( \Psi \approx 90^\circ \) and \( 270^\circ \). This is due to a small variation in the incoming velocity \( (U_\infty) \) at that location and was also observed by Gallant and Johnson [14] and McKinnon and Johnson [15] and is found in all data sets. The FAST model produced very comparable values to the experimental results but the slight non-uniformity are absent. The discrepancy between FAST and experimental data is mainly due to the discrepancy in \( C_n \) and is discussed in the next paragraph.

In Figure 3c, \( C_n \) shows a non-uniformity and minor oscillation with azimuth but the pattern is the same across different \( \lambda \). FAST was able to reproduce constant \( C_n \) values versus azimuth that are very representative of the experimental data. This is expected because the aerodynamic data of the S833 airfoil from the experimental campaign in Samara and Johnson [13] were imported to the model. The difference between FAST and the phase averaged experimental data is 4%, 2% and 7% respectively for \( \lambda = 3.5, 4.2 \) and 5.0. These minor discrepancies are mainly due to experimental and model uncertainties. Based on the \( \alpha \) values at \( r/R=0.82 \) obtained from the model, the airfoil section is not stalled for any of the \( \lambda \) cases. Typically, non-stalled cases are not challenging to predict and that is why FAST produced relatively accurate \( C_n \) values. This however is not the case when \( C_n \) is measured at \( r/R=0.66 \) and plotted in Figure 3d. The discrepancy between FAST and experimental measurements is 22%, 8% and 2% respectively for \( \lambda = 3.5, 4.2 \) and 5.0. There is a larger discrepancy when \( \lambda = 3.5 \) because the blade section is operating in stall as indicated by \( \alpha = 18^\circ \) thus higher than static stall angle. Experimental data indicate that the flow over the blade segment is attached because \( C_n \) kept increasing but FAST predicted stall because \( C_n \) decreased. 3D flow effects tend to delay stall on a rotating blade as explained in the background section. The \( C_n \) plots indicate that as long as the flow over the blade is attached, experimental and model data are similar to each other. However when the blade segment is operating in stall, the discrepancy starts to increase.

4.2. Yawed Turbine

Wind turbine aerodynamics in yawed conditions are very different than non-yawed operation. Due to yaw angle, \( \gamma \), the incoming wind speed and the induced velocity both vary as a function of azimuth position and that leads to a geometric change in angle of attack, \( \alpha \). The induced velocity is defined as the velocity reduction at the rotor plane due to the energy extraction process and its magnitude is a function of the axial induction factor, \( a \). Unlike the previous section where the theoretical velocity triangle was constant during rotation, in yawed flow, the angles and
velocity vectors are constantly changing with azimuth position producing cyclic loading on the blades. The variation in $\Delta$Torque, $M_{FW}$, $C_n$ and $\alpha$ are plotted in Figure 4 for different $\lambda$ values and for yaw angle, $\gamma = 30^\circ$.

Focusing on Figure 4a, experimental $\Delta$Torque measurements slightly vary with azimuth position and the trough and crest are located at $\psi \approx 155^\circ$ and $320^\circ$. On the other hand, FAST predictions show significant $\Delta$Torque variations with $\psi$ but the crest and trough location match the experimental data. This difference between experimental and FAST data is attributed to two main factors: angular momentum, and physical nacelle rig characteristics. Due to blade rotation and weight of the blades/hub, the momentum and inertia of the rotor significantly dampens out the torque variation with azimuth similar to what was reported by Gallant and Johnson [14]. The angular momentum of the rotating blades was calculated to be 230 kgm$^2$/s but the angular momentum change due to $\Delta$Torque of 30 Nm from FAST is about 0.23 kgm$^2$/s or 0.1% which is insignificant. Thus the torque sensor mounted to the wind turbine shaft does not see a significant change in torque despite a force increase on the blades because of the large angular momentum inherent in the rotor. FAST does not seem to accurately model angular momentum and to make sure of that, the blade mass was increased by tenfold but the predicted $\Delta$Torque did not change. Another less significant reason to why $\Delta$Torque is different between the model and experiments is due to the proportional-integral controller (PI) that controls the turbine rotational speed in the nacelle. Due to the single bladed rotor, the motor provides power.
to the rotor and not the other way around as previously mentioned. If the rotor experiences a change in load then the PI controller senses that change and sends more or less power to the rotor to keep the rotational speed constant thus dampening out the measured torque fluctuation. Since the torque sensor measures the torque difference between the rotor and generator, it cannot measure the change of torque from the rotor alone.

Figure 4: Turbine performance for various λ values for case 2 where β = 6° and γ = 30°. Solid lines represent experimental data while dotted lines represent FAST model data.

Looking at the $M_{FW}$ variation in Figure 4b, the experimental data for the three different λ cases converge around the cycle center ($\Psi = 180°$) and diverge at the cycle ends ($\Psi = 0°$ or 360°). This indicates that the blade load fluctuation increases as λ decreases. This trend is supported by the FAST model but is not as explicit. The trough in the experimental data is
not located $\Psi = 180^\circ$ but shifted to the right to $\Psi \approx 220^\circ$. When the trough is at $\Psi = 180^\circ$ this indicates that the load variation is dominated by the fluctuation of wind velocity relative to the blade. On the other hand, when the trough is shifted from the center, it indicates that the induced velocity component variation with azimuth is significant. The magnitude of the induced velocity is dependent on $a$ and that in turn is dependent on $C_{\text{power}}$ derived from the rotor torque. Even though rotor torque increases with an increase in free stream velocity, $C_{\text{power}}$ decreases as was seen in Samara and Johnson [11]. A reduction in $C_{\text{power}}$ leads to a lower axial induction factor, $a$. This shows that as $\lambda$ decreases so does $a$ and that in turn reduces the impact of the induced velocity. For this reason the trough for $\lambda = 3.5$ is located closer to $\Psi = 180^\circ$ than $\lambda = 5$ as seen more clearly in the FAST model and supported by Burton et al. [16]. The FAST model is very comparable to experimental data for $\lambda = 3.5$ but when $\lambda = 5$, the difference is more significant. These differences are due to the discrepancy in $C_n$ and are discussed in more detail in the next paragraph. Blade loading is determined by integrating $C_n$ across the blade span so any discrepancy in $C_n$ will cause error in blade loading.

The $C_n$ variation at $r/R=0.82$ for the different $\lambda$ cases are presented in Figure 4c. For all three cases, the troughs are located in the same position at $\Psi = 180^\circ$ unlike the $M_{\text{FW}}$ data. The $\alpha$-azimuth distribution at $r/R=0.82$ was obtained from FAST and plotted in Figure 4d. This plot indicates $\alpha$ does not exceed the stall angle for all cases presented and it also suggests that dynamic stall does not occur. This however is not the case at $r/R=0.66$ as seen in the $C_n$ and $\alpha$ distribution in Figures 4e and 4f. The $\alpha - \psi$ distribution indicate that dynamic stall is likely to be present only when $\lambda = 3.5$ because $\alpha$ is oscillating around the stall angle. FAST also simulated dynamic stall and this can be seen in the $C_n$ peak around $\psi = 70^\circ$. Experimental data indicate that there is a discrepancy in how FAST predicts dynamic stall. The source of discrepancies are explained next.

There is a significant discrepancy between experimental data and the model and there are multiple sources of errors, some more significant than others. One of the main sources of discrepancy is based on how the physical model was setup in FAST and what parameters were chosen to simulate unsteady wind turbine behavior. Even though FAST is a medium complexity code it requires tremendous effort and expert knowledge of rotor theory to set the model up, from obtaining accurate airfoil coefficients to tuning dynamic stall parameters to understanding the limits of the predictions. One of the main uncertainties in blade aerodynamics lies in the effects blade rotation has on the airfoil coefficients [3]. These coefficients are the most important input parameter that determines accuracy of the model and they should be corrected for 3D flow effects. These 3D flow effects are induced by the rotation of wind turbine blades and significantly alter the stall angle and slope of the $C_n - \alpha$ data as discussed in Section 2. The stall angle and $C_n - \alpha$ slope also change for different blade spanwise locations because 3D flow effects are more significant close to the root of the blade than the tip area. AirfoilPrep was used to modify the lift data independent of airfoil geometry to account for 3D flow effects. There is an inherent error associated with this modification because each airfoil may perform differently in 3D flow as reported by Schreck et al. [3, 7]. There are many other 3D flow effects on the blade such as tip/root losses discussed in Burton et al. [16] and post stall dynamics [4]. It was suggested that the choice of airfoil geometry has a strong influence on the strength and characteristics of 3D stall effect [3]. So even though FAST implements corrections to simulate 3D flow, these corrections are dependent on airfoil geometry and thus become the inherent error associated with these corrections. Despite the fact that the parameters used to model dynamic stall were tuned based on 2D experimental results, there is a discrepancy in dynamic stall behavior between wind turbine experimental results and FAST. Pereira et al. [9] found that there is a significant difference between 2D and 3D dynamic stall behavior and that might be causing the discrepancy mentioned here. Errors could also arise from the different aerodynamic models FAST uses in predicting wind turbine loads [4]. FAST is based on a BEM model that is executed independently
of airfoil geometry or aerodynamics. Another major source of error is FAST’s inability to predict an accurate $\alpha$ distribution over the blade span. Even if accurate airfoil coefficients that take into account 3D flow behavior are used, having the incorrect $\alpha$ distribution will lead to inaccurate turbine loading and can influence subsequent predictions of the rotor performance. Another unique source of error in this project is related to the single bladed rotor with constant pitch and chord. The lack of twist in the blade in order to make the blade modular forces a large section of the blade to operate in stall and in unsteady aerodynamics that are generally more difficult to predict and model. The final cause of error is due to experimental uncertainties.

5. Conclusions

Rotor torque, flapwise/edgewise blade root moment and normal force coefficient ($C_n$) at $r/R=0.82$ and 0.66 were experimentally measured on a wind turbine operating in a large scale wind generation facility. The experimental measurements have been compared to FAST predictions under different wind speeds and yaw angles. In steady non-yawed cases, FAST was capable of accurately predicting the load distribution when compared to experimental data. In non-yawed cases, the discrepancy between experimental and FAST data is less than 7% when the flow is attached and increases to 22% when the flow is stalled. In more challenging cases such as when the turbine is yawed, some of the FAST predictions diverged from the experimental data specially in the $C_n$ plots. Discrepancies between FAST predictions and experimental data highlight model weaknesses in tip loss, stall delay, post stall and 3D flow effects. The accuracy of FAST predictions is dependent on 2D experimental airfoil coefficients and properly tuning the dynamic stall parameters. One of the main sources of discrepancy found was in the process of correcting the airfoil coefficients to account 3D effects using AirfoilPrep. The data presented in this paper and in future subsequent publications strengthens and validates the aerodynamic physics models used in FAST. The data also provides a useful resource for modelers to further reduce the uncertainty and increase accuracy of certain aspects of the models that produced discrepancy such as 3D flow effects.

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