In-Blade Measurements of Cyclic Loading on Yawed Turbines with Trailing Edge Flap

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Abstract. Wind turbines operate predominantly in relatively unsteady flow conditions and are typically misaligned with the incoming wind. Based on the literature review, controlling a section of the trailing edge of the turbine blade is found to reduce load fluctuations on wind turbine blades. Here, a detailed experimental setup describes a 3.5 m diameter wind turbine equipped with a trailing edge flap (TEF). The instrumentation of the compact blade was capable of measuring surface pressure and root bending moment, as well as controlling a TEF simultaneously and in time-resolved fashion. The blade is of constant pitch and chord of 178 mm while the TEF covers 20% of the chord and 22% of the 1.47 m aerodynamic blade span. The turbine was tested in a controlled wind generation facility large enough to house the turbine with less than 7% blockage. The wind turbine was tested for a range of tip speed ratios, blade pitch angles, flap angles and yaw cases. Although the turbine blade is capable of cyclically and dynamically change the blade pitch and flap angle, this paper only investigates constant pitch and flap angles. The results show that changes to the flap or pitch angle are capable of manipulating the coefficient of power, root bending moment and normal force coefficient. The results also show that the flap demonstrates similar control authority to that of the pitch system with the flap occupying just 4% of the blade surface area without reducing the power output of the turbine.

1. Introduction
During normal everyday operation of wind turbines, the direction and magnitude of the incoming wind speed changes dynamically. For this reason, wind turbines spend most of the time in a relatively unsteady flow environment [1]. This could be due to many factors, including wind shear, rotor misalignment (yaw) and turbulence of the wind resource. These factors lead to unsteady and cyclic loading on the blades that is more problematic than static loads due to material fatigue. In general, extreme static loads are higher than unsteady loads, but fatigue life governs the design factors for larger wind turbines [2]. To decrease the electricity cost per kWh, it is imperative to understand and reduce the dynamic loading on the blades to increase turbine lifespan and decrease the cost of energy. Reduction in blade loading would also decrease the loads on the drivetrain, generator and tower further reducing the cost of manufacturing and maintenance. The aim of this study is to sense and mitigate load variation on wind turbine blades.
2. Background and Theory

In real environmental conditions, wind turbines experience yaw-misalignment on a regular basis because the rotor is not always capable of following the continuously changing wind direction. The turbine, then, spends most of its time in yawed conditions. Also, in recent years, wind farm operators intentionally yaw turbines to redirect the wake away from downstream turbines to increase the efficiency of the entire wind farm [3]. When a wind turbine is yawed, the angle of attack ($\alpha$) is constantly changing on each of the blades, thus causing load fluctuations and ultimately fatigue damage [4]. Figure 1 is presented to better understand how $\alpha$ changes with azimuthal position. The turbine sketch shows the sign convention for the yaw angle ($\gamma$), azimuthal position ($\Psi$), rotational speed ($\Omega$) and rotor radius ($R$). When the turbine is yawed, the incoming wind speed ($U_\infty$) is no longer perpendicular to the rotor plane and the blade rotational velocity vector $U_{\text{rot}} = \Omega r$ (where $r$ is the local radius of the turbine blade). The rotational velocity vector ($U_{\text{rot}}$) and the free stream incoming velocity vector ($U_\infty$) form the wind velocity vector ($W$) based on the following equation $W = \sqrt{[U_{\text{rot}}(1 + a')^2 + (U_\infty(1 - a))]^2}$ (where $a$ is the axial flow induction factor and $a'$ is the tangential flow induction factor). When the blade is rotating away from the wind ($90^\circ < \Psi < 270^\circ$) the yaw angle causes $\alpha$ to increase, while, in contrast, when the blade is rotating towards the wind ($270^\circ < \Psi < 90^\circ$), the yaw angle causes $\alpha$ to decrease. At 6 and 12 o’clock ($\Psi = 0^\circ$ or $180^\circ$) $\alpha$ is at its minimum and maximum respectively. As the blade rotates and cyclically moves away and towards the upstream wind, $\alpha$ oscillates causing load fluctuations. For this reason and similar situations, it is then vital to understand and reduce the impact of yawed conditions on wind turbine blades.

![Diagram of a horizontal-axis turbine with labels and a schematic of the velocity triangle for a yawed turbine.](image)

Figure 1: A diagram of a horizontal-axis turbine with labels and a schematic of the velocity triangle for a yawed turbine.

Different lift control strategies for turbine blades have been developed previously, such as leading edge blowing or suction, synthetic jets, leading edge plasma actuation, vortex generators, microtabs and trailing edge flaps (TEF). Barlas and van Kuik [2] summarized and reviewed the different control strategies mentioned to reduce the fatigue load on wind turbine blades. TEF were found to be the most efficient of the control strategies tested because of their control authority over the coefficient of lift and drag, linearity, high frequency response and the simplicity of use. The focus of this research will then be on TEF, which are implemented by hinging the trailing edge at a specific location, typically between 0.7 to 0.9 of the chord ($c$). When the TEF is deflected, the camber of the airfoil changes, altering the coefficient of lift and moment. When the flap is deflected towards the suction side, defined in this paper as positive flap angle ($\alpha_F$), the coefficient of lift ($C_n$) decreases and the opposite is true.
Individual pitch control is the most advanced technique used to reduce loading on wind turbines to date [2]. This technique is limited by the speed and reliability of pitch actuation specially, for large multi-MW turbine blades. Load reduction in highly fluctuating flow would require high pitch angles and rotational rates, which most standard pitch actuators cannot handle. To achieve a more refined and responsive load reduction, TEF are used. Changing the aerodynamic forces locally along the blade would allow for localized load reduction with a much faster response time.

Based on studies by different groups it is evident that the TEF is fully capable of reducing the loads on an airfoil inside a 2D wind tunnel setup [5, 6, 7]. Five different groups have tested a TEF on a full scale wind turbine and found a very similar conclusion. Hulskamp et al. [8] used piezoelectric benders covering half the chord to deflect the trailing edge by 2°. Their TEF was tested on a 1.8 m diameter wind turbine inside a wind tunnel. Navalkar et al. [9] implemented a free floating flap on a small scale wind turbine and was placed in a way that it was free to rotate. It was made from piezoelectric material that could deform the curvature of the flap. The flap and designed controller were able to suppress load variation on the blade for different load frequencies. Castaignet et al. [10] instrumented one of the blades of a 225 kW wind turbine with a TEF. The TEF span was 5% of the blade and 15% of the chord. Berg et al. [11] instrumented three 9 m CX-100 blades with a TEF, which compromised 20% of the chord and 20% of the blade span. Finally, Abdelrahman and Johnson [12] investigated the influence of TEF on a 3.4 m diameter wind turbine in a controlled environment. The results of these studies showed that dynamic load fluctuation reduction was attainable. In all cases, the load reduction was found to be between 14% and 20%. The studies have used a range of instrumentation from 5 hole pressure probe, to strain gages and accelerometers. None of the previous studies have measured the surface pressure on a blade with a TEF while in operation. Surface pressure also provides critical information on how the TEF influences separation on the blades. The aim of this study is then to understand, measure and mitigate the load variation experienced by the blade in unsteady conditions.

3. Experimental Setup

To quantify the influence of a TEF on the wind turbine blade an experimental setup was designed to sense the aerodynamic forces on the blade in real time and actuate the flap and blade pitch accordingly. In this section the experimental setup will be explained in detail. Firstly the UWaterloo controlled wind generation facility will be briefly discussed. The instrumented UWaterloo wind turbine will then be explained along with the aerodynamic blade that houses the TEF actuation system. The hub and blade pitch design system will be laid out in some detail. Finally the data acquisition system connecting all the components will be explained.

3.1. Wind Generation Facility

The wind generation facility acts as a large-scale open circuit wind tunnel using a fan bank of three across and two high. The open jet plenum is 8 m wide and 6 m high while the test area is 15.4 m wide, 19.5 m long and 7.8 m high. The maximum achievable wind speed is 13 m/s with a turbulence intensities in the range of 6% to 8% and a blockage ratio of around 7%. The combination of low blockage ratio and high turbulence intensity makes the facility an ideal place to test wind turbines because it is representative of the environmental conditions that wind turbines typically would be exposed to in the field. Figure 2 shows the facility test area, control building and fan layout. More information about the technical specification of the facility could be found in Gertz et al. [13] while flow characteristic and wake visualization could be found in [14].
3.2. **UWaterloo Wind Turbine**

The UWaterloo wind turbine is a custom designed and built upwind horizontal-axis wind turbine. The 3.7 kW motor is capable of acting both as a generator and motor to keep a desired rotation speed constant based on a feedback loop controller and an encoder attached to the motor. The turbine is designed to operate at a constant rpm range of 0-230 rpm and can be yawed between -40° to 40°. A rotary encoder coupled with a torque sensor (Futek TRS605) is mounted in-line between the gearbox and rotor shaft. The quadrature encoder has a resolution of 360°x4 with an index line. The torque sensor is a non-contact shaft to shaft sensor with a 200 Nm torque capacity. The encoder is used to track the azimuthal position of the turbine blade. The torque sensor is used to calculate the coefficient of power, \( C_{\text{power}} = \frac{2 \times \text{Torque} \times \Omega}{\rho_{\infty} \cdot U_{\infty}^3 \cdot A} \), where A is rotor cross-sectional area and \( \rho_{\infty} \) is the free stream fluid density, of the turbine.

3.3. **Wind Turbine Aerodynamic Blade**

To test a TEF system on a wind turbine the rotor was designed to have a single blade with a constant pitch and chord where the TEF system could be placed at \( r/R = 0.66 \) or \( r/R = 0.82 \). The rotor consists of a single aerodynamic blade and two cylindrical counterweights to balance the rotor dynamically. A 3D model of the airfoil with labels and dimensions is shown in Figure 4. The NREL S833 airfoil [15], designed for small wind turbines, was used for the experiments. The flap width was chosen to be 20\% of the 178 mm chord while the flap span was 22\% of the 1.47 m aerodynamic blade span. To incorporate the sensors and actuators the aerodynamic blade was 3D printed using ABS-M30 material. A stainless steel spar at the quarter chord that runs along the total length of the blade was used to support the 3D printed blades and hold all the components together. Two strain gauge groups were installed at the root of the blade to measure the edgewise (in-plane) and flapwise (out of plane) direction root bending moments. The designed blade was capable of housing all the instrumentation and the flap actuation system. Coefficient of normal force and moment were calculated by integrating surface
pressure from 54 pressure taps located on an aluminum airfoil section at midspan of the TEF. Four of these taps were located on the surface of the TEF. To measure the surface pressure at the airfoil at the frequency desired, the pressure measurements were simultaneous. To achieve this, 27 differential pressure transducers were used to measure the differential pressure between the suction and pressure side of the airfoil at the same x/c location. The differential pressure measurement was compared to single ended pressure measurements and the data was calibrated accordingly. The 3D printed blade model was capable of housing the pressure transducers and all the tubing needed to connect the transducers to the pressure taps. Refer to Figure 5 for more clarification and layout. The coefficient of pressure (∆C\textsubscript{p}) is calculated based on the following equation

\[ \Delta C_p = \frac{(p_{\text{suction side}} - p_{\text{pressure side}})}{\left(\frac{1}{2}\rho \infty W^2\right)} \]

where \(W\) is the local wind velocity vector defined in Section 2. More details about the experimental setup could be found in Samara and Johnson [16].

![Figure 4: Layout of the aerodynamic blade with the hub](image1)

![Figure 5: Internal organization of the rotor blade showing the TEF system and surface pressure transducers with the cover removed.](image2)

### 3.4. Hub and Pitch Design System

The hub was designed to house the pitch control and the data acquisition systems. A 3D model of the blade pitch system is shown in Figure 6. Two thrust bearings were used to support the blade onto the hub while allowing the blade to rotate about its quarter chord. To control the
pitch angle of the blade a stepper motor with a holding torque of 1.8 N.m was used. The motor was coupled with a 10:1 ratio gearbox with a maximum backlash of 0.25°. The motor assembly was placed above and parallel to the blade shaft and two ball joint linkages were used to transfer the motion from the motor to the blade shaft. The DMC-31017-2PB (Galil Motions) stepper motor controller along with an encoder were used to control the stepper motor in a closed loop system. Communication between the controller and the desktop computer was done wirelessly with the use of a wireless bridge. Power to the controller and other instrumentation was provided through a slip ring. A bore slip ring with a 12 channel circuits was used to pass power from the rotating side to the stationary side. The slip ring was placed between the rotor bearings and the hub assembly. Communication to the flap controller was also passed through the slip ring.

3.5. Data Acquisition System

It was of importance to collect all the data from the instrumentation simultaneously with no delay to capture temporal changes in parameters. Three National Instrument NI 9191 chassis were placed on the rotating hub. Figure 8 shows a diagram of the data acquisition system and summarizes all the components. Communication and data transfer from the DAQ cards to the computer was done wirelessly through a router located on the tower. The NI 9263 analog output card was used to transfer an analog signal to the pitch and flap controllers. The controllers are programmed to follow that analog signal at all times. The NI 9205 analog input was used to measure the signal from the 27 pressure transducers. The NI 9237 strain input was used to measure the strain from the two strain gauge groups located at the root of the blade. Two additional NI cards (NI 9402 and NI 9215) were used to measure the torque and encoder signal from the nacelle.

3.6. Running Conditions or Test Cases

The single bladed 3.5 m diameter wind turbine was designed for a tip speed ratio \( \lambda = \Omega R/U_\infty \) of 4.2 and a constant \( \beta = 6^\circ \) by Abdelrahman and Johnson [12]. Two other tip speed ratios were also chosen \( \lambda = 3.5 \) and 5 to study a range of performance. Blade pitch angles from 0° to 9° in steps of 3° were tested where positive \( \beta \) indicates pitch towards feather. Experiments with flap angles \( (\alpha_F) \) from -20° to 20° in steps of 10° were conducted. This \( \alpha_F \) range is chosen based on the literature review [11]. These different cases were tested to study the different types and range of loading on wind turbines. The turbine was also tested in a yawed condition to represent typical unsteady conditions on the turbine blades. A summary of the experimental test matrix
Figure 8: A diagram showing the configuration of the instrumentation and motor controllers

Table 1: Experimental test matrix for the wind turbine

| λ  | $U_\infty$ (m/s) | $\beta^\circ$ | $\gamma^\circ$ | $\alpha_F$ |
|----|-----------------|--------------|--------------|----------|
| 5  | 7.3             | [0, 3, 6, 9] | [0, 30]      | [-20, -10, 0, 10, 20] |
| 4.2| 8.7             | [0, 3, 6, 9] | [0, 30]      | [-20, -10, 0, 10, 20] |
| 3.5| 10.5            | [0, 3, 6, 9] | [0, 30]      | [-20, -10, 0, 10, 20] |

is shown in Table 1. These test cases explore the influence of the pitch and TEF on the loading on the turbine.

4. Results
The test matrix laid out in the experimental setup was followed to produce a series of results that are discussed here. The loading on the wind turbine blades will be discussed first to present the optimum running conditions for different blade pitch, $\beta$ angles. After that, the loading on the turbine was measured for different TEF angles for yaw and non-yawed conditions. Finally, a comparison between the pitch and flap system is presented.
4.1. Pitch influence on turbine loading

To measure the base loading of the present wind turbine, the turbine was run under different tip speed ratios and pitch angles. The coefficient of power ($C_{\text{power}}$), flapwise bending moment ($M_{FW}$) and $C_n$ are plotted for different $\lambda$ and $\beta$ conditions in Figure 9 for $\gamma = 0^\circ$, $\gamma = 30^\circ$. $C_{\text{power}}$ shows the performance of the entire turbine and $M_{FW}$ shows the loading on a single blade, while $C_n$ shows the forces on a small segment of the blade. These three load measuring techniques provide insight at three different levels to paint a full picture of the loads on the entire turbine. PROPID [17], a blade element method software, was used to predict the three variables mentioned and they are plotted for comparison with the experimental data. The lines in Figure 9a are from PROPID while the markers represent experimental data. PROPID data for yawed conditions was not available.

It is seen in both plots that $C_{\text{power}}$ increases as $\lambda$ increases or $U_\infty$ decreases for the small range tested. $C_{\text{power}}$ for $\beta = 6^\circ$, the analytical design condition, is higher than the other three $\beta$ cases indicating better performance. Both experimental and PROPID data follow the same trend and show that $\beta = 6^\circ$ leads to a more optimal running condition for this turbine, specially for lower wind speeds. When $\beta = 0^\circ$, $\alpha$ increases to such high angles of attack that the airfoil is then stalled decreasing lift while increasing drag and ultimately decreasing $C_{\text{power}}$ when compared to the $\beta = 6^\circ$ case. When the turbine is yawed to $\gamma = 30^\circ$, $C_{\text{power}}$ decreases in comparison to non-yawed conditions except when $\beta = 0^\circ$ where $C_{\text{power}}$ increased when the turbine is yawed. This could be explained by the fact that the blade is stalled during the entire rotation cycle for the non-yawed case but for the yawed case the blade goes in and out of stall increasing the average power output. As expected for all cases $C_{\text{power}}$ is small given the fact it is a single bladed turbine with a constant pitch and chord. $M_{FW}$ and $C_n$ follow the same trend and decrease when $\beta$ and $\lambda$ increase. $M_{FW}$ and $C_n$ distributions show that $\beta$ tends to have a larger influence on the blade loading at higher $\lambda$ and smaller influence at lower $\lambda$. This is because as $\lambda$ decreases, $U_\infty$ increases and that in turns increases the geometric angle of attack, $\alpha$, based on the blade velocity triangle in Figure 1. When $\alpha$ is higher and the blade operates at the onset of stall, $C_n$ is no longer linear and the airfoil is about to stall. $C_n$ for both experimental and theoretical cases matched because the lift curves for the airfoil were imported into PROPID from wind tunnel experiments for the S833 airfoil presented by Samara and Johnson [16].

![Figure 9: $C_{\text{power}}$, $M_{FW}$ and $C_n$ (at r/R=0.82) for different $\beta$ angles and tip speed ratios. (a) $\gamma = 0^\circ$, (b) $\gamma = 30^\circ$, (c) $\gamma = 30^\circ/\gamma = 0^\circ$](image-url)
4.2. TEF influence on turbine loading

The same parameters plotted in Figure 9 are presented in Figure 10 but instead of varying $\beta$, the flap angle, $\alpha_F$ changes. It is noted that $C_{\text{power}}$ has a smaller change when $\alpha_F$ is varied in comparison to $\beta$ changes especially at lower $\lambda$. This is because the TEF alters only 22% of the aerodynamic blade span while preserving the rest of the blade. The pitch system, changing $\beta$, on the other hand alters the entire aerodynamics of the blade. When $\beta$ is altered it also changes the percentage of the blade that is stalled for a constant pitch blade. The rate of change in $M_{FW}$ with respect to $\alpha_F$ is the same for different $\lambda$ unlike the pitch system. This indicates that the linearity of the flap system is not influenced by $\lambda$. The change in $C_n$ with $\alpha_F$ variation is much more significant and linear when compared to the pitch system. This is because experimental data showed that the influence of the TEF on $C_n$ is linear for the entire range of $\alpha$ and is not effected by the stall angle [16]. The data in Figure 10b is mostly shifted slightly lower when compared to Figure 10a because the turbine blade is partially stalled when the turbine is yawed to $30^\circ$. Figure 10b for $\gamma = 30^\circ$ also shows that the flap system does influence the three variables equally for yawed and non-yawed conditions.

![Figure 10: $C_{\text{power}}$, $M_{FW}$ and $C_n$ (at r/R=0.82) for different $\alpha_F$ angles at $\beta = 6^\circ$. (a) $\gamma = 0^\circ$, (b) $\gamma = 30^\circ$.](image1)

4.3. Pitch and Flap Comparison

To better show the differences between the pitch and flap system, the influence of $\beta$ and $\alpha_F$ on the three variables are plotted on the same graph for $\lambda = 4.2$ in Figure 11. $\alpha_F$ is presented in the bottom x-axis while $\beta$ is presented in the top x-axis. The plot clearly shows that the pitch system has a greater influence on $C_{\text{power}}$ than the flap system as concluded earlier. The slopes of the pitch and flap lines show that their influence over $M_{FW}$ is very similar. This is significant as it indicates that the TEF is capable of manipulating $M_{FW}$ better than or equal to pitching the entire blade and without influencing the power output. As expected the flap system has a greater influence over $C_n$ because $C_n$ is measured at midspan of the TEF. The TEF can increase or decrease $C_n$ in a linear fashion unlike pitching the entire blade. The TEF only occupies 22% of the aerodynamic blade span or about 4% of the blade surface area but its control authority is very similar to that of pitching the entire airfoil but without the negative impact of decreasing $C_{\text{power}}$. This could be explained by the fact that most of the power produced by the blade is located around r/R=0.77 as shown by Johnson et al. [18]. Placing the TEF at that location has the largest impact on the loading of the blade. This indicates that the TEF has a great deal of...
influence over the bending moment on the entire blade with just using 4% of the surface area. The TEF can increase or decrease $M_{FW}$ by about 15%, which aligns with what was found in the literature review. Based on the $M_{FW}$ plot in Figure 11a, the slope of the flap influence is 0.325 N.m/° while the slope of the pitch is 1.44 N.m/°. There is an order of magnitude difference between the two, but changing the pitch angle is much more difficult than changing the flap angle. Another important benefit for the TEF is that the load control is localized whereas the pitch system changes the loading on the entire turbine blade. It is important to re-iterate that the TEF is tested on a one bladed turbine with constant chord and pitch. The control authority of the TEF may be different for a twisted blade with variable chord.

![Figure 11: $C_{\text{power}}$, $M_{FW}$ and $C_n$ (at r/R=0.82) for different $\alpha_F$ (bottom axis) and $\beta$ (top axis) angles for $\lambda = 4.2$. (a) $\gamma = 0^\circ$, (b) $\gamma = 30^\circ$.](image)

5. Conclusions
The experimental setup is presented in detail showing how $C_{\text{power}}$, root bending moment($M_{FW}$) and $C_n$ are measured on a full scale wind turbine equipped with a TEF. The 3.5 m diameter wind turbine was tested in a large scale, controlled wind generation facility. The combination of the different sensors and actuators makes this setup very unique. All measurements were collected simultaneously to capture temporal changes with respect to the azimuthal position. The wind turbine was tested for different $\lambda$, $\beta$, $\alpha_F$ and yaw cases. It was found that when $\beta = 6^\circ$, $C_{\text{power}}$ is highest, indicating better performance. It was also found that the increase or decrease in $M_{FW}$ and $C_n$ when $\beta$ changes is not linear with $\lambda$, but it is linear with the flap motion. The experimental data showed that the TEF, with just 4% of the blade surface area, is capable of manipulating $M_{FW}$ and $C_n$ more effectively than pitching the entire blade and without impacting the power output. The next step is to use the motion of TEF and pitch system to dynamically reduce load fluctuations on the turbine when $\gamma = 30^\circ$.

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