In-blade Load Sensing on 3D Printed Wind Turbine Blades Using Trailing Edge Flaps

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In-blade Load Sensing on 3D Printed Wind Turbine Blades Using Trailing Edge Flaps

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Abstract. As wind turbines become larger the loading on the blades also increases. Controlling a section of the trailing edge of the turbine airfoil is found to reduce load fluctuations on wind turbine blades. Here a detailed experimental setup is described showing the development of a compact airfoil section capable of measuring the surface pressure, root bending moment, and controlling a TEF simultaneously and in time resolved fashion to quantify the influence of a TEF on a wind turbine. This experimental work includes a trailing edge flap that covers 20% of an S833 airfoil with a chord of 178 mm. Surface pressure and blade root strain are measured for varying angles of attack and flap angle. Coefficient of lift and moment are obtained from the 54 pressure taps. The lift and drag forces are also obtained from the strain gages at the root of the blade. A 3D printed blade section is designed and built to house the actuation and sensing on the airfoil. The trailing edge flap was tested inside a 0.61 m wind tunnel as a baseline case and the results showed how the lift, drag, and root moment on the airfoil can change for different flap angles. The coefficient of lift changed by 30% for flap angle of 20°. The entire blade with the flap will also be installed on a 3.4 diameter wind turbine to study the influence of a flap on load variation.

1. Introduction
During normal everyday operation of wind turbines, the direction and magnitude of the incoming wind speed changes. This could be due to many factors including wind shear, rotor misalignment, and turbulence of the wind resource. This leads to unsteady and cyclic loading on the blades that are 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 [1]. 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 here is to sense and mitigate load variation on the wind turbine blades.

2. Background and Theory
Various technologies have been developed to reduce the variation in loading on the blades, and they are often referred to as “smart blades”. The focus of this research will be on trailing edge flaps (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 is...
changing altering the coefficient of lift and moment. When the flap is deflected towards the pressure side (negative angle) the coefficient of lift \( (C_l) \) is increased and the opposite is true as shown schematically in Figure 1. Due to the discontinuity in the camber caused by the TEF aerodynamic performance is reduced slightly as seen in a decrease in the lift to drag ratio [1]. Barlas and van Kuik [1] summarized and reviewed different technologies that have been used in producing a “smart rotor” to reduce the fatigue load on wind turbine blades. Flaps and a deformable trailing edge were found to have the most influence on the coefficient of lift \( (C_l) \) of the airfoil.

![Figure 1. Influence of the flap deflection on the lift curve for ideal cases (Adapted from [2])](image)

Bernhammer et al. discusses the steps needed for the “smart blades” to be fully reliable and operate under standard environmental conditions [3]. They argue that the benefits of flap control extend beyond reducing root bending moment and the secondary benefits should be studied more carefully.

Individual pitch control is the most advanced technique used to reduce loading on wind turbines to date in wind farms [1]. It is basically controlling the pitch of each blade separately and not collectively. This technique is tailored to alleviate the dominant forces with a frequency of once-per-revolution (1P) such as wind shear, tower shadow, and yaw misalignment. This technique is limited by the speed and reliability of pitch actuation specially for large multi-MW blades. Excessive use of the pitch mechanism could lead to wear on the actuator and bearings which tend to be very expensive parts. Load reduction in highly fluctuating flow would require high pitch angles and rotation rates which most standard pitch actuators cannot handle. To achieve a more refined and responsive load reduction another technique is required. 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 the blades [4, 5, 6]. Five different groups have tested a TEF on a full scale wind turbine. Hulskamp et al. [7] used piezoelectric benders covering half the chord to deflect the trailing edge by 2°. The TEF was tested on a 1.8m diameter wind turbine inside a wind tunnel. Navalkar et al. [8] implemented a free floating flap on a small scale wind turbine. The flap was placed in a way that was free to rotate. The flap 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. [9] 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. [10] 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 [11] 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 tubes, 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.

3. Experimental Setup
To quantify the influence of a TEF on the wind turbine blade an experimental setup is designed to sense the aerodynamic forces on the wind turbine in real time and actuate the flap accordingly. All the testing will be done at the large University of Waterloo wind generation facility. The main features of the project is to incorporate an actuator inside the airfoil to control the flap angle internally. Surface taps at the flap location are used to measure the surface pressure to calculate the lift and moment forces. Using strain gages the root bending moment is found in the edgewise and flapwise direction. Finally an accelerometer is used to measure the vibration of the blade. As for the data acquisition system it operates in real time. All the sensors and actuators are enclosed inside the airfoil or hub.

In this section the experimental setup is explained in detail. Firstly the airfoil design and pressure taps are discussed. The flap and pitch actuation design are laid out along with the onboard sensors used. Finally the characterization of the wind tunnel and wind turbine are presented.

3.1. Airfoil Design and Pressure Taps
The NREL S833 airfoil [12], designed for small wind turbines, is used for the turbine blade. The flap width is chosen to be 20% of the chord while the flap span is 20% of the blade based on the studies mentioned in the introduction. To incorporate the sensors and actuators the aerodynamic blade is 3D printed using ABS-M30 material. Different research groups have used 3D printing techniques to manufacture small scale wind turbine blades. Navalkar et al. [8] 3D printed 1 m long blades in one piece and they were reinforced with a unidirectional carbon fiber spar cap. Sandia National Labs also used 3D printing techniques to print the TEF [10]. Abdelrahman and Johnson [11] 3D printed 1.7 m long blades in 5 modular pieces, and attached them together on a steel spar at the quarter chord of the airfoil. The latter method is used in this experimental setup. Some of the advantages of 3D printing the blades are: high level of complexity, high accuracy and repeatability, high speed with no molds, and high strength material.

One of the most complicated tasks that went into designing the blade is trying to make room for all the different components (pressure transducers, tubing, flap motor actuator, controllers, and all the electrical wiring). To this end, it is determined that the airfoil must be composed of three different parts, the suction side, pressure side, and the flap. To ensure that the suction side and leading edge are smooth they were 3D printed in one part. The designed model is capable of housing the pressure transducers and all the tubing needed to connect the transducers to the taps. The model also houses the flap actuation. Refer to Figure 2 for more clarification. Those three sections were printed and lightly polished to achieve a smooth surface finish.

To determine the coefficient of lift and moment, 54 surface pressure taps are located on an aluminum airfoil section at midspan with 4 of those pressure taps located on the flap as shown in Figure 3. The top and bottom taps are placed at the same x/c location. All the odd number taps are on one plane and all the even number taps are on the other plane. It was not possible to place all the pressure taps on one plane due to geometric constraints. The distance between the two planes is 8 mm, a negligible distance (at 200 rpm and a span wise location of 1.7 m that
would lead to a velocity of 35.60 and 35.77 m/s for each of the 2 planes). The pressure taps are denser at the leading edge than the trailing edge to increase resolution of the pressure at the leading edge. The distance between pressure taps is 4 mm at the leading edge and it goes to 7 mm at the trailing edge. The pressure taps were directly drilled on the surface of the airfoil to avoid any errors and ensure a smooth surface. The internal diameter of the taps is 0.4 mm while the length of the taps is 2 mm. 1/16 inch ID tubing is then used to connect the taps to the transducers.

To measure the surface pressure on the airfoil while rotating on the wind turbine with the frequency desired, the pressure measurements had to be simultaneous. To achieve this, 27 differential pressure transducers are used to measure the differential pressure between the suction and pressure side of the airfoil at the same x/c location. This technique was successfully used by Raiola et al.[6]. One of the advantages of having a differential pressure transducer is that it is not influenced by the centrifugal forces due to rotation inside the wind turbine blade. To determine the pressure range needed, Xfoil is used to determine the coefficient of pressure for the S833 airfoil. The transducers chosen for this project are manufactured by All Sensors with a model number of 120 cmH2O-D1-4V-MINI [13]. The pressure range is from -0.1 kPa to 11.8 kPa and a nominal error of ± 0.05%. A printed circuit board (PCB) is designed to connect the pressure transducers to the data acquisition system and is shown in Figure 4. The pressure transducers are individually calibrated (Druck DPI610 pressure calibrator).

3.2. Flap Actuation

Before choosing the appropriate flap actuator the flap hinge moment required is determined based on Xfoil simulations and dynamic mass moment of inertia and the torque needed is 0.122 Nm at a rotational speed of 160 rpm. There were also geometric requirements because it was placed inside the airfoil. The Maxon ECX series motor assembly is chosen with diameter of 8 mm and length of 40 mm. The assembly includes a motor, a 256:1 gearbox and a quadrature encoder with 4096 counts per turn. The backlash in the system is 2.5°. The Maxon EPOS2 24/2 controller is used to control the motor. The motor and controller are placed inside the airfoil and the motor is directly connected to the flap shaft. Two bearings are used on either side to support the flap on the main blade geometry. Both controllers are fixed inside the airfoil as seen in Figure 5. A fan is used to make sure that the motor does not overheat.
3.3. **Onboard Sensors**

Apart from measuring the airfoil surface pressure, the blades and the turbine are instrumented with numerous sensors to measure and monitor performance. A three-axis accelerometer is used to measure the acceleration at the tip of the blade. The acceleration is a good indicator if the blade is oscillating due to stall. Two strain gage groups are used to measure the strain at the blade support to obtain the lift and drag moment. Precision strain gages (Omega SGD-7/1000-DY11) were calibrated and connected in a full-bridge configuration to increase sensitivity and reduce temperature dependence. Figure 6 shows all the different parts internal to the airfoil. A non-contact shaft torque/encoder (Futek TRS 605) determines shaft torque and position. The encoder provides position and can be synchronized with the torque sensor to provide accurate power output. Figure 7 shows a schematic of the different sensors and actuators in the system with wireless data acquisition.

![Figure 4. The layout of the pressure transducers on the PCB](image1)

![Figure 5. Maxon motor and controller assembly and integration to the airfoil](image2)

3.4. **Airfoil Characterization**

Wind tunnel testing is employed to characterize the instrumented airfoil section separately from the turbine blade for different airfoil and flap angles. The test parameters are designed to represent the blade conditions on the wind turbine. The airfoil is cantilevered and supported on the drive side to resemble a blade. The strain gages are attached on the support side to measure...
the lift and drag moment. The pressure tap section is placed at the center of the wind tunnel section sandwiched between the 3D printed airfoil pieces. A schematic of the experimental setup is shown in Figure 8. Surface pressure measurements, strain measurements and acceleration measurements are collected during the experiments.

The airfoil was tested inside a closed loop wind tunnel at a chord Reynolds number of 350,000 so it matched that of the wind turbine. The wind tunnel has a contraction ratio of 9:1 and a cross section of 0.61m square. The uniformity is found to be within $\pm 0.4\%$ in the spanwise and vertical direction. The turbulence intensity is 0.1%. The free-stream velocity is set by the static pressure drop across the contraction with an uncertainty of less than 2.5%. More information about the wind tunnel calibration could be found in [14].

3.5. Large Wind Tunnel and Wind Turbine Model

The experiments were conducted using the University of Waterloo Wind Generation Research facility which is an open loop style wind tunnel and is capable of generating wind speeds up to 13 m/s. The fan discharge plenum is 8.2m wide and 5.8m high and a picture of the discharge area is given in Figure 9. More information about the facility geometry and specifications can be found in Devaud et al. [15]. The turbulent intensity is around 6% while the blockage ratio of the turbine is around 7%. The combination of high turbulence and low blockage is considered ideal to test cyclic loading on the turbine blades.

The test turbine is a custom designed 3.4m diameter upwind horizontal-axis wind turbine which is capable of individual blade pitch and torque control similar to the wind turbine described by Bottasso et al.[16]. One of the main features of the turbine is that the rotational speed could be controlled accurately and different yaw angles could be set. The rotor is compromised of one

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**Figure 7.** A sketch illustrating the communication lines connecting the different components.
3D-printed blade of constant chord and twist and two dynamically balanced rods. The rotor and wind turbine is designed and described in Abdelrahman et al. [11]. A picture of the turbine could be seen in Figure 10.

4. Results
The airfoil section was initially evaluated inside a 0.61m square wind tunnel for characterization purposes and to obtain the $C_l$ and coefficient moment ($C_m$). The angle of attack ($\alpha$) ranged from 0° to 20° in steps of 1° and the flap angle ($\alpha_F$) from -20° to 20° in steps of 5° (positive flap angles are defined when the flap is deflected to the suction side of the airfoil). Figure 11 shows the $C_l$ for different flap and $\alpha$ angles achieved by integrating the pressure coefficient along the
chord of the airfoil. As the flap angle decreases (increasing the camber of the airfoil), $C_l$ increases as expected. For $\alpha_F=-20^\circ$ the $C_l$ increased by 30% while for $\alpha_F=+20^\circ$ the $C_l$ decreased by 32% based on $\alpha_F=0^\circ$. Moment coefficient is also determined at the quarter chord using the pressure measurement, and the results are shown in Figure 12. The stall angle can be seen clearly in Figure 12 where $C_m$ drops significantly. As shown the stall angle is shifted to the right by 1$^\circ$ for $\alpha_F=+20^\circ$ and shifted to the left by 1$^\circ$ for $\alpha_F=-20^\circ$. The uncertainty in the coefficient of lift and moment was calculated to be ±0.03 and ±0.004 respectively. The uncertainty was based on the error in the pressure transducers and wind tunnel velocity. The uncertainty in the angle of attack and flap angle is ±0.1$^\circ$ and ±1$^\circ$ respectively. The blade loading on the airfoil is also determined using 2 sets of strain gages installed on the spar supporting the airfoil.

![Figure 11. $C_l$ for different flap and $\alpha$ angles.](image1)

![Figure 12. $C_m$ for different flap and $\alpha$ angles.](image2)

The strain gages can also measure the lift bending moment created by the airfoil at the root of the blade. The lift moment is plotted against the angle of attack for different flap angles in Figure 13. The lift moment trend is very similar to the coefficient of lift (Figure 11). This shows that the lift bending moment and the coefficient of lift are in agreement. The drag force is also measured and it is found that flap angle has a negligible influence on the drag force and for the purpose for this setup will be ignored. The uncertainty in the bending moment is ±0.35%. Figure 14 shows the standard deviation (STD) of the acceleration for different angle of attack and flap angles. The STD starts off very small and as soon as the airfoil stall or the flow separates the STD increases substantially. This is indicative that once the airfoil stall the vibration increases. This could be used a criterion when looking at way to reduce the loading on the blades.

The TEF airfoil section will be installed on the 3.4 diameter wind turbine to measure $C_l$, $C_m$ and moment at the root of the blade during normal operation of the wind turbine. Different flap angles will be set to study how the flap can change the loading on the entire turbine. These results are important because time resolved data could be collected on the turbine for different azimuthal positions. The results would be used to create a controller to dynamically reduce the load fluctuation on the turbine blades.

5. Conclusions

The experimental setup presented in this paper is a unique method to measure the lift forces on a full scale wind turbine equipped with a TEF. The blades of the 3.4 diameter wind turbine are 3D printed. There are 54 pressure taps along the chord on the section of the blade that is equipped with a TEF. The pressure transducers are installed in the blade for simultaneous
and time resolved coefficient of lift measurements. Strain measurements at the root of the blade will be used to measure the edgewise and flapwise bending moment. Preliminary results from a non rotating blade section tested inside a wind tunnel are presented. These results show that a TEF is capable of controlling the lift forces on the blades. The tests also show that the fully instrumented blade is providing useful data and can be installed on the wind turbine in the future.

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