Characterization and Control of Unsteady Aerodynamics on Wind Turbine Aerofoils

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Abstract. An experimental capability developed for testing two-dimensional aerofoils while dynamically pitching is discussed. Key to the approach are a dynamic pitch system, the rapid prototyping of aerofoils, inexpensive time-resolved pressure measurements, the ability to capture flow-field structure, and the ability to add compliance to the system. In addition to describing the system components, examples of typical results for characterization and control studies are given. Use of the data is also demonstrated through comparison of the results from a simulation with those from an experiment under the same conditions. Future uses of this experimental capability are also discussed.

1. Introduction

Although the rotor only represents 15% of the cost of a modern land-based wind turbine [1], its performance dominates power production. Furthermore, of the events that cause wind turbine shutdowns, events that involve the rotor, including the blades, have the highest rate of occurrence and represent the single largest cause of turbine downtime [2]. As a result, improvements in wind turbine blade design should have a significant impact on the cost of energy. As wind turbine blades grow larger, the importance of understanding the aerodynamics that create loads and power becomes even more important. Larger wind turbines experience larger loads that act over greater distances affecting important quantities from maximum blade tip deflection to blade fatigue. These loads are driven by unsteady aerodynamics that result from shear and turbulence in the atmospheric boundary layer, as well as yaw position. Unfortunately, our understanding of these unsteady flows is limited [3], and modeling the more complex cases is a challenge. To mitigate some of the loading issues on large wind turbine blades, some local flow control may be necessary, but identifying what is to be controlled is needed first. Similarly, our need to model these flows accurately is critical to improving our designs, but models require validation data to verify that they are providing reasonable results.

As a result of these needs, a five-year effort has developed a means of characterizing these complex flows. As a first step in this work, an experimental capability was developed that consisted of five critical pieces: 1) development of a pitch-oscillating test capability, 2) use of rapid-prototyping to construct aerofoils, 3) development of a robust unsteady pressure measurement system, 4) demonstration of flow-field structure imaging, and 5) addition of compliance to the pitch oscillation capability. In the process of demonstrating these capabilities, more than 40 configurations have been tested for a range of aerofoil shapes and for different levels of unsteadiness. The outcomes of this work are expected to result in three accomplishments: 1) an improvement of our understanding of these flows, 2) the identification of flow conditions with...
negative impacts that are candidates for control, and 3) the generation of data that can be used to validate computational models. In this paper, the experimental capability is first described, and then sample results are shown. Use of the results is also discussed.

2. Critical Testing Capabilities
Although none of the test capabilities described here are entirely new, it is the first time to the authors’ knowledge that they have been used together. Each of the individual capabilities is described below, with references given that provide more detail.

2.1. Dynamic Pitch Hardware
In order to provide pitch ranges and frequencies relevant to wind turbine blades, a pitch oscillating capability was developed. Figure 1 shows the components of the pitch system installed in the test section of an open return wind tunnel. Wind turbine simulations were used to identify relevant operating conditions that the system needed to replicate. As a result, the system was designed to provide oscillation frequencies of up to 20 Hz and oscillation ranges of ±45°. The components are briefly described here, and full details can be found in references [4] and [5]. A 2.2 kW motor is connected to the aerofoil through a four-bar linkage, a cam, and a pitch drive shaft. The mean pitch angle is controlled via an adjustable length rod, and the pitch amplitude is determined by selecting the attachment point on the cam for the pitch linkage rod. The frequency of the oscillation is variable and is regulated using a controller with feedback. The pitch drive shaft that connects the drive system to the aerofoil is hollow such that instrumentation connections can pass through the aerofoil and out into the laboratory. Encoders connected to shaft ends on both top and bottom indicate position of the pitch drive system and the aerofoil. All of the pitch system components were designed to occupy only a small space such that they did not interfere substantially with optical access to the wind tunnel. Aerofoils have been typically attached to the pitch drive shaft at the 1/4 chord point, but the capability to move this point fore and aft has been added recently [6].

This pitch system is installed in the test section of a low speed, open-return wind tunnel. Flow is conditioned through honeycomb and three screens before entering a 12:1 contraction that delivers the flow to a 0.61 x 0.61 x 1.22 m test section. The tunnel is capable of generating speeds up to 50 m/s in the test section, and the free-stream turbulence intensity has been measured to be 0.3%.
2.2. Rapid Prototype Aerofoil Models
Several different aerofoils have been tested ranging from 30% thick wind turbine aerofoils (DU-97-W-300) to a 9% thick helicopter aerofoil (SC1095). Chord lengths on the aerofoils tested have varied from 10-20 cm, whereas the spans have been \( \sim 61 \text{ cm} \) to span the test section. At low angles of attack, the aerofoils have a maximum blockage of 10% for the longer aerofoils. The aerofoils were built using rapid prototyping methods (see reference [7]) as they were able to provide fast design-to-test capability (as little as 2 weeks), pressure taps to 95% chord, and low cost compared to traditional manufacturing methods. Aerofoils were constructed in three sections: a central instrumented section and two outboard sections without instrumentation. The center section, an example of which is shown in Figure 2, was built using a stereo-lithography process with pressure taps and pressure channels embedded in the model. The high density material used for manufacturing these sections prevented leaks in the \( \sim 50 \) pressure channels included in the model. Stainless steel tubing connectors were attached to the model such that vinyl tubing could be connected to the pressure channels at the tubing connection point. The surfaces of this central section were lightly sanded and painted leaving them with a hydraulically smooth surface. The outboard sections of the aerofoil were manufactured using a less expensive ABS material as it was significantly cheaper and did not require the pressure-holding capability of the central section. The aerofoils are now spar mounted such that the spar carries much of the load as earlier models failed at higher oscillation frequencies. To provide flow relevant to their high-Re design, the aerofoils were typically tripped at one of more locations in the first 10% of chord such that they produced a lift curve similar to that of the same aerofoil tested at higher Reynolds numbers. Although the flow will still not be the same as that over the aerofoil at higher Reynolds numbers, it was felt that forcing a turbulent boundary layer at these lower Reynolds numbers would produce boundary layers more similar to those experienced on the same aerofoil at a higher Reynolds number, which makes the separation dynamics observed here more relevant to full scale Reynolds number flows.

2.3. Dynamic Pressure Measurement
Critical to characterizing the unsteady flows produced by pitch oscillation was the ability to measure many unsteady surface pressures. These measurements provided pressure distributions as well as lift and moment coefficients. In the past, surface mounted pressure transducers were used for such measurements. However, such transducers are expensive, and, in our experience, prone to failure in the harsh environment produced by high dynamic pitch frequencies. The approach taken here was to use traditional tap/tubing/transducer systems and to compensate for the distortion effects of such systems. The approach is briefly described here, and a more complete description of the theory and application can be found in the references [4, 5, 8, 9].

For the aerofoils tested here, two 32 channel Electronic Scanning Pressure (ESP) modules

Figure 2. Rendering of a rapid-prototyped aerofoil showing embedded pressure taps and connection points.
Figure 3. Pressure signals demonstrating the effectiveness of the correction process: $P_{\text{ESP}}$ is the pressure measured by the ESP transducer in the tap/tubing/transducer setup, $P_{\text{decon}}$ is the corrected pressure determined from $P_{\text{ESP}}$, and $P_{\text{ref}}$ is the pressure measured by the surface-mounted transducer.

were used. The 20 kHz sampling rate yielded 625 Hz per channel when all channels were used. To provide maximum flexibility in sampling the pressures, a National Instruments cRIO FPGA system was used to digitally address the ESP modules directly. The pressure channels in the aerofoil were connected to the ESPs through 107 cm of 0.86 cm tubing. Significant distortion of the pressure signals as they propagate down the tubing occurred through attenuation and resonance effects. To make these measurements useful, correction of the pressure signals was necessary. The correction approach taken here is based on the tap/tubing/transducer response model proposed by Bergh and Tijdeman [10]. Their method models the pressure at the output of the tubing based on an input pressure at the model surface. Here, the opposite result is desired: the prediction of the pressure at the surface given the pressure measured at the transducer. When Bergh and Tijdeman’s response model is directly used for this purpose, noise at high frequencies gets highly amplified. As a result, a different approach is required. Whitmore and Wilson [8] proposed a Wiener Filter based approach to attenuate the Bergh and Tijdeman response model at these higher frequencies. A single parameter, the signal-to-noise ratio, controls the frequencies that get attenuated. This approach was later adopted to correcting the many pressure measurements that are typically made in unsteady aerodynamic testing [9].

To demonstrate the effectiveness of the approach, an aerofoil was constructed that housed both flush mounted pressure transducers (taken to be the actual signal) and a tap/tubing/transducer system discussed above with a tap location at the same chordwise location. To produce an unsteady pressure signal, the aerofoil was oscillated in pitch at 10 Hz. Figure 3 shows the measured $P_{\text{ESP}}$, corrected $P_{\text{decon}}$ and actual $P_{\text{ref}}$ pressure signals for two SNR values. As is evident, the approach does an excellent job of reconstructing the pressure signal, with the SNR dictating the specific character of the corrected result. Figure 3 (a) corresponding to a low SNR exhibits a very smooth signal, but the corrected signal fails to capture the peaks and valleys of the pressure signal. In contrast, Figure 3 (b) now captures the peaks and valleys of the signal, but the resulting signal is noisier. Which corrected signal is more desirable depends on the exact application.

Having proven that the reconstruction process works sufficiently well for the purpose of measuring the time-dependent pressure signal on the aerofoil, measurements were next carried out on aerofoils with many pressure ports. Figure 4 shows the typical results of such measurements. The $y$-axis represents the relative location during one period, with the bottom being the start of the cycle, and the top being the end. The horizontal axis represents the location on the aerofoil as a percent of chord. The suction side of the aerofoil is the left contour
Pressure contours for a 0.127 m chord DU-91-W2-250 aerofoil oscillating at 10±7° at 12 Hz in a free-stream of 45 m/s yielding a chord Reynolds number \( \text{Re}=280,000 \) and a reduced frequency \( k=0.11 \). Also shown are traditional \( C_p \) plots for a few specific points in the cycle.

Displaying the pressure data in this way is particularly effective for determining what period of time and to what extent the aerofoil is separated. Separation can be easily identified by constant color (and thus constant pressure) in the horizontal direction, as can be observed, for example, in the result for \( t/T =0.5 \). This display approach is also effective for identifying vortical structures that develop and convect above the aerofoil surface as they often induce low pressure. In addition to revealing the details of the pressure distribution, these pressures may also be integrated to determine lift and pitching moment.

2.4. Flow-Field Imaging

To complement the pressure distributions, the flow-field structure above the aerofoil was captured using Particle Image Velocimetry (PIV). A LaVision PIV system that included two 2048 x 2048 Image Pro cameras was used. The setup for obtaining PIV data is shown in Figure 1, where two lasers are observed to illuminate the plane where data is to be captured in order to avoid shadowing caused by the aerofoil. Likewise, two cameras were used to capture data from both sides of the aerofoil, something that would have been difficult to do with a single camera as a result of a partially blocked view of the flow field near to the surface due to the aerofoil itself. Multiple images were acquired for a specific point in the oscillation cycle by phase locking the PIV system to the position transducer. Typically 100-200 images were taken at each point in the cycle and were averaged to eliminate noise and turbulence effects from the images, leaving only the phase-locked average flow. Images were analyzed using LaVision’s DaVis software to determine the velocity using a multiple pass, decreasing window size, correlation approach. To highlight the structure, phase-locked streamlines were determined by integrating the velocity data that resulted from the PIV data analysis.
2.5. Compliance
The final important capability developed for this pitch-oscillating system was the ability to model elastic effects in blades. Real blades bend and twist due to the loads they experience. To simulate this behavior, a compliant section was added between the pitch drive and the aerofoil. The compliance section consists of coaxial annuli connected by a number of linear springs. By varying the number of springs, the compliance could be adjusted. Providing variable compliance was important as actual aero-elastic systems have inertial, aerodynamic and elastic forces acting on them that are comparable. As such, it was necessary to balance these forces in the current system to get the appropriate response. Details of the compliance system are presented in reference [11].

3. Example Results
The system described above has been used to test many different cases: aerofoil shape, oscillation frequency, and pitch range are among the primary parameters that have been varied. An example case will be discussed here to demonstrate the typical results that are obtained using the hardware and instrumentation discussed.

The example case presented here uses the DU-97-W-300 aerofoil that is part of the DU series of aerofoils developed at TU Delft [12]. The aerofoil is a 30% thick aerofoil that is representative of aerofoils used on the inboard sections of wind turbine blades. The aerofoil was tested at conditions that produce dynamic stall: a nominal mean angle of attack of 15° oscillating with an amplitude of approximately 10° at a frequency f of 20 Hz. Actual angle of attack range varied slightly due to system response. The aerofoil of chord length \( c = 10.2 \text{ cm} \) was tested at a free-stream velocity \( U_\infty \) of 45 m/s, which yields a Reynolds number based on chord of \( \text{Re}=\rho U_\infty c/\mu = 220,000 \) and a reduced frequency \( k = 2\pi fc/(2U_\infty) \) of 0.142, where \( \mu \) is the viscosity.

The pressure distribution measured for this case is complex due to the dynamic stall and reattachment processes that take place. Figure 5 shows the pressure distribution in the form that was discussed above. The angles of attack shown in the figure represent the measured angle of attack, which was slightly different from the nominal values. Low pressure develops near the leading edge of the aerofoil as it pitches up as indicated by the region of deep blue on the suction surface. On the pressure surface, the stagnation point can be observed moving aft as the aerofoil initially pitches upward as indicated by the deep red color. At approximately \( t/T=0.3 \) (\( \alpha = 19° \) rising), the pressure distribution on the suction surface undergoes a large
Figure 6. Lift curve for a 0.102 m chord DU-97-W-300 aerofoil oscillating at a nominal angle of attack range of $15\pm10^\circ$ at 20 Hz in a free-stream of 45 m/s yielding a chord Reynolds number $Re=220,000$ and a reduced frequency $k=0.14$.

change. A region of constant pressure is initially observed for $x/c > 0.6$ that moves forward as $\alpha$ continues to increase. Simultaneously, the region of low pressure near the leading edge retreats forward as well until it essentially disappears at $t/T=0.42$ ($\alpha = 24^\circ$ rising). Just after this, the pressure increases (yellow region) before decreasing again (light blue) at $t/T=0.45$. A low pressure region (cyan region near trailing edge) also forms at $t/T=0.45$. At the same time, the stagnation point on the pressure surface moves to its furthest point aft. Just before and after $t/T=0.5$ ($\alpha = 26^\circ$), there are two lower pressure regions on the pressure side that appear to be associated with the cyan areas near the trailing edge on the suction side. After $t/T=0.6$ ($\alpha = 24^\circ$ falling), the aerofoil appears to be separated over almost the entire suction surface. As the aerofoil continues to pitch down, the separated region decreases as the flow starts to reattach from the front of the aerofoil.

The pressure distribution results contain a wealth of information, but often the interest is in the forces and moments that act on the aerofoil. Integrating the pressure distribution can provide some of these quantities. The lift curve associated with the pressure distribution shown in Figure 5 is shown in Figure 6. As aerofoil initially pitches upward, the lift closely follows the static lift curve result. As it continues to pitch upward, the flow stays attached well beyond the stall angle due to the relatively high reduced frequency for this case. At about $15^\circ$ rising, the lift curve starts to depart from its initially linear behavior. At about $21^\circ$ rising, the aerofoil stalls and lift drops as the pitch angle continues to increase. A cusp forms near the peak angle of attack that is associated with the complex changes in the pressure distribution present on the aerofoil in this region. Such features have been observed in previous experiments, e.g. reference [13]. The lift then continues to drop as the aerofoil completely separates. The flow does not fully reattach until the aerofoil hits the bottom of the cycle.

The pressure and lift results are informative that something complex is happening in the flow, but the surface measurements cannot alone explain the behavior. As a result, flow-field structure is used to help decipher what is occurring. Figure 7 shows streamlines determined from velocity data for the most relevant portion of the cycle. The figure shows the results for the cycle starting at $18^\circ$ rising and proceeding left-to-right and top-to-bottom. The flow is observed to start separating near the trailing edge at $18^\circ$ and the stalled region continues to develop and enlarge through $22^\circ$. As the aerofoil continues to rise, the flow grows more complex with the primary separation region losing some structure and a strong secondary vortex forming with it largest extent at $25.5^\circ$. This secondary vortex is associated with the low pressure region observed near the trailing edge in Figure 5 at this point in the cycle. The original stall region
appears to lift off the aerofoil at 25.5° rising, but then appears to redevelop by 25.5° falling. This flow structure is related to the complex structure in the pressure distribution observed in this part of the cycle as well as the cusp in the lift curve. After this primary stall region is reestablished, another secondary vortex appears at 24° falling and sheds rapidly with little apparent effect on the pressure distribution. After this, the flow shows a steadily decreasing size separated region with the flow reattachment moving aft. However, evidence of separation is still clear at 12° falling.

Clearly the combined results are necessary to understand what is occurring in these complex flows. The flow-field structure complements the surface pressure data to allow an understanding on why the forces and moments behave the way they do. Below, the importance of such results is described further.

In addition to understanding what occurs in these flows, the testing capability is also useful for assessing if these flows may be controlled. A recent effort has investigated the change of Gurney flap effectiveness under dynamic pitch conditions. Figure 8 shows the modification of the lift and moment curves when Gurney flaps are deployed on the suction and pressure sides of the aerofoil. The effects are complex in this case as the aerofoil is experiencing dynamic stall and the behavior of the Gurney flaps is not easily predicted under such conditions. Again, the value of the testing capability is clear. Additional details concerning the effect of the Gurney flap on wind turbine blade flows can be found in reference [14].

4. Example Uses of the Results

Generating the types of results shown here are useful for many reasons. For example a recent paper discussed that a range of dynamic stall processes were present depending on the aerofoil geometry, the angle of attack range, and the reduced frequency [15]. However, a key use of such results is expected to be used in the validation of computational simulations of these flows.

When comparing computational and experimental results, an integrated quantity, such as lift or moment coefficient, is normally compared. The problem with such comparisons arises when the results do not agree. Identifying the cause of the disagreement is nearly impossible with such data. Here, the comparison of more detailed information available from both computation and experiment is demonstrated.

The condition for which the results are compared is a 0.202 m chord NACA0012 aerofoil oscillating at 7 Hz with a nominal pitch range of 15°± 10° in a 45 m/s free stream resulting
Figure 8. Effect Gurney flap on lift and moment curves of a 0.203 m chord flatback version of a DU-97-W-300 aerofoil oscillating at a nominal angle of attack range of 15°± 5.5° at 10 Hz in a free-stream of 45 m/s yielding a chord Reynolds number Re=440,000 and a reduced frequency $k=0.14$. Results are shown for a Gurney flap with a height of 5% of chord deployed on both suction and pressure sides of the aerofoil.

in a chord Reynolds number Re of 440,000 and a reduced frequency $k=0.10$. Experiments were performed as discussed above, and the computations were performed using an in-house code FLOWWYO. This code solves the compressible Unsteady Reynolds-Averaged Navier-Stokes equations (URANS) using the Spalart-Almaras turbulence model. The solutions were performed on a curvilinear mesh, and were third-order accurate in space and second-order accurate in time. The case discussed here took approximately 2 hours running on 16 cores.

The comparison of the experimental and computational results is shown in Figure 9 where the pressure distribution results compare favorably. Both cases show evidence of leading edge stall in this case, identified by the dark blue streak starting around $t/T=0.4$ and moving aft on the aerofoil with time. This is characteristic of a vortex forming near the leading edge and propagating downstream. The simulation result is somewhat stronger and delayed in time compared to the experimental result. In both cases, a similar event is recognized after the aerofoil starts pitching down (after $t/T=0.5$) with similar differences observed in the timing and strength. In the computational result, it is also observed that strong low pressure regions develop near the trailing edge at $t/T = 0.5$ and $t/T = 0.65$. These structures, which are much weaker in the experiment, have a large effect on the lift and an even larger effect on the moment due to their location. As a result, the lift and moment differ substantially in this region due to the presence of these structures in the computation. Now that the cause of the difference is known, addressing the difference can be undertaken by identifying the flow-field structure that causes these results. For example, the sensitivity of the flow structure in the computation to turbulence model could be evaluated using the experimental data as a reference. Similarly, the sensitivity of the flow structure in the experiment to tripping of the boundary layer could be evaluated against the computation. Although this discussion only starts to demonstrate the possibilities combined flow-field and pressure data provide, it does suggest the importance of flow-field and surface data to fully comparing and contrasting experiment and computation.

5. Summary
An experimental capability has been developed for understanding the flow on dynamically pitching aerofoils. The combination of rapid prototyping and use of off-the-shelf pressure instrumentation allows for inexpensive and rapid testing of two-dimensional aerofoils. Currently, pressure distributions and the lift and moment curves calculated from them can be obtained very rapidly. Work remains to speed the capture of the flow-field structure. Nonetheless, the approach...
discussed here is now ready for continued exploration of the complex flows that wind turbine blades experience. It is expected that the better understanding obtained from this work will lead to better tools and thus better wind turbine designs.

Currently, the development of a database of existing results is underway so that the community can use these results for a range of applications. For example, with the ability to capture pressure distributions for an aerofoil over a wide range of conditions rapidly, dynamic stall model evaluation can be performed as well as the development of new models. Such results could help applications based on Blade Element Momentum (BEM) theory improve through better prediction of stall effects. The speed of developing and testing models can also be used to test new aerofoil designs and to develop optimized blades in conjunction with computational approaches. Exploration of dynamic pitch effects for motion other than sinusoidal pitching is also of interest as is the evaluation of flow control methods under the dynamic conditions wind turbine blades experience. It is expected that other potential research applications will arise as dynamic testing is explored further.

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