In-blade angle of attack measurement and comparison with models

T E Gallant, D A Johnson
Wind Energy Group, Mechanical and Mechatronics Engineering, University of Waterloo, 200 University Ave W, Waterloo, Canada N2L 3G1
E-mail: David.johnson@uwaterloo.ca

Abstract. The torque generated by a wind turbine blade is dependent on several parameters, one of which is the angle of attack. Several models for predicting the angle of attack in yawed conditions have been proposed in the literature, but there is a lack of experimental data to use for direct validation.

To address this problem, experiments were conducted at the University of Waterloo Wind Generation Research Facility using a 3.4 m diameter test turbine. A five-hole pressure probe was installed in a modular 3D printed blade and was used to measure the angle of attack, $\alpha$, as a function of several parameters. Measurements were conducted at radial positions of $r/R = 0.55$ and 0.72 at tip speed ratios of $\lambda = 5.0, 3.6, \text{ and } 3.1$. The yaw offset of the turbine was varied from $-15^\circ$ to $+15^\circ$.

Experimental results were compared directly to angle of attack values calculated using a model proposed by Morote in 2015. Modeled values were found to be in close agreement with the experimental results. The angle of attack was shown to vary cyclically in the yawed case while remaining mostly constant when aligned with the flow, as expected. The quality of results indicates the potential of the developed instrument for wind turbine measurements.

1. Introduction

As developments in wind turbine design continue to grow, so too does the need for accurate experimentation and testing of new wind turbine blade designs. One variable that has a critical impact on the performance of a wind turbine blade is the angle of attack, which is directly related to the forces generated on the blade. Conventionally during wind turbine testing, the upstream wind speed is measured via a separate meteorological tower upstream of the turbine, and this wind speed is used in combination with the wind turbine geometry and operational characteristics to model the angle of attack. However, upstream wind speed measurements do not accurately represent the wind speed at the turbine blades for many reasons including the axial induction of the rotor. The angle of attack is therefore calculated using models (e.g. the blade-element momentum method) using measurements several steps removed from the leading edge of the blade. The result is a lack of accurate experimental data for validating theoretical models.

To address this problem, a five-hole pressure probe has been mounted to the leading edge of a rotating wind turbine blade to accurately measure the local flow angle (LFA) to determine the angle of attack, $\alpha$, in the rotational plane. Experiments were conducted to measure the variation in $\alpha$ as a function of the azimuthal angle of the blade, $\phi$, the tip speed ratio $\lambda$, and...
the yaw angular position, $\gamma$. Experimental results were then compared to theoretical results calculated using a model proposed by Morote [1].

2. Background
The use of five-hole pressure probes to measure the wind turbine blade angle of attack is not a new concept, though the method is relatively uncommon in the literature. The most notable example of such studies are the NREL Unsteady Aerodynamics Experiments (UAE) [2]. Phase VI of those experiments involved a 10 m diameter, stall regulated 20 kW wind turbine consisting of two twisted and tapered blades. The turbine was well equipped with measurement instrumentation, including five-hole pressure probes. While the Phase VI report [2] does not include experimental results from the project, the report does provide equations necessary to convert flow pitch and spanwise angles relative to the probe to flow angles with respect to the blade. The Local Flow Angle (LFA) relative to the blade chord is defined as [2]:

$$LFA = \arctan \frac{\cos \alpha_p \cos (\beta_p + \epsilon) \sin \theta + \sin \alpha_p \cos \theta}{\cos \alpha_p \cos (\beta_p + \epsilon) \cos \theta - \sin \alpha_p \sin \theta}$$ (1)

where $\alpha_p$ is the local flow angle with respect to the probe, $\beta_p$ is the spanwise flow angle with respect to the probe, $\epsilon$ is the spanwise probe angle offset and $\theta$ is the local flow angle offset and these angles are shown in Figures 1 and 2 for clarity. Local flow angle measurements from the NREL experiments [2] were analyzed and presented as angle of attack measurements in Schepers and van Rooij [3] after a correction for induction due to the bound circulation was applied via the Biot-Savart law. Similar corrections were applied for other pressure probe experiments by Butterfield [4] and surface pressure methods by Shen et al. [5].

![Figure 1](image1.png)  
**Figure 1.** Demonstrative diagram of flow angles relative to the airfoil profile

![Figure 2](image2.png)  
**Figure 2.** Demonstrative diagram of flow angles relative to the airfoil (plan view)

Five-hole pressure probes at 38.5% and 55.8% radius were used by Maeda and Kawabuchi [6] to measure the angle of attack for a three-bladed, 10 m diameter, upwind turbine in the open environment with yaw positions of $-45^\circ$ to $+45^\circ$ in increments of $15^\circ$. Results of their experiments showed that at a $0^\circ$ yaw-offset the inflow velocity measured throughout the blade rotation (azimuthal angle $\phi$) was essentially constant although they found a variation in $\alpha$ of as much as $2.5^\circ$ with azimuthal position that they described as the influence of the atmospheric boundary layer [6]. However, when the turbine was yawed $\pm45^\circ$ relative to the upstream wind
direction, the inflow velocity fluctuated significantly with azimuthal position, increasing as the blade rotated towards the wind and decreasing as the blade rotated away from the wind. In the yawed conditions the angle of attack was observed to vary differently than the flow velocity, reaching a minimum when the velocity was at a maximum for the -45° yaw case and remaining relatively constant throughout the rotation during the +45° yaw case. The variation in the angle of attack was found to be as high as 10° throughout the blade rotation. Multi-hole probes have also been used to characterize the flow field upstream of a wind turbine. Recently, Petersen et al. [7] developed a method for evaluating the upstream flow velocity, axial induction factor and inflow turbulence by extrapolating flow measurements at the leading edge of the blade. They demonstrated the method using five-hole probe measurements taken from the DANAERO project [8], as well as simulations. The method proposed was shown to provide accurate estimations of the flow field upstream when compared with independent measurements and simulations. Directional pressure probes are not the only method being used to measure the angle of attack at a radial location on a wind turbine blade. Johnson et al. [9] conducted experiments using a three bladed 3.4 m diameter turbine installed in a large-scale wind generation research facility. Wind turbine blade performance was measured indirectly via simultaneous measurements of the wind turbine output and the wind velocity upstream and downstream of the rotor. Using the measured velocities, Johnson et al. [9] used methods described by Hansen et al. [10] and Johansen and Sørensen [11] to calculate the axial and tangential induction factors, $a$ and $a'$, respectively. These values were then used to calculate the blade angle of attack. Johnson et al. [9] found that the method resulted in angle of attack estimates within 15-20% of airfoil design data indicating that the use of velocity measurements to validate five-hole probe measurements may be appropriate.

### 2.1. Theoretical Models

While experimental measurements of the wind turbine blade angle of attack are lacking in the literature, several theoretical models for the variation in $\alpha$ with azimuthal position and yaw angle have been developed. The simplest model for calculating the angle of attack can be derived from the basic velocity relationships for an airfoil, where the angle of attack, $\alpha$, is defined as the angle between the rotational velocity of the turbine rotor and the relative wind velocity vector, $W$. This geometric angle of attack can be calculated using equation (2) [1]:

$$\alpha_{geom0} = \arctan \frac{\cos \beta - \lambda \sin \beta}{\lambda \cos \beta + \sin \beta}$$

where $\alpha_{geom0}$ is the geometric angle of attack in axial flow conditions, $\beta$ is the blade pitch at the radial location of interest, $r$, and $\lambda$ is the tip speed ratio at the same location.

While equation (2) is appropriate for a quick estimation of the blade angle of attack, the error associated with neglecting the axial and tangential flow induction factors ($a$ and $a'$, respectively) associated with the turbine in a three-dimensional space can be detrimental to the accuracy of the prediction. When the wind turbine is yawed, determining the angle of attack becomes more complex as it varies with the azimuthal position of the blade, $\phi$. Burton et al. [12] present a more complete model for calculating the angle of attack by combining several models and correction factors to accommodate these variations. While the model reported by Burton et al. [12] has historically been considered sufficient, a more recent publication by Morote [1] presents a new model for calculating the effective angle of attack, $\alpha_{eff}$, based again on the geometric angle of attack defined in equation (2). In this model, interference functions are defined to accommodate the axial interference and span-wise interference, labeled as $f(r)$ and $g(r)$ respectively. From Morote [1],
where \( a_0 \) is the radially dependent induction factor for axial flow at the blade lifting line, and

\[
f(r) \approx 1 - \frac{a_0 \lambda}{(1 + \lambda^2) \tan(\alpha_{geom0})}
\]

(3)

where

\[
g(r) \approx -\sqrt{A^2 + B^2}
\]

(4)

where

\[
A = \frac{a a_0}{(1 + \lambda^2)^2 \tan(\alpha_{geom0})} \left( \frac{\lambda(1 + \lambda^2)(r/R)}{2(1 + a_0)} \right)
\]

(5)

\[
B = \frac{a a_0}{(1 + \lambda^2)^2 \tan(\alpha_{geom0})} \left( \lambda^2 - 1 - \frac{2\lambda}{\sin(2\alpha_{geom0})} \right)
\]

(6)

Here, \( a a_0 \) is the radially dependent azimuthally averaged induction factor for axial flow. The equation for \( g(r) \) is only valid at certain radial positions, which means a phase shift \( \Delta \) is also required. This phase shift accounts for the change in azimuthal position of the blade as an air particle travels over the blade chord, which would result in a slight variation in the angle of attack along the chord line. The phase shift can be calculated as:

\[
\Delta \approx \arctan\left(\frac{B}{A}\right)
\]

(7)

Combining the interference functions and phase delay with the geometric model identified in equation (2), the Morote [1] model for calculating the effective angle of attack is defined as:

\[
\sin \alpha_{eff} = \sin \alpha_{geom} [f(r) + g(r) \delta \sin(\phi + \Delta)]
\]

(8)

where \( \delta \) is \( \sin \gamma \).

While Morote [1] has compared modeled pressure distributions over the blade to experimental data, neither Burton et al. [12] or Morote [1] present any experimental measurements of the angle of attack to validate their mathematical models. In fact, other than the studies discussed previously, there is a significant lack of experimental validation data concerning the variation in the angle of attack with turbine yaw and azimuthal position.

2.2. Development and Calibration of a Five-Hole Pressure Probe

The custom five-hole pressure probe and in-blade data acquisition system (DAQ) used here was constructed and calibrated in-house and described in Moscardi and Johnson [13]. The probe was calibrated in an open jet wind tunnel for pitch and yaw positions of \( \pm 50^\circ \). Calibration experiments were conducted at the blade design Reynolds number with several methods evaluated to determine pressure coefficients.

Moscardi and Johnson [13] used cubic interpolation, as well as equation (1) to calculate \( \alpha \) from pressure distribution measurements. More DAQ and blade details are provided in Sect. 3.

3. Experimental Methods

All experiments were conducted at the University of Waterloo Wind Generation Research Facility [14], which houses a fan bank capable of generating wind speeds up to 13 m/s. Flow fields generated by the facility have turbulence intensities in the range of 5.9% to 6.2%, and the blockage ratio of the test turbine in the facility is approximately 7%. The combination of high turbulence and low blockage is considered ideal for wind turbine testing, as it is representative of the environmental conditions that wind turbines would be exposed to in the field. More detailed
information about the facility geometry and generated flow field can be found in Moscardi and Johnson [13].

The test turbine is a custom-built 3.4 m diameter upwind horizontal-axis wind turbine, pictured in Figure 3. The rotor for these experiments consisted of one 3D-printed blade formed from five identical modules and two dynamically balanced rods. The blade, described in Abdelrahman et al. [15], was designed for a tip speed ratio of 4.2. The blade radius is 1.7 m with a constant 178 mm chord S833 airfoil and 6° pitch.

A separate blade module developed by Moscardi and Johnson [13] was used to house the five-hole pressure probe and corresponding electronics. The electronics board consisted of five differential pressure transducers mounted to a custom-built circuit board which converted analog voltages to a digital signal transmitted wirelessly via a Bluetooth transmitter. This modular configuration allowed the probe and electronics to be installed at different radial locations on the blade without significant modifications to the blade. The probe extended 0.8 c out from the leading edge at an angle approximately 15° offset from the chord and is installed in the blade in Figure 4. Further details concerning the five-hole probe can be found in Moscardi and Johnson [13].

Testing was conducted at λ = 5.0, 3.6 and 3.1 with the probe installed at r/R = 0.55 and 0.72. The yaw position, γ, was varied from -15° to +15° in increments of 5°. A summary of the test configurations completed is provided in Table 1. Before testing, each pressure transducer was calibrated individually to generate a calibration curve suited to the experimental testing conditions. Preliminary validation experiments were also conducted by simultaneously measuring the angle of attack with the five-hole pressure probe and a sonic anemometer using the method described by Johnson et al. [9]. Results of these experiments are not discussed here, but did show that the five-hole probe provided accurate measurements of the flow over the leading edge of the blade while also requiring less manual, repetitive intervention than the sonic anemometer required.

The experimental conditions were also used as input parameters for modeling the variation in α using the method described by Morote [1]. Wind speeds of 7.1 m/s, 10.0 m/s and 11.5
m/s were implemented with a constant turbine rotational speed of 200 rpm. The geometry of the blade, as well as the range of test conditions described, were also used. To estimate the axial induction factor, the PROPID [16] code used to originally design the blade was used to iteratively calculate the influence of the blades on the flow field. Inputs to the PROPID model included the design speed and dimensions of the blade, the number of blades, lift and drag coefficients for the S833 airfoil [17], and the Prandtl tip loss model [16]. For more information on the PROPID model, refer to [15]. Estimates of the $a$ values used based on the PROPID calculations are summarized in Table 2. These axial induction values are low but typical of a lightly loaded single blade wind turbine. The scale of these values was confirmed by the five-hole probe measurements using a method described by Petersen et al. [7].

| Table 1. Summary of Test Configurations |
|----------------------------------------|
| Range | Units           |
| $U_{\infty}$ | [7.1, 10.0, 11.5] m/s |
| Rotational Speed | 200 rpm |
| $\lambda$ | [5.0, 3.6, 3.1] |
| $\gamma$ | [+15 : 5 : -15] $^\circ$ |
| $r/R$ | [0.55, 0.72] |

| Table 2. Summary of Model Axial Induction Factors |
|--------------------------------------------------|
| $r/R$ | $\lambda = 5.0$ | $\lambda = 3.6$ | $\lambda = 3.1$ |
| 0.55 | $a = 0.076$ | $a = 0.059$ | $a = 0.042$ |
| 0.72 | $a = 0.104$ | $a = 0.094$ | $a = 0.074$ |

4. Results
For all experimental results presented here a minimum of 150 data points were measured within each of the 36 azimuthal bins, which combined with estimates of bias uncertainty in the instruments and set-up results in overall uncertainties of less than $\pm 0.3^\circ$. An azimuthal position of $0^\circ$ is defined as the test blade being in the 6 o’clock position. Axial induction factors calculated using PROPID [16] were used in combination with the Biot-Savart law to adjust local flow angle measurements to the blade angle of attack.

4.1. $r/R = 0.55$
Measured and modeled results for radial position $r/R = 0.55$ are presented in Figures 5 and 6 for yaw positions of $0^\circ$ and -15$^\circ$, respectively. Results at $r/R = 0.55$, $\gamma = 0^\circ$ show that $\alpha$ is relatively constant with azimuthal position, with some variation over the azimuthal range that was also seen in the measurements of Maeda and Kawabuchi [6]. Increases in $\alpha$ appearing at approximately $\phi = 100^\circ$ (where $\phi=0^\circ$ corresponds to the 6 o’clock position) at each tip speed ratio in the experimental data are attributed to a slight non-uniformity in the flow at the Wind Generation Research Facility, as described by Best [18]. The similar $\alpha$ values at azimuthal positions of $0^\circ$ and $180^\circ$ indicate that the effect of the wind shear is negligible in this facility in comparison to Maeda and Kawabuchi [6] that showed considerable angle of attack variation at these azimuthal values. As would be expected given the velocity relationships at the airfoil, $\alpha$ increases as the wind speed increases and $\lambda$ decreases.

As the turbine is yawed -15$^\circ$, the experimental $\alpha$ values plotted in Figure 6 show a cyclical variation with the azimuthal position. Neglecting the effects of the non-uniformity, the angle
reaches a minimum at $\phi = 0^\circ$ when the blade rotates towards the wind and a maximum at $\phi = 180^\circ$ when the blade rotates with the wind direction. Results at $r/R = 0.55, \gamma = +15^\circ$ showed a similar trend. These trends agree with Maeda and Kawabuchi [6] as discussed in Section 2.

The cyclical angle of attack can best be described by reviewing the effect of the yaw-offset on the idealized two dimensional velocity relationships at the airfoil. As demonstrated in Figure 7, when the blade is rotating away from the wind the upstream wind vector, $U_{wind}$, is no longer perpendicular to the blade rotation due to yaw angle $\gamma$ and the angle of attack is increased. In contrast, the angle of attack decreases as the rotor is moving into the wind. As the turbine blade rotates and cyclically moves towards and away from the upstream wind, $\alpha$ oscillates as shown in Figure 6.

Comparing the experimental results to the Morote [1] model results shows close agreement to the experimental results. At $\lambda = 3.6$, the modeled values slightly overestimated the angle of attack, as can be seen in Figures 5 and 6, though results remain within $\pm 1^\circ$ of each other. Discrepancies at $\lambda = 3.6$ are likely caused by inaccuracies in the calculated axial induction factors, as was confirmed by modeling the $\alpha$ distribution with arbitrarily changed $a$ values. However, at the lowest and highest wind speeds the experimental and theoretical values are in close agreement, indicating the potential accuracy of the modeled results.

4.2. $r/R = 0.72$

Moving the five-hole probe module outboard to $r/R = 0.72$ and repeating the experiments resulted in the $\alpha$ measurements presented in Figures 8 and 9 for $\gamma = 0^\circ$ and $-15^\circ$, respectively. These results closer to the blade tip show a decrease in the angle of attack relative to those at $r/R = 0.55$, which is to be expected given the increased tangential speed $(\Omega r)$ of the blade at $r/R = 0.72$ and constant $U_\infty$ thus decreasing $\alpha$. In comparison to the $r/R = 0.55 \gamma = 0^\circ$ case, the measured results exceed the model predictions somewhat and the $\lambda = 3.6$ experimental
Figure 6. Measured and model $\alpha$ distribution for $r/R = 0.55, \gamma = -15^\circ$

Figure 7. Demonstrative diagrams of the effect of wind direction on $\alpha$ for a blade rotating with the wind and against the wind

results are lower similar to the $r/R = 0.55$ case. The effects of flow facility non-uniformity are evident at $r/R = 0.72$ but the trends are similar to the $r/R = 0.55$ case.

It should be noted that the S833 airfoil used for the modular 3D printed turbine blade stalls statically at $\alpha$ values greater than $15^\circ$, which would indicate that the blade would be experiencing stall at $\lambda = 3.1$ given the experimental and modeled results presented. However, given that the Morote [1] model relies purely on the geometry of the airfoil, the upstream flow characteristics and the axial induction factor, dynamic stall effects would have no effect on the modeled $\alpha$. Static stall effects are included in the model via the reduced axial induction factors at the upper wind speed, as predicted by PROPID [16]. This can be inferred from the agreement between the modeled and experimental results at $\lambda = 3.1$ in both Figures 8 and 9. If blade stall due to dynamic conditions were included in the model the cyclical blade loads such as lift would be similar to those modeled by Hansen [19], and measured and modeled by Gharali and Johnson [20, 21, 22].
Figure 8. Measured and model $\alpha$ distribution for $r/R = 0.72$, $\gamma = 0^\circ$

Figure 9. Measured and model $\alpha$ distribution for $r/R = 0.72$, $\gamma = -15^\circ$
5. Conclusions

A novel in-blade five-hole pressure probe and DAQ system was developed, calibrated, and used to measure the angle of attack at the leading edge of a wind turbine blade. Experiments were conducted to determine the variation in $\alpha$ as a function of the tip speed ratio, azimuthal position and yaw-offset. Results were compared to a model proposed by Morote [1].

Results of the experiments showed that $\alpha$ was relatively constant with azimuthal position at a $0^\circ$ yaw-offset, indicating that the effect of the wind shear was negligible. When the turbine was yawed $\pm 15^\circ$, $\alpha$ was shown to vary cyclically with azimuthal position, decreasing as the blade rotated towards the wind and increasing as the blade rotated away from the wind as expected and matches the trends observed in [6].

Comparisons with the Morote [1] model showed agreement in the data trends between the theoretical and experimental values. Given that the model is based on known blade geometry, experimental parameters and the axial induction factor confirmed using the Petersen [7] method, discrepancies are attributed to the variability of wind conditions and induction factor predictions. Further experiments will be conducted with a three-bladed rotor, which would increase the rotor loading and axial induction factors and allow further investigation of the proposed model.

The results of the five-hole pressure probe experiments presented here demonstrate the potential for a compact, in-blade five-hole pressure probe and DAQ system which can measure the angle of attack directly at the leading edge of the blade. Using such technology allows for controlled measurements directly at the point of interest with low uncertainty.

References

[1] Morote J 2015 Wind Energy 19 681–702
[2] Hand M M, Simms D A, Fingersh L J, Jager D W, Cotrell J R, Schreck S and Larwood S M 2001 Unsteady Aerodynamics Experiment Phase VI : Wind Tunnel Test Configurations and Available Data Campaigns Tech. Rep. NREL/TP-500-29955 National Renewable Energy Laboratory Golden CO
[3] Schepers J G and van Rooij R P J O M 2008 Analysis of Aerodynamic Measurements on a Model Wind Turbine placed in the NASA-Ames Tunnel. ECN-E-08-052 Tech. rep.
[4] Butterfield C P 1989 Three-Dimensional Airfoil Performance Measurements on a Rotating Wing. SERI/TP-217-3505 Tech. rep.
[5] Shen W Z, Hansen M O L and Sørensen J N 2009 Wind Energy 12 91–98
[6] Petersen M, Larsen T, Madsen H, Larsen G and Toldborg N 2015 33rd Wind Energy Symposium, AIAA SciTech, (AIAA 2015-1467) (FL, USA)
[7] Madsen H, Bak C, Schmidt U, Gaunaa M, Fuglsang P, Romblad J, Olesen N, Enevoldsen P, Laursen J and Jensen L 2010 The DAN-AERO MW Experiments Final report Tech. Rep. Risø-R-1726(EN) Riso DTU
[8] Johnson D, Abdelrahman A and Gertz D 2012 Wind Engineering 36 717–738 ISSN 0309-524X
[9] Hansen M, Sørensen N and Michelsen J 1998 EWEC 1997 (Dublin, Ireland)
[10] Johansen J and Sørensen N 2004 Wind Energy 7 283–294
[11] Burton T, Jenkins N, Sharpe D and Bossanyi E 2011 Wind Energy Handbook 2nd ed (Chichester, UK: Wiley) ISBN 0471489972
[12] Moscardi A and Johnson D A 2016 Wind Engineering 40 360–378
[13] Waterloo Wind Energy Group 2016 UW Wind Generation Research Facility URL http://windenergy.uwaterloo.ca/facil.firelab.php
[14] Abdelrahman A and Johnson D 2014 Journal of Physics: Conference Series 524 012059 ISSN 1742-6596
[15] UHUC Applied Aerodynamics Group 2016 PROPID for Horizontal Axis Wind Turbine Design URL http://m-selig.ae.illinois.edu/propid.html
[16] Somers D M 2005 The S833, S834, and S835 Airfoils. SR-500-36340 Tech. rep.
[17] Best C 2010 Measurement of Fuel Regression Rate of a Pool Fire in Crosswind With and Without a Large Downwind Blocking Object MASc thesis University of Waterloo
[18] Hansen A C 1992 Yaw dynamics of Horizontal Axis Wind Turbines. NREL/TP-442-4822 Tech. rep.
[19] Gharali K and Johnson D A 2014 Exp Fluids 55 1803
[20] Gharali K and Johnson D A 2015 Wind Energy 18 237–251
[21] Gharali K, Johnson D A, Lam V and Gu M 2015 Wind Engineering 39 557–567