Experimental Study on Inflow Estimation Using Pressure Sensor Mounted on Spinner of Horizontal Axis Wind Turbine

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Abstract. The spinner anemometer can measure the wind velocity in front of rotor by ultrasonic wind sensors mounted on the spinner. To estimate the undisturbed wind speed in far upstream, the detail calibration is required. This study proposes the wind speed measurement by pressure sensors mounted on the spinner as a new technology. The inflow wind speed and the inflow angle are estimated with the pressure sensors mounted on a spinner. The performance of wind speed measurement is evaluated by wind tunnel measurements with a model HAWT. The measured wind speed by stagnation and static pressures show good agreements between reference wind tunnel speed and accuracy of measured wind speed was assessed.

1. Introduction

HAWT is operated under wind conditions varying in wind speed and wind direction. It is necessary to precisely understand inflow wind velocity for optimization of power production. Generally, wind speed is observed by anemometers mounted on the nacelle behind the rotor. Therefore, the rotor wake increases the uncertainty of wind speed measurements. There is technology to measure inflow wind by anemometer mounted on the spinner put into use [1][2]. The spinner anemometer measures wind in front of the rotor without the rotor wake, however the measured wind speed to be calibrated because wind speed in the induction zone decreases. The wind velocity measurement with three one-dimensional sonic anemometers on the spinner has been used. However, this method is influenced by the spinner shapes because the control volume of the sonic anemometer is close to spinner surface, and the detailed calibration is required [3]. Giorgio states that a mast with hub height measurements of wind speed and wind direction is required for anemometer calibration [4]. However, it is difficult to install the mast because the mast is high-rise due to the large size of the wind turbine and a large site is required. Also, there is technology to measure inflow wind by lidar mounted on the spinner [5]. This has a problem of high cost. And more, in the wind turbine performance test, the inflow wind is measured with a mast installed upstream. When measuring by wind speed, it is problem whether the measured wind flows into the wind turbine or not. For this reason, IEC61400-12 has detailed normative about the position of an anemometer for wind turbine [6]. When measuring by pressure, no matter where the incoming wind, it is reliably converting to dynamic pressure at the stagnation point. Therefore, it is possible to eliminate all problems related to the installation of the anemometer. This study proposes the wind measurement
by pressure sensors mounted on the spinner surface as new technology to measure inflow wind. Pressure sensors has the advantage of easy to introduce into existing wind turbine and low cost.

2. Objectives
The purpose of this study is to discuss possibility of inflow wind measurement by pressure sensors mounted on the spinner. The measured wind speed by stagnation pressure is compared with reference wind tunnel speed. The measurements are performed in a wind tunnel. The operational conditions of wind turbine are set power production with maximum power coefficient, constant power by pitch regulation and standstill. Furthermore, experiment was also performed in yawed flow condition. The accuracy of wind speed and wind direction measurement was assessed.

3. Methodology

3.1. Experimental equipment
In this experiment, wind tunnel with an outlet diameter of 3.6 m was used. A test wind turbine with a rotor radius of \( R = 0.8 \) [m] was installed in the wind tunnel test section. The test wind turbine is shown in figure 1. Generally speaking, the rotor test in wind tunnel has small Reynolds number and the airfoil performance becomes poor due to low \( Re \). Therefore, the test wind turbine blade uses Avistar airfoil which is capable of maintaining enough performance in \( Re \geq 1.0 \times 10^5 \). The Reynolds number during the experiment was \( 1.2 \times 10^5 \). Thrust \( T \) acting on the wind turbine was measured by a 6-component balance mounted between the nacelle and the tower. The wind tunnel speed was calibrated with the reference pitot tube and the turbine position pitot tube without the test wind turbine. The wind speed of the reference pitot tube is \( U_0 \), and the wind speed of the turbine position pitot tube is \( U_0' \).

Figure 2 shows the spinner shape of the wind turbine and pressure sensor position. The pressure on the spinner surface was measured by pressure sensors. LPS33HW manufactured by STMicroelectronics [7] was used for the pressure sensor. Absolute pressure is detected by a piezoelectric device mounted on the base. The measurement range is 260 to 1260 hPa, the resolution is 0.02 Pa, and the accuracy is \( \pm 10 \) Pa. When atmospheric pressure is the same as the standard atmosphere, this sensor can accept the maximum velocity of 200m/s by production spec sheet. Raspberry Pi 3 Model b+ [8] was used as a data collection device, and controlled via remote control from external computer.

Figure 3 shows the spinner front view. The azimuth angle \( \psi \) is defined as \( \psi = 0 \) [\(^\circ\)] where the position of each pressure hole is vertically upward and is positive in the rotational direction of rotor. Rotational direction is clockwise when viewed from upstream. The azimuthal position of pressure holes is set middle between two neighbor blades. The diameter of hole is 0.4mm.

3.2. Experimental conditions and methods
The test conditions of wind turbine operation are optimum tip speed condition, pitch regulated condition, standstill condition and yawed flow condition. The accuracy of wind speed measurement was assessed for each condition. The sampling frequency of the pressure sensor was 75 Hz, and the measurement time was 30 seconds. Optimum tip speed condition and pitch regulated condition were determined based on \( C_p-\lambda \) curve in the rotor performance test. Details are shown below.

3.2.1. Rotor performance test
In the rotor performance test, the correlation between the power coefficient and the change in the tip speed ratio at various pitch angles is confirmed. The test was performed by setting the blade pitch angles of \( \theta = 0, 5, 10 \) [\(^\circ\)], and changing the tip speed ratio, \( 0<\lambda<7 \). Figure 4 shows \( C_p-\lambda \) curve at each pitch angle. The horizontal axis shows the tip speed ratio \( \lambda \), and the vertical axis shows the power coefficient \( C_p \). The variation of the measured power coefficient was within \( \pm 0.002 \).

From figure 4, the power coefficient shows the maximum value of \( C_p = 0.381 \) when \( \theta = 0 \) [\(^\circ\)] and \( \lambda = 6.1 \). Therefore, the optimum pitch angle of the test wind turbine is \( \theta = 0 \) [\(^\circ\)], and the optimum tip speed ratio is \( \lambda = 6.1 \).
3.2.2. Standstill condition
In this experiment, the condition where the rotor is stopped was simulated. The wind tunnel speed was changed, \( U_0 = 6.0, 8.0, 10.0, 12.0, 14.0, 15.0 \) [m/s]. The inflow wind estimated with the sensor was calibrated in consideration of the error between the inflow wind \( U_0' \) and the calculated wind speed \( U_i \) with the sensor signal.

3.2.3. Optimum tip speed condition
Optimum tip speed condition is operating conditions in the wind speed range from the cut-in wind speed to the rated wind speed. In this wind speed range, the wind turbine is operated at optimum tip speed ratio and optimum pitch angle shown in the rotor performance test. In this experiment, the wind tunnel speed was set at \( U_0 = 5.0, 6.0, 7.5 \) [m/s], the rotor speed was set at \( n = 365, 440, 545 \) [rpm], and the optimum tip speed ratio \( \lambda = 6.1 \) was fixed. Table 1 shows the experimental conditions in optimum tip speed condition.

| Wind tunnel speed \( U_0 \) [m/s] | Rotor speed \( n \) [rpm] | Tip speed ratio \( \lambda \) | Pitch angle \( \theta \) [°] |
|----------------------------------|--------------------------|--------------------------|--------------------------|
| 5.0                             | 365                      | 6.1                      | 0                        |
| 6.0                             | 440                      | 6.1                      | 0                        |
| 7.5                             | 545                      | 6.1                      | 0                        |

3.2.4. Pitch regulated condition
Pitch regulated condition is operating conditions in which the wind speed exceeds the rated wind speed, the rotor speed and power are kept constant by pitch angle control. Assuming a rated wind speed of 7.5 m/s, operation when the rated wind speed is exceeded is simulated. The pitch angle was changed to keep the rated rotor speed and rotor power. The pitch angle above rated wind speed was fined from \( C_p-\lambda \) curve with various pitch angle. The selected experimental conditions are the pitch angle of \( \theta = 5, 10 \) [°]. Table 2 shows the experimental conditions in pitch regulated condition.

| Wind tunnel speed \( U_0 \) [m/s] | Rotor speed \( n \) [rpm] | Tip speed ratio \( \lambda \) | Pitch angle \( \theta \) [°] | Power coefficient \( C_p \) |
|----------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 8.0                             | 545                      | 5.7                      | 5                        | 0.304                    |
| 9.1                             | 545                      | 5.0                      | 10                       | 0.206                    |

3.2.5. Yawed flow condition
Yawed flow condition is conditions which the wind direction does not coincide with the direction of rotor axis. Since yaw control is generally based on the average wind direction for 10 minutes, there is yawed flow operation of wind turbine due to the time delay. In this experiment, the wind direction is changed under optimal operation condition. Table 3 shows the experimental conditions in yawed flow condition.

| Wind tunnel speed \( U_0 \) [m/s] | Rotor speed \( n \) [rpm] | Tip speed ratio \( \lambda \) | Pitch angle \( \theta \) [°] | Yaw angle \( \varphi \) [°] |
|----------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 7.5                             | 545                      | 6.1                      | 0                        | 5, 10, 15                |
3.2.6.  **Thrust change condition**

In this test, the effect of the thrust change on the detection of inflow wind speed by the pressure sensors is verified. The rotor thrust was changed by changing the rotor speed at fixed wind speed. Table 4 shows the experimental conditions. The rotor thrust \( T \) was measured with the 6-component balance.

### Table 4. Experimental conditions of thrust change

| Wind tunnel speed \( U_0 \) [m/s] | Rotor speed \( n \) [rpm] | Tip speed ratio \( \lambda \) | Pitch angle \( \theta \) [°] | Yaw angle \( \varphi \) [°] |
|-----------------------------------|--------------------------|-----------------------------|--------------------------|--------------------------|
| 7.5                               | 40~600                   | 0.44~6.66                   | 0                        | 0                        |

![Figure 1. Wind tunnel and experimental arrangement](image)

**Figure 1.** Wind tunnel and experimental arrangement

![Figure 2. Spinner shapes and pressure sensor position](image)

**Figure 2.** Spinner shapes and pressure sensor position

![Figure 3. Spinner front view](image)

**Figure 3.** Spinner front view
4. Experimental results and discussion

4.1. Axial flow condition

4.1.1. Standstill condition

Figure 5 shows the estimated inflow wind in standstill condition. The horizontal axis shows the calculated wind speed $U_s$ with sensor signal, the vertical axis shows the turbine position wind speed $U_0'$. The broken line in the figure shows a linear approximation of each plot. According to figure 5, $U_s$ is 2.6% higher than $U_0'$. The calibration factor was determined based on the linear approximation. $U_c$ is the calibrated wind speed for this proposal system.

\[ U_c = 0.974 U_s \]  

(1)

4.1.2. Optimum tip speed condition

Figure 6 shows the time series data of the calibrated wind speed $U_c$ and the turbine position wind speed $U_0'$ in optimum tip speed condition. Wind tunnel speed is $U_0 = 5.0$ [m/s] for figure 6(a) and $U_0 = 7.5$ [m/s] for figure 6(b). According to figure 6, $U_c$ fluctuates because the sensor contains error of ±10 Pa. Furthermore, fluctuation of $U_c$ decreases as $U_0$ increases. Table 5 shows error and average of wind speed of $U_c$ and $U_0'$ in optimum tip speed condition. $U$ shows instantaneous wind speed and $\bar{U}$ shows average of $U$. According to table 5, the maximum error between $\bar{U}_0'$ and $\bar{U}_c$ was 2.3%. The reason of the error is considered to be due to ±10 Pa error of the sensor.

Table 5. Average of wind speed in optimum tip speed condition

| Wind tunnel speed $U_0$ [m/s] | Average of the turbine position wind speed $\bar{U}_0'$ [m/s] | Average of the calibrated wind speed $\bar{U}_c$ [m/s] | Error [%] |
|-------------------------------|-----------------------------|-----------------------------|----------|
| 5.0                           | 4.80                        | 4.69                        | 2.3      |
| 6.0                           | 5.83                        | 5.89                        | 1.1      |
| 7.5                           | 7.25                        | 7.32                        | 0.8      |
4.1.3. Pitch regulated condition

Figure 7 shows the time series data of the calibrated wind speed $U_c$ and the turbine position wind speed $U_0$ in pitch regulated condition. Wind tunnel speed is $U_0 = 8.0$ [m/s], pitch angle $\theta = 5$ [°] for figure 7(a) and wind tunnel speed $U_0 = 9.1$ [m/s], pitch angle $\theta = 10$ [°] for figure 7(b). Table 6 shows error and average of wind speed of $U_c$ and $U_0'$ in optimum tip speed condition. According to table 6, the maximum error between $U_0'$ and $U_c$ was 0.5 %. The reason of the error is considered to be due to ± 10 Pa error of the sensor.

| Wind tunnel speed $U_0$ [m/s] | Average of the turbine position wind speed $U_c'$ [m/s] | Average of the calibrated wind speed $U_c$ [m/s] | Error [%] |
|-------------------------------|---------------------------------|---------------------------------|-----------|
| 8.0                           | 7.75                            | 7.77                            | 0.2       |
| 9.1                           | 8.90                            | 8.86                            | 0.5       |

4.1.4. Thrust change condition

Figure 8 shows the calibrated wind speed $U_c$ and the turbine position wind speed $U_0'$ for various thrust coefficient $C_T$. The wind tunnel speed is $U_0 = 7.5$ [m/s]. The horizontal axis shows $C_T$, the vertical axis shows $U_c$ and $U_0'$. Legends in the figure indicate $U_c$ with blue square, $U_0'$ with red circles. According to figure 8, $U_c$ and $U_0'$ show a constant value for various $C_T$. In addition, $U_c$ and $U_0'$ agree well, and the maximum error between $U_c$ and $U_0'$ was 1.4 %.

4.2. Yawed flow condition

4.2.1. Pressure distribution on spinner surface in yawed flow condition

Figure 9(a) to (d) show the measured pressure of sensor 1 to 4 at wind tunnel speed $U_0 = 7.5$ [m/s], optimum tip speed ratio $\lambda = 6.1$, and yaw angle $\varphi = 0, 5, 10, 15$ [°]. The horizontal axis shows the azimuth angle $\psi$, the vertical axis shows the surface pressure obtained by subtracting the absolute pressure measured with the reference sensor for static pressure. The plots in the figure are bin averages at each azimuth angle of 1°. According to figure 9(a), the pressure of sensor 1 mounted at spinner tip show almost constant value even when the yaw angle changes. Also, the pressure at spinner tip decreases as the yaw angle increases. This is because the stagnation point moves away from the tip of spinner as the yaw angle increases, and the flow speed at tip of spinner surface increases. According to figure 9(b) to (d), the pressure of sensor 2 to 4 on the side of spinner reaches the maximum value near azimuth angle $\psi = 90$ [°]. Thereafter, the pressure decreases and reaches a minimum value near the azimuth angle $\psi = 270$ [°]. This is because there is a stagnation point of the inflow wind near the azimuth angle $\psi = 90$ [°], and there is a flow separation near the azimuth angle $\psi = 270$ [°]. By using these pressure variations with azimuth angle, the yaw angle can be detected in 4.2.2.

4.2.2. Measurement of inflow angle

A method for measuring inflow angle from the pressure measured with sensor 2 to 4 is discussed. According to figure 9, at any yaw angle, the pressure of each sensor shows a peak around the azimuth angle $\psi = 90$ [°]. On the other hand, the pressure of sensor shows a flat bottom around the azimuth angle $\psi = 270$ [°]. Therefore, the refer azimuth angle to detect inflow angle is set as $\psi \approx 270$ [°]

Figure 10 shows the relationship between the factor $A_i$ and the yaw angle $\varphi$. The horizontal axis shows the yaw angle $\varphi$. The vertical axis shows the factor $A_i$ for sensor 2 to 4. The factor $A_i$ shows pressure ratio between sensor $i$ and sensor 1 and it is defined as

$$A_i = \frac{P_{i,\psi=270}}{P_{i,\psi=90}} - \frac{P_i}{P_{i=1}}$$
where, \( \overline{P}_{i,\psi} = 270 \) is the averaged pressure of sensor \( i \) at \( 260<\psi<280 \), and \( \overline{P}_{i} \) is the averaged of sensor \( i \) at \( 0\leq\psi<360 \).

According to figure 10, the factor \( A_i \) decreases almost linearly as the yaw angle increases. Therefore, the relationship between the factor \( A_i \) and the yaw angle was approximated linearly, and equation for estimating the inflow angle from the pressure measured with sensor 2 to 4 was constructed. This is shown in the following equations (3), (4), and (5). \( \varphi_2 \) to \( \varphi_4 \) shows the inflow angle estimated with the following equation.

\[
\begin{align*}
\varphi_2 &= -44.3A_2 - 0.6 \\
\varphi_3 &= -52.3A_3 - 2.2 \\
\varphi_4 &= -60.9A_4 - 1.4
\end{align*}
\]

Table 7 shows the measured inflow angle in yawed flow condition using the following equation. According to table 7, the set yaw angle and the measured inflow angle with equations (3) to (5) were almost the same, and the error was less than 0.5°. Therefore, when the factor \( A \) is find for a certain yaw angle by calibration, the inflow angle can be estimated.

Table 7. Estimated inflow angle in yawed flow condition

| Yaw angle \( \varphi \) [°] | Measured inflow angle with sensor 2 \( \varphi_2 \) [°] | Measured inflow angle with sensor 3 \( \varphi_3 \) [°] | Measured inflow angle with sensor 4 \( \varphi_4 \) [°] |
|-------------------------|-----------------|-----------------|-----------------|
| 5          | 5.1             | 4.8             | 4.8             |
| 10         | 9.5             | 9.7             | 9.9             |
| 15         | 15.3            | 15.3            | 15.1            |

4.2.3. Measured inflow wind speed

The error of wind speed measurement was about 3% at yaw angle \( \varphi = 0 \) to 10 [°]. However, the error was 15% at the yaw angle \( \varphi = 15 \) [°], and the error became large as increase of yaw angle. Because the sensor 1 deviates from the stagnation point and the sensor 1 could not measure the stagnation pressure.
Figure 6. Time series of calibrated and turbine position wind speed (optimum tip speed condition)

(a) $U_0 = 5$ [m/s], $n = 365$ [rpm]

(b) $U_0 = 7.5$ [m/s], $n = 545$ [rpm]

Figure 7. Time series of calibrated and turbine position wind speed (pitch regulated condition)

(a) $U_0 = 8.0$ [m/s], $\theta = 5$ [$^\circ$]

(b) $U_0 = 9.1$ [m/s], $\theta = 10$ [$^\circ$]

Figure 8. Calibrated wind speed $U_c$ and Turbine position wind speed $U'_0$ for various thrust coefficient $C_T$
5. Conclusion
In this study, in order to discuss possibility of inflow wind measurement by pressure sensor mounted on the spinner, the wind tunnel experiment was performed in which a test wind turbine equipped with a pressure sensor on a spinner. In the wind tunnel experiment that simulated operating conditions such as optimum tip speed condition, pitch regulated condition and yawed flow condition, the estimation accuracy of the inflow wind speed and the inflow angle was evaluated. The results of this study are shown below.
The calculated wind speed of the pressure sensor in optimum tip speed condition and pitch regulated condition agree with the inflow wind speed well. The maximum error between the calibrated wind speed $U_c$ and the turbine position wind speed $U_0'$ was 2.3% in optimum tip speed condition and 0.5% in pitch regulated condition.

The effect of the change in thrust coefficient on the calibrated wind speed $U_c$ and the turbine position wind speed $U_0'$ was little, and it was confirmed that measurement was possible without any effect by thrust change.

In yawed flow condition, the pressure value of each sensor on the side of the spinner takes the maximum at around the azimuth angle of 90° and the minimum at around the azimuth angle of 270°.

A method was devised for estimating the inflow angle from the factor $A$ in yawed flow condition. The error between the set yaw angle and the measured inflow angle was less than 0.5°.

6. Future work

The preparation of field rotor test with reference masts is going on. The number of sensors is increased to measure the stagnation pressure in yawed flow condition.

7. References

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