Original Paper

Study of Flow Field and Pressure Distribution on a Rotor Blade of HAWT in Yawed Flow Conditions

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Abstract

This paper describes the flow field and the blade pressure distribution of a horizontal axis wind turbine in various yawed flow conditions. These measurements were carried out with 2.4m-diameter rotor with pressure sensors and a 2-dimensional laser Doppler velocimeter for each azimuth angle in a wind tunnel. The results show that aerodynamic forces of the blade based on the pressure measurements change according to the local angle of attack during rotation. Therefore the wake of the yawed rotor becomes asymmetric for the rotor axis. Furthermore, the relations between aerodynamic forces and azimuth angles change according to tip speed ratio. By the experimental analysis, the flow field and the aerodynamic forces for each azimuth angle in yawed flow condition were clarified.

Keywords: Wind Turbine, Rotor Aerodynamics, Fluid Machinery, Yaw, Flow Field, Pressure Distribution

1. Introduction

The wind energy is the most reliable renewable energy and the installed capacity of wind turbines in 2008 was the largest in all generation plants [1]. However to reduce the energy from fossil fuel the production of electricity by wind turbines is still not enough. There are many ways to increase the amount of energy production, which are upsizing of the rotor, finding the most suitable layout of the wind turbine and improving of the capacity factor, and so on. These ways are much affected by the aerodynamic efficiency of wind turbine rotor.

Therefore, the efficiency improvement of wind turbine rotor is necessary to increase the amount of energy production. The commercial wind turbines are operated in natural wind where both direction and speed are unsteady. The nacelle direction is changed at some intervals to follow the mean wind directions. It means the wind turbine may be operated under yawed flow conditions. The flow field around yawed rotor is very complicated. There are some numerical studies related to the flow field around yawed rotor [2], and the experimental studies are also done for the averaged flow field around yawed rotor [3],[4]. However the experimental data are not sufficient for verification in the instantaneous pressure distribution on the blade. The detailed measurements of local and instantaneous pressure distribution will give deep understanding of the yawed flow properties and be used for the verification of the numerical studies.

In this study, the flow field and the instantaneous aerodynamic forces for each azimuth angle were clarified by reproducing yawed flow conditions in a wind tunnel and measuring the flow field around the wind turbine and the pressure distribution on the blade.

2. Experimental apparatus and method

Figure 1 shows a test section of a wind tunnel [5],[6]. The wind tunnel is a closed circuit low speed wind tunnel with opened test section and an outlet diameter of 3.6m. The test wind turbine is a three bladed horizontal axis wind turbine. The rotor diameter is $D=2.4\text{m}$. Table 1 shows the test blade specification. The test blades are tapered and twisted blades that were designed based on Blade Element Momentum Theory, BEM [5],[6]. The cross sections of the blade were composed of the following four airfoil sections in order from blade root: DU91-W2-250, DU93-W-210, NACA63-618 and NACA63-215. A setting position of the test wind turbine is $1D$ downstream from the wind tunnel outlet. A servo-motor controls rotational speed of rotor and detects rotor torque, azimuth angle, and rotational speed. The velocity measurement around wind turbine was done by a two-dimensional laser Doppler velocimeter (LDV) set on the traverse device of the wind tunnel test section. The flow velocity is measured in the horizontal plane. The measured components are u (x -axis direction) and v (y -axis direction). The measurement points are set in horizontal (x - y) plane at the hub height. The intervals for each measuring point are set 150mm for both x and y axis. The coordinate origin ($x=0$, $y=0$) is set at the center of the tower. The pressure measurement on the blade surface was performed by a multiport pressure sensor installed in the hub. The diameter of pressure tap on the blade surface is 0.4mm. The number of pressure

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taps for each blade cross-section is 32. The pressure taps are drilled at perpendicular to the pitch axis at radial position of $r/R=0.3, 0.5, 0.7$ and 0.9 . The pressure was measured once per rotation with changing trigger timing to study the aerodynamic force depending on the azimuth angle. The dynamic response of the pressure tubing was calibrated using a pressure wave of 3Hz - 40Hz.

The main wind speed is set at $U_0=7\text{m/s}$. The pitch angle of blade is set at the optimum of $\beta = -2^\circ$. The pitch angle is defined as the angle between the rotor plane and the chord line of blade tip, and the positive value is shown when the leading edge inclines to the upstream. The yaw angle Φ is defined as the angle between the rotor axis and the undisturbed wind, and it is defined counterclockwise direction as positive angle, seeing from the top. The azimuth angle Ψ is defined as the angle from the position of $\Psi=0^\circ$ where the instrumented blade is vertical upward, and it is defined clockwise direction (rotating direction) as positive angle, seeing from the upstream. The velocity measurements were performed at the optimum tip speed ratio for each yaw angle setting. At the optimum tip speed ratio, $\lambda=5.2$, the Reynolds number was about 2.0×10^5 . In this study, the Reynolds number changes between $9.2 \times 10^4 \sim 2.4 \times 10^5$ depending on the tip speed ratio, radial position, yaw angle and azimuth angle. However in all conditions, the tendency of the change of rotor performance was similar without Re number effect. The measured velocity was averaged with 5° BIN of the blade azimuth angle. The LDV cannot get velocity data continuously. When the particles pass the control volume, the LDV receives reflection and can calculate the velocity. To discuss the phase locked averaged flow field, the BIN averaged value is used for discussion. The pressure measurement was performed every 30° of azimuth at 22 kinds of tip speed ratios at $\Phi=0^\circ, 15^\circ, 30^\circ$ and 45° .

Fig. 1 Test section of a wind tunnel

Table 1 Test blade specification

r/R [-]	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
c [mm]	($\phi 70$)	147.4	139.6	131.8	124.0	116.2	108.4	100.6	92.8	85.0
θ [°]	-	18.33	12.00	8.33	5.00	4.68	2.86	1.44	0.91	0.00

In this experiment, the local relative velocity to the blade test section cannot be measured. Therefore, local dynamic pressure p_d is calculated on the undisturbed wind velocity in the wind tunnel and circumferential velocity at the test section. As a result, the pressure at the stagnation point obtained by the surface pressure measurement shows good agreement with this estimated dynamic pressure, therefore the surface pressure is shown by the pressure coefficient based on this estimated dynamic pressure in the following discussion. The local dynamic pressure p_d is expressed in the Eq. (1).

$$p_d = \frac{1}{2} \rho (U_0 \cos \Phi)^2 + \frac{1}{2} \rho (r\omega - U_0 \sin \Phi \cos \Psi)^2 \quad (1)$$

Generally, the lift and the drag coefficients are used for the evaluation of the blade sectional performance. To define lift and drag forces, the direction of undisturbed upstream flow should be detected. For the flow on the rotating blade, the flow direction of undisturbed upstream flow is difficult to be defined. In this study, rotational force coefficient C_r is defined to evaluate the sectional aerodynamic characteristics of the rotating blade. The rotational force coefficient C_r is expressed in the Eq. (2). The p_i is pressure at the pressure port.

$$C_r = \frac{\int_s p_i ds_a}{p_d c} \quad (2)$$

Figure 2 shows the definition of the rotational force coefficient. The positive value of C_r is defined as blade rotating direction.

Fig. 2 Definition of aerodynamic force coefficients

3. Results and discussion

Figure 3 shows the power curves for various yaw angles. In case of $\Phi=0^\circ$, C_{power} increases as decrease of λ in higher tip speed region over $\lambda=5.0$, then it shows maximum value of power coefficient $C_{power}=0.43$ at $\lambda=5.2$. In lower tip speed region, C_{power} suddenly decreases because the angle of attack for the blade section becomes too high and the flow along the blade becomes stall. At $\Phi=15^\circ$, 30° and 45° , the relations between C_{power} and λ are similar to that of $\Phi=0^\circ$, however the change of C_{power} for the λ becomes gentle. The maximum value of power coefficient for each yaw angle decreases with increase of yaw angle. At low tip speed region, C_{power} slightly increases with increase of yaw angle. This phenomenon is discussed later with rotational force coefficient.

Fig. 3 Power coefficient C_{power} against tip speed ratio λ

3.1 Velocity field around wind turbine rotor

3.1.1 Change of velocity field due to yaw angle

Figure 4(a) shows the averaged velocity distribution around the rotor at $\Phi=0^\circ$. The velocity data are taken when a seed particle passes the control volume of LDA, so the sampling number of the particle for each azimuth angle is not the same. To avoid the effect of sampling number, the averaged velocity in Fig. 4 is calculated by 5° BIN value. As shown in Fig. 4(a), the flow around rotor at $\Phi=0^\circ$ is slow down axially and the low velocity area is expanded radially. The axial velocity behind rotor is strongly reduced at outboard. The flow at $\Phi=0^\circ$ is axially symmetric. The high axial velocity is observed near nacelle. The high axial velocity was caused by the displacement effect by bluff body and the flow that passes the blade root part where the blade cross-section is not airfoil.

Figure 4(b) shows the averaged velocity distribution around the rotor at $\Phi=30^\circ$. As shown in Fig. 4(b), the axial velocity behind downstream side of rotor plane ($y/D < 0$) is not reduced compare to that of upstream side ($y/D > 0$). From these differences in the velocity of the wake, it seems that the energy extraction in downstream side of rotor plane is smaller than that in upstream side. The reason is discussed later with the azimuthal power coefficient evaluated from pressure distribution in section 3.2.3.

Fig. 4 Average velocity distribution for optimum tip speed ratio

3.1.2 Change of velocity field due to azimuth angle

Figure 5 shows the velocity distribution for various azimuth angles. As shown in Fig. 5, the fluctuation of the velocity vector was observed in the downstream region of blade tip. It is thought that these fluctuated vectors show the velocity by a part of vortex that shed from the blade tip. In addition, the position of the fluctuated vectors is fixed in each yaw angle for every azimuth angle. Therefore, it is thought that the tip vortices of blade move along averaged velocity field.

Fig. 5 Velocity distribution for various azimuth angles

3.2 Pressure distribution on blade

3.2.1 Change of pressure distribution of rotor blade in yawed flow condition due to azimuth angle

Generally, when $\Phi=0^\circ$, the pressure distribution on the blade hardly changes with azimuth angle variation. When Φ is not 0° , the relative velocity to blade section changes with azimuth angle. So the angle of attack of blade section changes based on azimuth angle. Thus, the pressure distribution on the blade changes with azimuth angle. In case of static state, the blade sectional performance depends on only the angle of attack for the same Reynolds number. However in case of dynamic change of angle of attack, the blade sectional performance depends on the instantaneous angle of attack, the amplitude and the frequency of angle of attack oscillations.

Figure 6 shows the pressure distribution on $\lambda=3.5$. There is a separation bubble at the suction surface of $x/c<0.1$ for $\Psi=270^\circ$, it is thought that the flow is reattaching on the blade section. The position of negative pressure peak for $\Psi=300^\circ$ is away from the leading edge. The peak position for $\Psi=330^\circ$ moves to the trailing edge side compared to $\Psi=300^\circ$. It seems that this moving of negative pressure peak is caused by dynamic stall vortex that flows on the suction surface. At $\Psi=0^\circ$, the relative inflow velocity to the blade section becomes lowest and the surface pressure becomes small. Therefore, it is thought that the reliability of the pressure distribution for $\Psi=0^\circ$ is low. As a result, it is thought that the pressure distribution in Fig. 6 is obtained. Also it may have effect by dynamic stall vortex passing.

Fig. 6 Pressure distribution ($\Phi=30^\circ$, $r/R=0.3$, $\lambda=3.5$)

3.2.2 Change of rotational force coefficient of rotor blade in yawed flow condition due to azimuth angle

In case of dynamic stall condition, the hysteresis characteristic of aerodynamic forces acting on the blade section is discussed with the relations between each sectional geometrical angle of attack and rotational force coefficient. The sectional stall angle is thought as a geometrical angle of attack that C_r shows sudden decrease at $\Phi=0^\circ$ for static state. The sectional stall angles for each section are 32° at $r/R=0.3$, 24° at $r/R=0.5$, 19° at $r/R=0.7$ and 17° at $r/R=0.9$.

Figure 7 (a)-(d) shows the relations between a geometrical angle of attack and rotational force coefficient at $r/R=0.3-0.9$ for $\Phi=30^\circ$. The symbols in figures show the tip speed ratio. In case of higher tip speed ratio, $\lambda=5.0$, the geometrical angle of attack stays in small values during rotation and the C_r increases as the α increases. The hysteresis loop of the $C_r-\alpha$ is small when the geometrical angle of attack is not beyond the static stall angle. However the big hysteresis loop is seen when the geometrical angle of attack is beyond a static stall angle for lower tip speed ratio. The size of hysteresis loop seems some dependency on the radius. The hysteresis loop for $r/R=0.9$ is smaller than that of other section. It is thought that the Reynolds number, the average and amplitude of fluctuating angle of attack, and the chord length at the section affect the size of hysteresis loop. The C_r decreases when the geometrical angle of attack exceeds the static stall angle. However C_r for $\Phi=30^\circ$ shown in Fig. 7 (a) keeps high value in high angle of attack compared to the static state. It is thought that this phenomenon is caused by the increase of lift caused by dynamic stall vortex and contributes to the increase of C_{power} at low tip speed region in yawed flow condition mentioned above.

Fig. 7 Rotational force coefficient for various tip speed ratio

3.2.3 Aerodynamic forces of whole blade

The aerodynamic force acting on the whole blade is evaluated from pressure distribution at $r/R=0.3, 0.5, 0.7$ and 0.9 . The measured sections are limited to only 4 span-wise positions, therefore the aerodynamic force for intermediate section is estimated by interpolation from two measured sections. The sectional aerodynamic forces for $r/R<0.3$ and $r/R>0.9$ assumes those for $r/R=0.3$ and $r/R=0.9$, respectively. Tip/root-losses are ignored because the rotor torque calculated without considering these losses shows the best agreement with the real one.

Figure 8 shows the azimuthal power coefficient for various tip speed ratio. The azimuthal power coefficient is calculated for the single blade. The azimuthal power coefficient $C_{p,azimuth}$ is expressed in the Eq. (3). It is assumed that the inflow energy for a single blade is constant during rotation. Therefore inflow energy does not depend on azimuth angle. As shown in Fig. 8(a), $C_{p,azimuth}$ becomes minimum at $\Psi=180^\circ$ and maximum at $\Psi=300^\circ$ for $\lambda=6.0-4.4$. The variation of azimuthal power coefficient seems to agree with variation of the geometrical angle of attack. Because in this tip speed ratio, the blade is operated without stall. $C_{p,azimuth}$ at $\Psi=270^\circ$ is bigger than one at $\Psi=90^\circ$. It is thought that this phenomenon is due to the difference between axial velocity behind upstream side and downstream side of rotor plane. As shown in Fig. 8(b), near the region of $\Psi=0^\circ-90^\circ$, the $C_{p,azimuth}$ for $\lambda=4.2$ keeps high value compare to other λ . In case of $\lambda=3.5$, the $r/R=0.3$ shows the dynamic stall from Fig.6, however the other section show clear drop of C_r in $r/R\geq 0.5$ from Fig.7. C_r for $\lambda=4.0$ do not show the clear drop in $r/R>0.5$. Therefore, it is thought that the sectional performance at tip region affects to this phenomenon. In all λ , $C_{p,azimuth}$ tends to be higher at $\Psi=180^\circ-360^\circ$ than that at $\Psi=0^\circ-180^\circ$. This is because of the hysteresis of the sectional lift caused by a dynamic change of angle of attack at this particular blade section.

$$C_{p,azimuth} = \frac{\omega \int_0^R r \int_0^S p_i ds_a dr}{\frac{1}{3} \left(\frac{1}{2} \rho A U_0^3 \right)} \quad (3)$$

Fig. 8 Azimuthal power coefficient for various tip speed ratio ($\Phi=30^\circ$)

4. Conclusion

As a result of the measurements of the pressure distribution on the blade and the velocity field around the wind turbine in yawed flow condition in a wind tunnel, the followings points have been cleared up.

- (1) The traces of the blade tip vortices in the rotor wake are decided by the averaged velocity field.
- (2) In yawed flow condition, the wind velocity behind rotor for upstream side is much reduced compared to that of downstream side. It is thought that because of the hysteresis of the sectional lift caused by a dynamic change of angle of attack to blade section, the rotor blade in upstream side shows higher performances than in downstream side.
- (3) In yawed flow condition which is not accompanied with a stall during rotation, the hysteresis loop of the C_r affects yawed rotor performance.

Nomenclature

A	Rotor swept area	[m ²]	T	Rotor torque	[N·m]
c	Local chord length	[m]	U_0	Wind tunnel speed (=7)	[m/s]
C_p	Pressure coefficient ($=p_i/p_d$)	[-]	α	Angle of attack	[°]
C_{power}	Power coefficient ($=T\omega/(1/2\rho\pi R^2 U_0^3)$)	[-]	β	Pitch angle (=2)	[°]
$C_{p,azimuth}$	Azimuthal power coefficient	[-]	θ	Twist angle	[°]
C_r	Rotational force coefficient	[-]	λ	Tip speed ratio ($=R\omega/U_0$)	[-]
D	Rotor diameter (=2.4)	[m]	ρ	Air density	[kg/m ³]
p_d	Dynamic pressure	[Pa]	Φ	Yaw angle	[°]
p_i	Pressure at the pressure port	[Pa]	Ψ	Azimuth angle	[°]
r	Spanwise position of rotor blade	[m]	ω	Rotor angular velocity	[1/s]
R	Rotor radius (=1.2)	[m]			

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