Application of flow control using plasma actuator to horizontal axis wind turbine

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Abstract. In this study, the clarification of the effect of plasma flow control on the rotor performance was carried out as a wind turbine control technology. The flow fields around rotor and the loads acting on wind turbine were measured by wind tunnel test using a test wind turbine with plasma actuator. As a result, in the low tip speed ratio, the power coefficient of Plasma On is larger than that of Plasma Off and the thrust coefficient of Plasma On slightly increased. In particular, the remarkable increase in the power coefficient was 24% at the most effective tip speed ratio. The wind turbine thrust increased slightly in the low tip speed ratio regime, but was less affected by the plasma flow control. In addition, when the power coefficient and thrust coefficient were calculated using the velocity components of the flow field around the wind turbine, the same tendency as in the wind turbine performance test was shown.

1. Introduction
Wind turbines placed in complex terrains are expected to operate in a harsh environment that is highly turbulent. These turbulences lead to poor energy production and higher failure rate of wind turbines. For this problem, wind turbine control technologies that can deal with fluctuating wind are considered as a solution. The local aerodynamics control device to increase local efficiency or to reduce the fatigue loads due to instantaneous flow around turbine blade is called ‘smart rotor’ [1] and it is actively studied by institutes around the world. Devices used as ‘smart rotor’ include trailing-edge flap [2] introduced on aircraft wings and Vortex Generator Jets [3] to suppress flow separation. In this study, the plasma flow control device as one of the active flow control technology of the turbine blade was focused on. A plasma actuator is the device that suppresses flow separation by accelerating the flow on the blade suction surface. Some of the advantages are as follows; 1. It is fully electric and can provide high speed response, 2. It requires no moving parts (moving parts always brings mechanical troubles), and 3. It can laminate into the turbine blade surface (no additional drag force is generated even if the actuator is broken) [4]. The device performance is still unknown, so it has been rarely used in previous studies. If the device performance becomes clear, it can be applied to increase the turbines efficiency under fluctuating wind. Toward practical application, it is necessary to investigate the device performance. In our previous study [5], the power performance by plasma actuation and a part
of flow fields by using ultrasonic velocimeter were shown. In this study, the torque and thrust of rotor were evaluated using detailed flow fields measured by a laser Doppler velocimeter (LDV).

2. Objectives
To clarify the effects of plasma flow control, flow fields and aerodynamic loads were measured by wind tunnel test using a test wind turbine with plasma actuator. The flow fields around rotor were measured using a LDV. The aerodynamic loads acting on wind turbine rotor were measured by a 6-components balance. To verify the effects of plasma flow control, the measurements were carried out for both Plasma On and Off.

3. Methodology
3.1. Experimental equipment
Figure 1 shows the experimental setup. The closed-circuit wind tunnel was used for the experiment. The measurement section is open section with a longitudinal length of 6.2m and an outlet diameter of 3.6m. The test wind turbine was set at 2.4m downstream from a wind tunnel outlet. The main flow velocity and main flow temperature were measured with a pitot tube installed at the wind tunnel outlet and a platinum resistance temperature detector. The test wind tunnel is a three-bladed upwind horizontal axis wind turbine with a rotor radius of $R = 0.8 \text{ m}$ and a hub height of $H = 1.6 \text{ m}$. Generally speaking, the rotor test in wind tunnel has small Reynolds number and the airfoil performance becomes poor with low $Re$. To avoid this difficulty, the Avister airfoil was selected for test blade. The airfoil performance in $Re \geq 1.0 \times 10^5$ is adequate for our rotor test. Reference $Re$ based on a chord length and tangential speed of blade tip for measurements is $1.4 \times 10^5$. The test blades are made of carbon fibre. The test wind turbine is controlled by a servo motor. The wind turbine power was calculated by rotor torque $Q$ and rotational speed $\omega$ which were acquired the value by the servo motor controller.

Figure 2 shows a cross-sectional view of the blade with a plasma actuator attached to leading edge. The Plasma actuator consist of copper tape for electrode and Kapton® tape for insulator. The thickness of copper tape and Kapton® tape are 80 $\mu$m, respectively. The withstand voltage of Kapton® tape is 125 kV/mm. The installation length of plasma electrode is 480 mm in the radial direction, $r/R = 0.25-0.85$.

A 6-components balance was used to measure the aerodynamic force acting on the wind turbine rotor. The rated capacity and accuracy of the 6-components balance are shown in table 1. The velocity distribution was measured using a 3-D laser Doppler velocimeter (LDV) made by Dantec Dynamics A/S. The method of measuring velocities by LDV utilizes three pairs of laser beams which are emitted from two LDV probes, A and B. LDV probe A has a focal length of 1600 mm and emits two violet lasers for radial velocity component. The LDV probe B has a focal length of 1000 mm and emits two blue lasers and two green lasers for axial and tangential velocity component. In this study, oil mist was used as seeding.

| Model Name  | LFM-A-1kN |
|-------------|-----------|
| $F_x$ [N]  | 1000      |
| $F_y$ [N]  | 1000      |
| $F_z$ [N]  | 1000      |
| $M_x$ [Nm] | 50        |
| $M_y$ [Nm] | 50        |
| $M_z$ [Nm] | 25        |

| Nonlinearity | Within $\pm 0.5\%$ R.O. |
| Hysteresis   | Within $\pm 0.5\%$ R.O. |
3.2. Experimental conditions and methods

3.2.1. Setting of plasma flow control
Figure 3 shows the concept of plasma flow control parameters. As shown in figure 3, AC voltage is applied between two electrodes to activate plasma flow control. The frequency of the applied AC voltage is called a fundamental frequency. In this study, the applied voltage was set to 6kV_{p-p} and the fundamental frequency was set to 15kHz. A duty ratio and a pulse modulation frequency \( f_m \) were set. Plasma flow control improves the wind turbine performance more effectively by repeatedly turning it on and off at regular interval \([6]\). The ratio of plasma-on time during the period is called duty ratio. In this experiment, duty ratio was set to 5%. In addition, the plasma flow control can change the effective radial position by adjusting the modulation frequency \( f_m \). The modulation frequency \( f_m \) is given by

\[
f_m = \frac{S_t \times U_r}{c_r}
\]  

(3.1)

where \( S_t \) is the Strouhal number, \( c_r \) is the chord length and \( U_r \) is the tangential velocity at any radial position \( r \) respectively. \( S_t \) is set to 1 with reference to previous study \([7]\). Therefore, to set \( f_m \), the radial position \( r \) must be determined, and the effective radial position of plasma flow control are varied by \( f_m \). From the previous study \([5]\), the turbine power increase by plasma actuator was seen when the effective radial position was set to the outer position. In this study, the effective radial position is set to the non-dimensional radial position of \( r/R = 0.8 \).

3.2.2. Measurement of power and thrust
In this experiment, the power and thrust of the wind turbine were measured for various tip speed ratio from 0.5 to 9.0. Tip speed ratio \( \lambda \) was varied every 0.1 in the regime of \( \lambda = 3.5-4.5 \), where the effects of the plasma actuation is remarkable due to blade stall, and every 0.5 in other regimes. In this study, the pitch angle was set optimum, 0 deg and yaw angle was set to 0 deg.

3.2.3. Flow field measurement around wind turbine rotor
In this experiment, the flow field around the rotor was measured. Operating condition for measurement was \( \lambda = 3.9 \), where the power increase by the plasma flow control was most significant. Flow field was measured by the LDV system. The LDV probes were set on the traversing equipment to measure the velocity distributions around rotor. The velocity measuring points were set on a horizontal plane at the rotor axis height. The axial position was set at \( x/R = -0.125, 0, 0.125, 0.25, 0.375, 0.625, 1.25 \) from upstream to

![Figure 1. Test wind turbine](image-url)
downstream. The origin of the x coordinate was the rotor plane. The radial position was measured at intervals of 0.1 from \( r/R = 0.4 \) to 1.2. For the measurement data, one rotation of the wind turbine was divided into BINs with azimuth angles of 1.0°, and a total of 360 data were averaged.

4. Experimental results and discussion

4.1. Wind turbine performance test

In this study, the wind turbine power and thrust were measured by changing tip speed ratio \( \lambda \). The results of the wind turbine power and thrust are shown. The wind turbine performance for Plasma On and Plasma Off test was measured, and the modulation frequency of the plasma actuator was set to the radial position \( r/R = 0.8 \).

![Figure 2. Cross section of blade with plasma actuator attached to leading edge](image1)

![Figure 3. Schematic diagram of pulsed modulation frequency](image2)
The relationship between the power coefficient $C_p$ and tip speed ratio $\lambda$ is shown in figure 4. The power coefficient for Plasma Off shows maximum value $C_p=0.36$ at $\lambda=6.5$. From figure 4, the power coefficient of Plasma On is larger than that of Plasma Off in the low tip speed ratio regime of $2.5 < \lambda < 4.2$, and is almost the same in the regime of $\lambda > 5.0$. In the low tip speed ratio regime of $\lambda < 4.5$, the wind turbine blades cause flow separation due to excessive angle of attack. The plasma actuator has the suppressing effect of the flow separation by accelerating the flow on the suction surface of the blade. Therefore, it is assumed that the power coefficient in the regime of $2.5 < \lambda < 4.0$ was increased by the suppressing effect of the flow separation. The increase in the power coefficient was 24% at the tip speed ratio of $\lambda = 3.9$, where the most remarkable power increase by the effect of plasma flow control was obtained. Also, in the high tip speed ratio regime, there is no increase in power due to the plasma actuator because flow on the blade surface does not separate.

The relationship between the thrust coefficient $C_t$ and tip speed ratio $\lambda$ is shown in figure 5. From figure 5, the thrust coefficient $C_t$ increases with tip speed ratio increasing in each case. In addition, the thrust coefficient of Plasma On in the low tip speed ratio regime of $2.5 < \lambda < 4.0$ is slightly larger than Plasma Off, but is almost the same above the optimal tip speed ratio of $\lambda = 6.5$.

### 4.2. Flow field measurement

In this section, the results of the flow field measurement around the wind turbine rotor are shown. The operating tip speed ratio for flow field measurement was set at $\lambda = 3.9$ from the performance test results. At $\lambda = 3.9$, the power increase by the plasma actuation was obvious. The flow field measurements were carried out under two conditions of Plasma On and Plasma Off.

#### 4.2.1. Effect of plasma actuation in flow field

The measurement results of the flow field around the wind turbine obtained in this experiment are shown. The axial velocity distribution and the tangential velocity distribution at the axial position $x/R=0.125$ is shown in figures 6 and 7. The vertical axis shows the axial velocity $u/U_0$, the tangential velocity $v/U_0$, and the horizontal axis shows the radial position $r/R$. Legends in the figure indicate Plasma On with filled red circles and Plasma Off with open blue circles, respectively. The axial velocity distributions at $x/R=0.125$, 0 are shown in figures 8 and 9. From Figures 6, 8 and 9, the axial velocity at $x/R=0.125$ is lower than at $x/R=-0.125$, 0 for both Plasma On and Plasma Off in the regime of $r/R \leq 1$. This is because the momentum of the air passing through the wind turbine rotor is reduced by the rotor thrust. In the regime of $0.75 \leq r/R \leq 0.85$, the axial velocity of Plasma On is lower than Plasma Off. This is thought to be related with the slight increase in thrust coefficient in low tip speed ratio regime.

The tangential velocity distributions at $x/R=-0.125$, 0 are shown in figures 10 and 11. From figures 7, 10 and 11. The tangential velocity was almost zero at $x/R=-0.125$, 0, positive at $x/R=0.125$. The wind passing through the rotor obtains angular momentum in the opposite direction due to the reaction of the rotor torque. Therefore, the tangential velocity in figure 7 captures the rotating components of the wake. In the span wise position of $0.65 \leq r/R \leq 0.85$, the tangential velocity of Plasma On is larger than that of Plasma Off. Therefore, the rotating components of the wake is increased by the plasma actuation, and the torque obtained by the wind turbine increases accordingly. As a result, it is assumed that the power coefficient increased in the low tip speed ratio regime.

#### 4.2.2. Derivation of wind turbine power and thrust from flow field measurement

In this section, the power coefficient and thrust coefficient were obtained from the velocity components obtained by the flow field measurement. Power coefficient and thrust coefficient were calculated by the angular momentum and the axial momentum theory, respectively. These are compared with the result of the wind turbine performance test. The effect of plasma flow control on wind turbine performance and flow field is discussed. The calculation was performed with Plasma On
and Plasma Off using velocity components obtained at the axial direction position $x/R = 0.375$ and the tip speed ratio $\lambda = 3.9$.

4.2.2.1. Wind turbine power

In this section, the power coefficient was calculated from the angular momentum theory. Considering the angular momentum of the air flowing into and out rotor, the torque $Q$ received by the wind turbine is expressed by equation (4.1),

$$Q = \rho G v_{out} r - \rho G v_{in} r$$  \hspace{1cm} (4.1)

where, $G$, $v_{in}$, and $v_{out}$ indicate the flow rate of the fluid, inflow and outflow tangential velocity, respectively. The control surface is considered as a small area, and the torque $dQ$ applied per small area is expressed by equation (4.2). In this study, the tangential velocity flowing into the rotor was set to $v_{in} = 0$ [m/s] because of the uniform flow upstream of the rotor surface. The tangential velocity flowing out of the rotor was defined as the local tangential velocity $v_{r}$ measured at $x/R = 0.375$. In this calculation, the inflow speed $U'$ on the wind turbine rotation surface was used as the inflow velocity.

$$dQ = \rho U' v_{r} r 2\pi r dr$$  \hspace{1cm} (4.2)

When the $dQ$ obtained by equation (4.2) is integrated into the rotor area, it becomes as shown in equation (4.3), and the torque $Q$ received by the wind turbine can be obtained.

$$Q = \int_{0.4r}^{R} dQ$$  \hspace{1cm} (4.3)

The power obtained by the wind turbine was calculated from the torque $Q$ and the angular velocity, and the power coefficient was calculated from $Q$. In this experiment, since the data was acquired on the blade root $r/R > 0.4$, the rotor torque acquired on $r/R < 0.4$ was ignored. Table 2 shows the comparison of power coefficient from performance measurements and flow field measurements. The calculation was performed by supplementing the tangential velocity components obtained from the wind tunnel experiment every $r/R = 0.016$ by interpolation. The complementary tangential velocity distribution used in calculation is shown in figure 12. The vertical axis shows tangential velocity $v/U_0$, and the horizontal axis shows radial position $r/R$. Legends in the figure indicate experimental value of Plasma On with filled red circles, experimental value of Plasma Off with filled blue circles, interpolated value of Plasma On with yellow square and interpolated value of Plasma Off with navy square, respectively.

|             | Power coefficient (angular momentum) | Power coefficient (rotor torque) |
|-------------|--------------------------------------|----------------------------------|
| Plasma On   | 0.229                                | 0.240                            |
| Plasma Off  | 0.204                                | 0.194                            |

From table 2, the power coefficient calculated from the angular momentum is smaller than that from the rotor torque measurement. One of the reasons is that the blade root side at $r/R < 0.4$ is not considered. In addition, the power coefficient for Plasma On calculated from the angular momentum is higher than that for Plasma Off, and the power coefficient from the rotor torque measurement show similar tendency. Therefore, it was confirmed that the power can be improved by the plasma actuation. From figure 12, the effects of the plasma actuation is significant at $0.65 \leq r/R \leq 0.85$, and the improvement of the power coefficient obtained from the angular momentum theory is considered to be due to the flow field at $0.65 \leq r/R \leq 0.85$. 


4.2.2.2. **Wind turbine thrust**

In this section, the thrust coefficient was calculated from the momentum theory. The momentum theory holds when there is no pressure change in the continuous fluid. Comparison of the velocity distribution when Plasma Off at \( x/R = 0.25, 0.375, 0.625, \) and 1.25 obtained from experiment is shown in figure 13. From figure 13, the axial velocity shows tendency of decreasing as increase of \( x/R \). In other words, in this experiment, fluid pressure changes due to pressure recovery behind the wind turbine. Therefore, the axial velocity at \( x/R = 1.25 \), which is less affected by the pressure change, is used in calculation. Considering the momentum of the air flowing into and out rotor, the thrust \( T \) received by the wind turbine is expressed by equation (4.4),

\[
T = \rho G u_{out} - \rho G u_{in} \tag{4.4}
\]

where, \( G, u_{in}, \) and \( u_{out} \) indicate the flow rate of the air, inflow and outflow axial velocity, respectively. The control surface is considered as a small area, and the thrust \( dT \) applied per small area is expressed by equation (4.5). In this study, the axial velocity flowing into the rotor was defined as the main flow velocity \( U_0 \), and the axial velocity flowing out of the rotor was defined as the local axial velocity \( u_r \) measured at \( x/R = 1.25 \).

\[
dT = \rho U_0 (U_0 - u_r) 2\pi r dr \tag{4.5}
\]

When the \( dT \) obtained by equation (4.5) is integrated in the radial direction, equation (4.6) is obtained, and the thrust \( T \) can be obtained.

\[
T = \int_{0.4R}^{R} dT \tag{4.6}
\]

Then, the thrust \( T \) received by the wind turbine was obtained by adding the thrusts for each radius obtained by equation (4.6). The thrust coefficient was calculated from the momentum theory. In this experiment, since the data was not acquired on the blade root side from \( r/R = 0.4 \), the blade root side from \( r/R = 0.4 \) was not considered. Table 3 shows the calculation results.

| Table 3. Comparison of thrust coefficient |
|------------------------------------------|
| Thrust coefficient (momentum) | Thrust coefficient (balance measurement) |
| Plasma On | 0.290 | 0.533 |
| Plasma Off | 0.280 | 0.520 |

From table 3, the thrust coefficient calculated from the momentum is lower than that from the balance measurement. In the calculation using the axial velocity, the calculation was performed ignoring the axial velocity at the nacelle projected area. However, the balance measurement includes the drag of nacelle. This is one of the reasons why the thrust coefficient from the momentum theory was lower than that from the balance measurement. The thrust coefficient from the momentum theory was slightly different from that of Plasma On and Plasma Off. The rate of change between Plasma On and Off is almost same for both momentum theory and balance measurement. In other words, the thrust increases slightly by the plasma actuation in the low tip speed ratio regime.
Figure 4. Power coefficient curve

Figure 5. Thrust coefficient curve

Figure 6. Non-dimensional axial velocity distribution ($x/R = 0.125$)

Figure 7. Non-dimensional tangential velocity distribution ($x/R = 0.125$)

Figure 8. Non-dimensional axial velocity distribution ($x/R = -0.125$)

Figure 9. Non-dimensional axial velocity distribution ($x/R = 0$)
5. Conclusion
In this study, a wind tunnel experiment was performed by attaching plasma actuator to the leading edge of the wind turbine. Then, the load acting on the horizontal axis wind turbine and the surrounding flow were measured by a 6-component balance and a laser Doppler velocimeter. The effect of the plasma flow control was discussed from the obtained velocity components of the flow field.

The results of this study are shown below.

(1) The wind turbine power increased in the low tip speed ratio regime due to the effect of plasma flow control. The tip speed ratio, which shows a remarkable increase in the power coefficient, was \( \lambda = 3.9 \), and the increase in the power coefficient due to plasma flow control was 24%.

(2) As a result of the wind turbine performance test, the wind turbine thrust slightly increased in the low tip speed ratio regime, but was almost the same above the optimal tip speed ratio.

(3) At the operating tip speed ratio that increases the effect of plasma flow control, the wind turbine wake at the condition of Plasma On showed a larger tangential velocity than at the condition of Plasma Off.

(4) When the torque change was analyzed from the angular momentum theory using the velocity components of the flow field, the power improvement effect by the plasma flow control was confirmed as in the wind turbine performance test.
When the load change is analyzed from the momentum theory using the velocity components of the flow field, the thrust increases slightly due to the plasma flow control in the low tip speed ratio regime.

6. References

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