Investigation of the Flow Field around the Horizontal Axis Wind Turbine with the Flanged-diffuser Shroud in Steady and Sinusoidally Oscillating Velocity Winds

Kazuhiko Toshimitsu¹, Hironori Kikugawa¹ Masatoshi Saiki² and Taiga Arakane³

¹Department of Mechanical Engineering, Oita National College of Technology
1666 Maki, Oita 8700152, Japan, tosimitu@oita-ct.ac.jp, kikugawa@oita-ct.ac.jp
²KYOCERA Corporation
³Undergraduate student, Mechanical and Environmental System Engineering, Advanced Course of Oita National College of Technology

Abstract

The wind turbines with a flanged-diffuser shroud-so called “wind-lens turbine”- are developed as one of high performance wind turbines by Ohya et al. In the paper, the wind turbine performances are investigated for both steady and unsteady winds. First of all, power coefficients of the wind turbines and flow structure are shown for steady wind. As the results, the compact-type wind-lens turbine has higher efficiency than the only rotor wind turbine in the steady wind. Secondly, the performances of the only rotor and the compact-type wind-lens turbines for the harmonic oscillating velocity wind are experimentally investigated. The effects of frequency of the oscillating wind on the power coefficients are presented. Consequently, the compact-type wind-lens turbine shows better performance than the only rotor one in sinusoidally oscillating velocity wind. Furthermore, the several important flow structures on the wind-lens turbine performances are made clear by the PIV measurement in the unsteady flow. In particular, it is newly found that the blockage vortex periodically generates in downstream for the same wind oscillating frequency, and decreases the power coefficient. However, the blockage vortex is vanished from the time averaged results of PIV. As the results, the unsteady measurement and analysis are very important for the appropriate design of the wind turbine in the unsteady flow.

Keywords: Wind Turbine, Unsteady Flow, Wind Energy, Power Coefficient, Flanged Diffuser, PIV, CFD

1. Introduction

In order to promote the use of sustainable energy, it is important issue that a wind power generation as one of natural energy sources is improved to raise the efficiency. According to the background, the wind turbines with a flanged-diffuser shroud-so called “wind-lens turbine”- are developed as one of high performance wind turbines by Ohya et al. [1]. In particular, the wind-lens turbine can generate electric power even in low velocity wind since the flanged-diffuser shroud increases the wind velocity at rotor. For the long and compact-type wind-lens turbines, we studied the detail flow structure around the wind-lens turbines with a particle image velocimetry in authors’ previous work [2, 3]. Recently, the research subjects of wind turbines in unsteady flows become important, which are the effects of fluctuating wind velocity and flow direction, non-uniform inflow, turbulence and other factors. They have effect on the wind turbine performance. In particular, the wind in Japan is more unstable than western country, namely wind velocity is easy to fluctuate. Thus it is important that the characteristics of the wind turbines in unsteady wind should be made clear. In previous concerned works, the numerical performance estimation of the oscillating wind velocity is proposed by Karasudani et al. [4-6].

In the paper, we will focus on the effect of the oscillating wind velocity upon the wind turbine performance. The experimentally and numerically performances of the ordinary rotor wind turbine and the compact-type wind-lens turbine are investigated in harmonic oscillating velocity wind. Furthermore, the experimental results are presented to demonstrate the dependences of the wind velocity frequency on power coefficients of the wind turbines. Also, the several important flow structures are made clear by PIV experiment in steady and unsteady wind.
2. Experimental Apparatus

2.1 Wind Turbine Model

The schematic designs and photographs of the compact-type wind-lens turbine are shown in Figure 1. The diffuser profile and the flange height are determined by Ohya et al. [1]. The rotors are designed for the two tip-speed ratios, $\lambda_D = 3.7$ and 5.0. Here the basic blade profile of $\lambda_D = 5.0$ is designed by Furukawa et al. [7]. The blade cross section profile is changed from NACA63218 at root to NACA63212 at tip along a span. The specific dimensions of the diffusers and the rotor are listed in Table 1 and 2 respectively.

2.2 Measurement System of the Wind Turbine Performance

The torque and rotational speed of the rotor are measured by the experimental apparatus as shown in Figure 2. The wind turbines are set up at the center of cross section of the wind tunnel. The measurement system of the wind turbine power is consisted of the torque detector, the rotational speed sensor, the torque converter, the DC motor and the DC power supply. The DC motor and the DC power supply work as a power generator, which control the rotor load and the rotational speed. Here the generated air flow is actively controlled by the 66 fans of the multi-fan wind tunnel in Oita National College of Technology.

![Fig. 1 Schematics and photograph of the compact-type wind turbine with the flanged-diffuser shroud](image1)

![Fig. 2 Schematics of measuring system of wind turbine performance](image2)

| Table 1 Dimensions of the wind turbine with the flanged-diffuser shroud |
|--------------------------|------------------|
| Tip clearance, $h_r$     | 3mm ($h_r / D = 1.5\%$) |
| Diffuser length, $L / D$ | 0.225             |
| Flange height, $h / D$   | 0.1               |

| Table 2 Dimensions of the rotor blades |
|-----------------------------|------------------|
| Rotor diameter $D_r$ ($= 2\pi r$) | 194 mm |
| Hub to tip ratio $D_h / D$    | 0.2            |
| Design tip-speed ratio $\lambda_D = \omega r / U$ | 3.7, 5.0 |
| Blade profiles               | NACA63218 (root) - NACA63212 (tip) |
3. Wind Turbines Performance in Steady Flow

3.1 Power Coefficients of the Wind Turbines in Steady Flow

The power coefficients of wind turbine are defined by

\[ C_{pw} = \frac{P}{\rho A U^3 / 2}, \tag{1} \]

where \( P \), \( \rho \), \( A \) and \( U \) denote generated power of a wind turbine, fluid density, receiving area of wind and upstream wind velocity, respectively. In the experiment, the upstream wind velocity is 5m/s, and the power coefficients of the only rotor and the compact-type wind-lens turbines are normalized by the rotor swept area, i.e. \( A = \pi D^2 / 4 = 2.96 \times 10^2 \text{ m}^2 \) and the circular area based on diameter of the flange, i.e. \( A = \pi D^2 / 4 = 5.56 \times 10^2 \text{ m}^2 \), respectively. It is found that the maximum power coefficients \( C_{pw} \) of the compact-type wind turbines are 1.5 times as large as the only rotor. It means that the wind-lens turbine clearly shows higher efficiency than the conventional wind turbine.

![Fig. 3 Relationship of Power coefficients and tip-speed ratio in the steady wind velocity 5m/s](image)

3.2 Flow Structures around the Wind-lens Turbines in Steady Flow

The importance of the flow structures behind the wind-lens turbines was pointed out to increase the velocity at rotor in the previous papers [1]. In order to investigate the mechanism of the increasing flow velocity at the rotor, an experimental and numerical time-average streamlines around the compact-type wind turbine at the tip-speed ratio \( \lambda = 3.9 \) and mean velocity \( U = 7 \text{ m/s} \) are shown in Figure 5 and 6 respectively. The experimental and CFD analysis streamlines have been conducted by PIV measurement and the commercial software ANSYS CFX 14.5 respectively in authors’ previous works [2, 3]. The numerical analysis is based on the 2nd order upwind implicit scheme for the conservation equation and \( k - \varepsilon \) turbulence model. Figure 4 shows the multi-block 3-D mesh for the numerical analysis, which is consisted of 6.4 million nodes. The rotor mesh block rotates at 2700 rpm. The boundary conditions are identified as the inflow conditions of \( U = 7 \text{ m/s} \), the exit pressure of 101.3kPa, slip flows on the outside walls and nonslip flows on the rigid object surfaces. The flow structure behind the flange of both PIV and

![Fig. 4 Multi-blocks unstructured mesh for CFD](image)
Fig. 5 Time average streamlines on meridional plane by PIV\textsuperscript{[2]}

Fig. 6 Time average streamlines on meridional plane by CFD\textsuperscript{[3]}

Fig. 7 Pressure distribution on the meridional plane in steady flow at $U = 5$ m/s and $\lambda = 3.5$ by CFD

Fig. 8 Schematic flow structures around the wind-lens turbine in steady wind

CFD results qualitatively agree with. The two vortices are found behind the flange. The pressure distribution of CFD analysis around the wind-lens turbine on the meridional plane is presented for $U = 5$ m/s, $\lambda = 3.5$ in Fig. 7. According to the results, the flow structure is illustrated in Fig. 8. Hence, it is concluded that the vortices, “A” and “B” behind the flange mainly produce the low pressure region and increase the wind velocity at rotor.

4. Performance in Sinusoidally Oscillating Velocity Flow

The performance of the wind-lens turbine in sinusoidally oscillating velocity wind is discussed in this chapter.

4.1 Experimental conditions of sinusoidally oscillating flow to investigate the wind turbine performance

The upstream wind velocity of the wind turbine is undergoing identical harmonic oscillation as follow,

$$U(t) = \bar{U} + \tilde{u} \sin(2\pi ft).$$

The performances of the wind turbines are investigated as the upstream mean velocities $\bar{U} = 5$ m/s with oscillating amplitudes $\tilde{u} = 1.0$ m/s. The wind velocity oscillates at frequencies $f = 0.033, 0.05, 0.083$ and $0.25$ Hz. Detail data are listed in Table 3. The time histories of the oscillating wind velocities at $\bar{U} = 5$ m/s and $\tilde{u} = 1.0$ m/s with $f = 0.25$ and $0.033$ Hz are shown in Fig. 9, which are measured at 1.4 m upstream location from the wind turbine front by a L-type Pitot tube. It is found that the experimental wind correctly oscillates with the specific conditions.

The characteristic frequency of the oscillating wind based on the turbine rotor dynamic response and the power coefficient in steady wind is proposed by Karasudani et al. \textsuperscript{[4]} as follow,

$$f_r = \frac{3\rho\pi^4 C_w(\lambda_w)\bar{U}}{2I\lambda_w^2},$$

where $\rho$, $r$, $I$, $\lambda_w$ and $C_w(\lambda_w)$ mean fluid density, rotor radius, moment of rotor inertia, the tip-speed ratio at the maximum power coefficient and the estimated power coefficient integrated the power coefficients in the steady flow, respectively. Here, the moment of inertia of the rotor is $I = 1.52 \times 10^4$ kgm$^2$. Equation (3) has the basic assumptions which the rotor response
is the quasi-steady state and turbine rotor torque is depended only on tip-speed ratio [5, 6]. In other words, the flow transient time which the flow field around the rotor corresponds with the oscillation wind is sufficiently small, thus the quasi-steady state is satisfied. It means that the turbine rotor can responsively rotate to the fluctuating wind velocity for \( f < f_r \). Here, we should mention that Karasudani et al. insist that the real only rotor turbine does respond for \( f < f_r / 3 \) by numerical simulation [5].

We are going to examine whether the quasi-steady response can be applied to this equipment. Let the rotor speed be 3,000 rpm, i.e. the time of one rotation be \( t_r = 0.02 \) seconds. If the inflow velocity decreases to 1m/s, the flow pass at the rotor tip of the thickness 2mm for \( t_{bp} = 2 \times 10^{-3} \) seconds. Since the time \( t_{bp} \) is sufficiently smaller than \( t_r \), thus the flow field around the rotor can enough changed during one rotation. Furthermore the rotor blade passing time \( t_{rp} \) of the wind should be sufficiently smaller than the wind oscillating period. Since the axial length of the rotor equals about 4cm, the rotor blade passing time \( t_{rp} \) equals 0.04 seconds. Hence \( t_{rp} \) is much smaller than the wind oscillating period (4 seconds at \( f = 0.25 \)Hz). Consequently, the flows around the rotor can be regarded as the quasi-steady state for this experiment. The experimental values \( \lambda_w \) and \( f_r \) are shown in Table 4.

### Table 3 Conditions of oscillating winds

<table>
<thead>
<tr>
<th>( \sigma ) [m/s]</th>
<th>( \bar{u} ) [m/s]</th>
<th>Oscillation Frequency, ( f ) [Hz]</th>
<th>Oscillation Period, ( f = 1/t ) [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>1.0 (20%)</td>
<td>0.25 (4)</td>
<td>0.083 (12)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.05 (20)</td>
<td>0.033 (30)</td>
</tr>
</tbody>
</table>

### Table 4 Turbine characters

<table>
<thead>
<tr>
<th>( \lambda_w )</th>
<th>( f_r )</th>
<th>( (1/3 f_r) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only Rotor</td>
<td>2.09</td>
<td>3.7</td>
</tr>
<tr>
<td>Compact</td>
<td>3.06</td>
<td>3.51</td>
</tr>
</tbody>
</table>

![Fig. 9 Comparison of experimental and theoretical oscillating wind velocities in the wind tunnel](image)

### 4.2 Power coefficients of the Wind Turbines in Oscillating Velocity Flow

In the section, we present the effects of the wind frequencies \( f \) upon the power coefficients \( C_w \) as the function of the mean tip-speed ratio \( \lambda \) for the only rotor and compact-type wind-lens turbines with the designed rotor tip speed ratio \( \lambda_D = 5.0 \) are shown in Figure 10 and 11.

The maximum coefficients are presented at \( \lambda \approx 2.7 \) and 3.5 for the only rotor and the compact-type wind turbines respectively. The power coefficient increases with decreasing the frequency \( f \).

Let discuss the effect of the wind frequency on the difference between the steady and unsteady power coefficients by the wind turbine types. The power coefficients in the steady wind are smaller than ones of the oscillating winds of \( f = 0.033, 0.05 \) and 0.083Hz for the only rotor. While, the case of \( f = 0.25 \)Hz is smaller than one of steady wind for \( \lambda = 1.6 \) to 2.8. It is indicated that the rotor do not respond the oscillating wind at \( f = 0.25 \)Hz for the range of tip speed ratio. On the other hand, the power coefficients of the compact-type wind-lens turbine for all frequencies are larger than one of steady flow. It is found that the compact wind-lens turbine work well for the higher oscillating wind frequency. Therefore, the compact-type wind-lens turbine is suitable for the oscillating velocity wind than the only rotor one.

In order to clearly indicate the dependency of the turbine type on performance, we define the increasing ratio \( \varepsilon \) of the maximum power coefficient on the basis of steady wind as follow.
where $\tilde{C}_w$ and $\overline{C}_w$ are maximum power coefficients in unsteady and steady winds respectively. The increasing ratio $\varepsilon$ for the only rotor and the compact-type with $\lambda_D=5.0$ is presented in Fig. 12. As you see, the compact-type turbine shows larger increasing ratio than the only rotor for all frequencies.

5. Flow Structure in Oscillating Velocity Wind by PIV measurement

In order to explicate the physical relationship between performance and flow field for the sinusoidally oscillating velocity wind, we will present the PIV measurement and analysis in the chapter.
5.1 Experimental facility and Image Analysis

The experimental facility is shown in Fig. 13. The PIV measurement system is consisted of the non-interlace CCD camera (Megaplus ES1.0, Kodak, 1024×1024 pixels), the double pulse Nd-YAG laser (PIV-400-10, Spectra Physics, 400mJ/pulse, 10Hz) and the pulse generator (DG535, Stanford Research Systems Inc.). The PIV images are photographed by the synchronizing laser light and the CCD camera under the control of the personal computer. The pair images of PIV analysis are acquired for 0.1Hz and total pair images number is 127, so the continuous experimental duration time is 12.7 seconds. The optical system consists of YAG mirrors and two cylindrical lenses. Using the optical system, laser light beam is expanded like as a fan shape with thickness 2mm. One will seed the fog tracer particle from the inlet of the wind tunnel by the fog generator (Fog generator 2001, DANTEC/INVENT measurement tech. GmbH). The fog diffuses almost uniformly in the measurement section of the wind tunnel.

The areas of PIV images and the positions of the laser light sheet are shown in Fig. 13. The image size, interrogation size and interval time are 400×400mm, 12.5×12.5mm and 150\(\mu\)s, respectively. Here, the PIV images are analyzed through cross correlation method by the commercial PIV software, PIVview-2c of PIVTEC GmbH.

![Fig. 13 Experimental Facility and Image view of PIV](image)

![Fig. 14 Instantaneous velocity distribution around wind-lens turbine in unsteady flow of \(\bar{U}=5\text{m/s}, \overline{\nu}=1\text{m/s}\) by PIV](image)

![Fig. 15 Time averaged stream line in unsteady flow of \(\bar{U}=5\text{m/s}, \overline{\nu}=1\text{m/s}\) by PIV.](image)
5.2 Instantaneous Velocity Distribution around a Wind-lens Turbine

An example of the instantaneous velocity vectors distribution around the compact-type wind-lens turbine in the sinusoidally oscillating velocity flow is presented in Fig. 14. The frequencies of the wind are 0.083 and 0.25 Hz and other conditions are same as Table 3 and 4. The tip speed ratio of rotor operating condition is 3.5 with the rotor blade $\lambda_D = 5.0$.

The flow structure is consisted of the overcoming flow (1), outflow through the diffuser (2), the unsteady vortices behind the shroud (3) and downstream blockage vortex (4). The unsteady vortices (3) are as same as the two vortices “A” and “B” of Fig. 8 behind the shroud in steady flow. Thus the vortices (3) increase the flow velocity at rotor. On the other hand the vortex (4) has the effect as an obstacle in main flow, i.e. the vortex (4) is so called “blockage vortex”. It is appear once in one cycle of wind oscillation. As the result, the performance of wind turbine decreases with increasing the wind frequency. Here, we will present the animation of the vortices’ behavior for 0.25 Hz and 0.083Hz in the conference presentation.

5.3 Time Averaged Streamline around a Wind-lens Turbine

Figure 15 shows the time average streamline around the wind-lens turbine in the oscillating velocity flow with 0.25 and 0.083Hz. The vortices (3) exist behind the shroud, which are as same as the described previous section 5.2. However, the blockage vortex (4) disappears in both cases of 0.083 and 0.25Hz. This is mentioned that the unsteady analysis of PIV is quite important to design the wind turbine in the oscillating velocity flow. In other word, only steady analysis is not enough for the suitable design of the wind turbine to take account of the oscillating velocity effect.

6. Conclusions

The paper presents the performances of the only rotor turbine and the compact-type wind-lens turbine in steady and unsteady winds. In steady wind, the flow structure around the wind-lens turbine is made clear by CFD and PIV. Also, it is shown that the compact wind-lens turbine generates larger power than the only rotor wind turbine.

In unsteady wind, the performance of the wind turbines is investigated for the upstream mean velocities $\bar{U} = 5 \text{ m/s}$ with the sinusoidally oscillating amplitude $\bar{u} = 1.0 \text{ m/s}$ at frequencies $f = 0.033$, 0.05, 0.083 and 0.25 Hz. The experimental and numerical results are presented to make clear the effect of the wind velocity frequency on power coefficient of the wind turbines in the oscillating velocity wind. The compact wind-lens turbine generates larger power than the only rotor one for wide frequency range, so that the wind-lens turbine is suitable for the oscillating velocity wind. The PIV experiment newly made clear the relationship between the unsteady flow structure and turbine performance. In particular, it is found that the blockage vortex periodically generates in downstream for the same wind oscillating frequency, and decreases the power coefficient. However, the blockage vortex is vanished from the time averaged results of PIV. As the results, the unsteady measurement and analysis are very important for the appropriate design of the wind turbine in the unsteady flow.

Consequently, the compact-type wind-lens turbine indicates the higher performance than an only rotor one in both steady and unsteady winds.

Acknowledgments

The work was supported in part by the Grant-in-Aid for Scientific Research through grant number 21560823 from the Ministry of Education, Science, and Culture of Japan, and the Collaborative Research Program of Research Institute for Applied Mechanics, Kyushu University. The authors gratefully acknowledge the support of Prof. Yuji Ohya, Prof. Takashi Karasudani and Prof. Masato Furukawa of Kyushu University, to this investigation.

References