Experimental Investigation of Performance of the Wind Turbine with the Flanged-diffuser Shroud in Sinusoidally Oscillating and Fluctuating Velocity Flows

Kazuhiko TOSHIMITSU¹, Hironori KIKUGAWA², Kohei SATO³ and Takuya SATO⁴

¹. Dept. of Mechanical Engineering, Oita National College of Technology, 1666 Maki, Oita 870-0152, Japan, E-mail: tosimitu@oita-ct.ac.jp
². Dept. of Mechanical Engineering, Oita National College of Technology
³. Dept. of Mechanical Engineering, Kyushu University (Graduate Student)
⁴. Dept. of Mechanical Engineering, Oita National College of Technology (Undergraduate Student)

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 this paper, the wind turbine performances are investigated for both steady and unsteady winds. The compact-type wind lens turbine show higher efficiency than the rotor only wind turbine. Also, the flow structure around the compact-type wind turbine is made clear by CFD and PIV in steady wind. Furthermore, the performances of the only rotor and the compact-type wind-lens turbines for unsteady wind are experimentally and numerically investigated. Experimental and numerical results are presented to demonstrate the dependence of frequency of the harmonic oscillating velocity wind on the power coefficients. Consequently, the compact-type wind-lens turbine show better performance than the only rotor one in sinusoidally oscillating velocity wind. Furthermore, the numerical estimation can predict the power coefficients in the oscillating flows to an accuracy of 94 to 102%. In addition, the dependency of the turbine performance on turbulent intensity and vortex scale of natural fluctuating wind is presented.

Keywords: Wind Turbine, Unsteady Flow, Wind Energy, Power Coefficients, Flanged Diffuser, Natural Wind

Introduction

It is important issue that a wind power generation is improved to raise the efficiency as one of natural energy sources in order to promote the use of sustainable energy. 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 turbine with a particle image velocimetry in authors’ previous work [2]. Recently, 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 affect on the performance and fatigue problem. In particular, wind in Japan is more unstable than western country, namely wind velocity and flow direction are easy to change. Thus it is important that the characteristics of the 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. [3-5].

In this paper, we will focus on the effect of the fluctuating wind velocity upon the wind turbine performance. We experimentally and numerically investigate the performances of the ordinary rotor wind turbine and the compact-type wind-lens turbine in harmonic oscillating velocity wind. Experimental and numerical results are presented to demonstrate the dependences of the wind velocity frequency on power characteristics of the wind turbines. Furthermore, the effects of the turbulent intensity and vortex scale in natural fluctuating velocity wind on the turbines performance are investigated.

Experimental Apparatus

Wind turbine model
The schematic designs and photographs of the compact-type wind-lens turbine are shown in Fig. 1. The optimum 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. [6], which 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.

**Measuring system of the wind turbine performance**

The torque and rotational speed of the rotor are measured by the experimental apparatus as shown in Fig. 2. The wind turbines are set the center of the wind tunnel which is cross section 1m×1m. The wind turbine power measuring system is consisted of the torque detector, the rotational speed sensor, the torque converter, the DC motor and the DC power supply. They 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 ONCT.

**Wind Turbines Performance in Steady Flow**

**Power coefficients of the wind turbines in steady flow**

The power coefficients of wind turbine are defined by

\[
C_w = \frac{P}{\frac{1}{2} \rho A U^3},
\]

where \( P \), \( \rho \), \( A \) and \( U \) denote generated power of a wind turbine, fluid density, normalize wind swept area and the upstream wind velocity, respectively. The power coefficients of the only rotor and the compact-type wind turbines are normalized by the rotor swept area \( A = \pi D_r^2 / 4 \) = 2.96 x 10^2 m^2 and the flange circular area \( A = \pi D_f^2 / 4 \) = 5.56 x 10^2 m^2, respectively. It is found that the maximum power coefficients \( C_w \) of the compact-type turbines are 1.5 times as large as the only rotor. It means that the wind-lens turbine clearly shows higher efficiency compared than the conventional wind turbine.

**Flow structures around the wind-lens turbines in steady flows**

The importance of the flow structures behind the wind-lens turbines is pointed out to increase the velocity at rotor in the previous papers [1, 2]. In order to investigate the mechanism of the increasing flow velocity at the rotor, herewith we present an experimental and numerical time-average streamlines around the compact-type wind turbine for the tip-speed ratio \( \lambda = 3.9 \) and mean velocity

**Table 1 Dimensions of the wind turbine of the flanged-diffuser shroud.**

| Tip clearance, \( h_t \) | 3mm (\( h_t/D = 1.5\% \)) |
|-------------------------|-----------------------------|
| Diffuser length, \( L/D \) | 0.225 |
| Flange height, \( h/D \) | 0.1 |

**Table 2 Dimensions of the rotor blades.**

| Rotor diameter \( D_r \) (=2r) | 194 mm |
|-------------------------------|--------|
| Hub to tip ratio \( D_h/D \)   | 0.2    |
| Designed tip-speed ratio \( \lambda_D = \omega r / U \) | 3.7, 5.0 |
| Blade profiles                | NACA63218 (root) ~ NACA63212 (tip) |

**Fig. 1 Schematics and photograph of the compact-type wind turbine with the flanged-diffuser shroud.**

**Fig. 2 Schematics of measuring system of wind turbine performance.**

**Fig. 3 Relationship of Power coefficients and tip-speed ratio in the steady wind velocity 5m/s.**
\( \bar{U} = 7 \text{m/s} \). The experimental streamline by PIV measurement is shown in Fig. 4. Also the CFD analysis with the commercial software ANSYS CFX 12 is presented in Fig. 5. The numerical analysis is based on the 2nd order upwind implicit scheme for the conservation equation and \( k - \varepsilon \) turbulence model. Figure 6 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 \( \bar{U} = 7 \text{m/s} \), the exit pressure of 101.3kPa, slip flows on the outside walls and nonslip flows on the rigid object surfaces.

The vortex structure behind the flange of both PIV and CFD results qualitatively agree with. Twin vortices are found behind the flange. According to the results, the flow structure is illustrated in Fig. 7. The vortex “A” behind the flange mainly caused the low pressure region. Thus it increases the wind velocity at rotor. The maximum velocity at rotor surface is calculated 9.5m/s as velocity rising.

**Performance in Sinusoidally Oscillating Velocity Flow**

In this chapter, we experimentally and numerically discuss the performance of the wind turbine in sinusoidally oscillating velocity wind.

**Experimental conditions of sinusoidally oscillating flow to investigate the wind turbine performances**

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

\[
U(t) = \bar{U} + \bar{u} \sin(2\pi f t).
\]  

(2)

The performances of the wind turbines are investigated as the upstream mean velocities \( \bar{U} = 5 \text{m/s} \) with oscillating amplitudes \( \bar{u} = 1.0 \text{m/s} \). The wind velocities oscillate at frequencies \( f = 0.033, 0.05, 0.083 \) and 0.25Hz. Detail data are listed in Table 3. The examples time history of the oscillating winds at \( \bar{U} = 5 \text{m/s} \) and \( \bar{u} = 1.0 \text{m/s} \) with \( f = 0.25 \) and 0.033Hz are shown in Fig. 8, which is measured at 1.4m upstream 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 analysis and the power coefficient in steady wind is proposed by Karasudani et al. [4] as follow,

\[
f_r = \frac{3 \rho r^2 C_w(A_w) \bar{U}}{2 T_d},
\]  

(3)
should be sufficiently small than the wind oscillating period. Since the axial length of the rotor equals 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 ($f = 0.25Hz$). Consequently, the flows around the rotor can be regarded as the quasi-steady state for this experiment. The physical values $\lambda_w$ and $f_r$ are shown in Table 3.

Power coefficients of the wind turbines in oscillating velocity flows

In this section, we present the example results of the mean flow $\bar{U}=5m/s$ and $\bar{u}=1.0m/s$ (i.e. $\bar{u}/\bar{U}=20\%$) in the conditions of Table 3. 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 turbines with the designed rotor tip speed ratio $\lambda_p=5.0$ are shown in Fig. 9 and 10.

The maximum coefficients are presented at $\lambda \equiv 2.7$ and 3.5 for the only rotor and the compact-type wind turbines respectively. The power coefficient is increased with decreasing the frequency $f$.

Let discuss the dependency of the wind frequency on the turbine type performances. For the only rotor, the power coefficients in the steady wind are smaller than ones of the oscillating winds of $f =0.033, 0.05$ and 0.083Hz. While the case of $f=0.25Hz$ is small than one of steady wind for $\lambda = 1.5 \sim 3.0$. It is indicated that the rotor do not respond the oscillating wind for the tip speed ratio. For the compact-type wind-lens turbines, the power coefficients in steady flow are smaller than the all wind frequencies $f =0.033, 0.05, 0.083$ and 0.25Hz. It is made clear 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 wind velocity than the only rotor one.

In order to make clear the turbine type performance in the oscillating flows, we define the increasing ratio $\varepsilon$ of the maximum power coefficient on the basis of steady wind as follow

$$\varepsilon = \frac{C_{w} - C_{\lambda}}{C_{w}} \times 100 \%$$

, where $C_{w}$ and $C_{\lambda}$ are maximum power coefficients in unsteady and steady winds respectively. Figure 11 presents the increasing ratio $\varepsilon$ for the only rotor and the compact-type with $\lambda_{p}=5.0$. As you see, the compact-type turbine is better than the only rotor.

Numerical estimations of the power coefficients of the wind turbines in oscillating flow

Karasudani et al. suggest that the numerical estimation of turbine performances for the oscillating wind [4]. Here it is assumed that the oscillating wind velocity

Table 3 Conditions of oscillating winds and turbine characters.

| $U$ [m/s] | Oscillation Frequency, $f$ [Hz] | $\lambda_p$ | $\epsilon$ |
|----------|-------------------------------|-------------|---------|
| 5.0      | 0.02                          | 3.7         | 0.04    |
| 5.0      | 0.04                          | 3.7         | 0.04    |
| 5.0      | 0.08                          | 5.0         | 0.04    |

Fig. 8 Comparison of experimental and theoretical oscillating wind velocities in the wind tunnel.

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 coefficients and the estimated power coefficients integrated the power coefficients in the steady flow, respectively. (The details of the numerical treatment are described in the later section entitled "Numerical estimations of power coefficients of the wind turbines in oscillating flows"). The measured rotor’s moment of inertia is $I = 1.52 \times 10^{-4} $kg·m$^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 $\lambda$ for the only rotor and compact-type wind turbines respectively. Figure 11 presents the increasing ratio $\varepsilon$ for the only rotor and the compact-type wind turbines respectively. The power coefficient is increased with decreasing the frequency $f$. Let discuss the dependency of the wind frequency on the turbine type performances. For the only rotor, the power coefficients in the steady wind are smaller than ones of the oscillating winds of $f =0.033, 0.05$ and 0.083Hz. While the case of $f=0.25Hz$ is small than one of steady wind for $\lambda = 1.5 \sim 3.0$. It is indicated that the rotor do not respond the oscillating wind for the tip speed ratio. For the compact-type wind-lens turbines, the power coefficients in steady flow are smaller than the all wind frequencies $f =0.033, 0.05, 0.083$ and 0.25Hz. It is made clear 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 wind velocity than the only rotor one.

In order to make clear the turbine type performance in the oscillating flows, we define the increasing ratio $\varepsilon$ of the maximum power coefficient on the basis of steady wind as follow

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, where $C_{w}$ and $C_{\lambda}$ are maximum power coefficients in unsteady and steady winds respectively. Figure 11 presents the increasing ratio $\varepsilon$ for the only rotor and the compact-type with $\lambda_{p}=5.0$. As you see, the compact-type turbine is better than the only rotor.
\[ U(t) \text{ consists of the linear combination of the steady velocity } U \text{ and unsteady velocity } u(t) \text{ as } U(t) = \bar{U} + u(t). \] In addition, it is assumed that the unsteady component \( u(t) \) no correlates to the unsteady power coefficient in the wind. The time averaged power coefficient \( C_w \) of the rotor is determined through the steady power coefficient \( C_w^0 \) as the following Eqs. (5) to (12),

\[ C_w \equiv C_w^0(1 + 3\sigma^2), \quad (5) \]

**Fig. 9** Effect of the wind frequencies \( f \) on the time averaged power coefficients \( C_w \) for the only rotor with \( \bar{U} = 5\text{m/s}, \bar{u} = 1.0\text{m/s} (\bar{u}/\bar{U} = 20\%) \) and \( \lambda_D = 5.0 \).

\[ C_w^A = \frac{1}{2 \rho (f/\bar{f}_r)^{1/7} \lambda_D w} \int_{\lambda_c}^{1+} C_w(\lambda) d\lambda, \quad (6) \]

\[ \lambda_\pm = \lambda_w \pm g(f/\bar{f}_r) + h(f/\bar{f}_r) \varepsilon \lambda_w, \quad (7) \]

\[ \Delta \lambda_{\infty} = \lambda_w \sqrt{2\sigma}, \quad \varepsilon \lambda_w = \lambda_w 2\sigma^2, \quad (8), (9) \]

\[ \sigma^2 \equiv \frac{1}{T} \int_0^T \left\{ \frac{u(t)}{\bar{U}} \right\}^2 dt = \frac{1}{2} \left( \frac{\bar{u}}{\bar{U}} \right)^2, \quad (10) \]

\[ g(f/\bar{f}_r) = 1.04 \left\{ 1 - \exp \left( -7.49 \frac{f}{\bar{f}_r} \right) \right\}, \quad (11) \]

\[ h(f/\bar{f}_r) = 1.37 \left\{ 1 - \exp \left( -3.76 \frac{f}{\bar{f}_r} \right) \right\}. \quad (12) \]

Here it is mentioned that the approximated terms of \( g(f/\bar{f}_r) \) and \( h(f/\bar{f}_r) \) are independent of moment of inertia, rotor radius, power coefficient and control time. The power coefficient in unsteady wind is \( 3\sigma^2 \) larger than one in the steady wind. The power coefficient ratio \( \eta \) is defined to compare the experiment result \( C_{wE} \) and numerical estimation \( C_{wT} \),

\[ \eta = \frac{C_{wE}}{C_{wT}} = \frac{C_{wE}}{C_{w0}(1+3\sigma^2)}. \quad (13) \]

**Fig. 10** Effect of the wind frequencies \( f \) on the time averaged power coefficients \( C_w \) for the compact-type with \( \bar{U} = 5\text{m/s}, \bar{u} = 1.0\text{m/s} (\bar{u}/\bar{U} = 20\%) \) and \( \lambda_D = 5.0 \).

**Fig. 11** Increasing ratio of maximum power coefficient for oscillating wind on the basis of one for steady wind.

Figure 12 summarizes \( \eta \) for all cases. The same pattern of bar graph presents the wind turbine type i.e. the only rotor and compact-type from left to right for each frequency. As you see, the numerical estimation can predict the power coefficients in the oscillating flows to an accuracy of 94 to 102%.

### Performance in Natural Fluctuating Velocity Flow

The natural fluctuating wind is generated by the active controlled multi-fan wind tunnel on the basis of Karman's power spectral equation as follows;

\[ S_u(f) = 4 I_t^2 L_v \bar{U} \left\{ \frac{1}{1 + 7.08 \left( \frac{f L_v}{\bar{U}} \right)^{1/5}} \right\}^2, \quad [\text{m}^2/\text{s}] \quad (14) \]

\[ I_t = \frac{\sigma}{\bar{U}}. \quad (15) \]

Here, \( I_t \) and \( L_v \) mean turbulent intensity and vortex scale respectively.

We basically examine the effect of the main factors of the natural wind on power coefficients of the only rotor and the compact-type wind turbines for mean wind velocity 5m/s. Experimental condition and effect of turbulent intensity on power coefficient are shown in Table 4 and Fig. 13 respectively. According to experimental results, both \( I_t \) and \( L_v \) are increase with increasing \( C_w \) for both only rotor and compact-type wind turbines.
Fig. 12 Comparisons of the experimental and numerical maximum power coefficients of the wind turbines.

Table 4 Natural fluctuating wind conditions at $\bar{U} = 5\text{m/s}$

| Case | $I_t$ | $L_v$ |
|------|------|------|
| 1    | 5%   | 10%  |
|      | 15%  | 3m   |
| 2    | 1m   | 3m   |
|      | 6m   | 10%  |

Fig. 13 Effect of the turbulent intensity on power coefficient for the natural fluctuating wind of time average wind velocity 5m/s and vortex scale 3m.

Conclusions

This paper presented wind performances of the only rotor turbine and flanged diffuser shroud which are so called "the compact-type wind-lens turbine" in steady and unsteady winds. The flow structure around the compact-type wind turbine is made clear by CFD and PIV in steady wind. Also, it is shown that the compact wind-lens turbine works higher power generator than the only rotor wind turbine. The performances of the wind turbines are investigated in the harmonic oscillating velocity wind as the upstream mean velocities $\bar{U}=5\text{m/s}$ with oscillating amplitudes $\bar{a}=1.0\text{m/s}$ at frequencies $f=0.033, 0.05, 0.083$ and $0.25\text{Hz}$. Experimental and numerical results are presented to make clear the dependence of the wind velocity frequency on power characteristics of the wind turbines in sinusoidally oscillating velocity wind.

Consequently, the compact-type wind-lens turbine indicates the higher performance than an only rotor one in both steady and unsteady wind. In particular using the present designed rotor, the compact-type wind-lens turbine is suitable for the oscillating velocity wind for higher wind frequency. The characteristic frequency proposed by Karasudani can be one of index to estimate turbine performance in the oscillating wind. In the experiment, the numerical estimation can predict the power coefficients within 94 to 102% accuracy in the harmonic oscillating winds.

Furthermore, performance dependence on turbulent intensity and vortex scale of natural fluctuating velocity wind is investigated. Both factors are increase with increase power coefficient for the only rotor and compact-type wind turbines.

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