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Investigation of Horizontal Axis Wind Turbine Performance in Simulated Natural Wind by an Active Control Multi-Fan Wind Tunnel

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The effects of turbulent intensity and vortex scale of simulated natural wind on performance of a horizontal axis wind turbine (HAWT) are mainly investigated. Generally, the unsteadiness and turbulence of wind in Japan are stronger than ones in Europe and North America. Hence, Japanese engineers should take account of the velocity unsteadiness of natural wind at installed open-air location to design a higher performance wind turbine. Using the originally designed five wind turbines on the basis of NACA and MEL blades, the effects of the wind frequency and vortex scale on the power coefficient are presented in the simulated natural wind. As the results, the power coefficient of the newly designed rotor (MEL3) in the simulated natural wind is 130% larger than one in steady wind.

Keywords: Wind Turbine, Wind Energy, Natural Wind, Unsteady Flow, Rotor Design, Turbulence

Introduction

Recently, it is important that one should consider the effects of unsteadiness and turbulence of the wind on the performance for high output power of a wind turbine. This is because that a wind turbine in natural wind with velocity fluctuation and turbulence show larger power than one in steady wind for some installation locations [1]. For the reasons, it is improved that the design of a wind turbine is considered the disturbance effect of the wind [2, 3].

In general, a wind turbine is developed through the following procedure. Firstly, a design developer evaluates performance of a newly designed wind turbine in steady wind through a wind tunnel test to determine the basic design. Secondly, performance of a scaled model of a prototype wind turbine is investigated at the installation location for a year to evaluate the performance. Finally, the developer determines the design. For these procedures, it is necessary long time and large cost to develop a new wind turbine. These design and manufacturing procedures require long time and large expense.

The purpose of this study is to establish the method of a wind turbine design, which is tailor-made for the natural wind at installation location without the field test. In order to evaluate the performance in natural wind, simulated natural wind is generated by a multi-fan type active control wind tunnel. In this study, output powers of five rotors are examined in the wind. It is generated on the basis of Karman's power spectrum density function. The paper shows the effects of turbulent intensity and vortex scale on the wind turbine performance.

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Nomenclature

A	Wind received area [m^2]	U , u	Wind velocity [m/s]
C_t	Torque coefficient	**Greek letters**	
C_w	Power coefficient	ρ	Fluid density [kg/m^3]
C_{ws}	Maximum power coefficient in steady wind	σ	Standard deviation of wind velocity
C_{wu}	Maximum power coefficient in unsteady wind	ω	Circular frequency [rad/s]
f	Wind oscillation frequency [Hz]	λ	Tip speed ratio
I	Turbulent intensity [%]	**Subscripts**	
L	Vortex scale [m]	D	Design value
P	Output power of wind turbine [W]	s	Steady wind, steady component
S_u	Power spectrum density function [m^2/s]	u	Unsteady wind, unsteady component
T	Torque [Nm]	$(\bar{\ })$	Time averaged value
T_w	Wind oscillation period [s]	$(\tilde{\ })$	Unsteady value

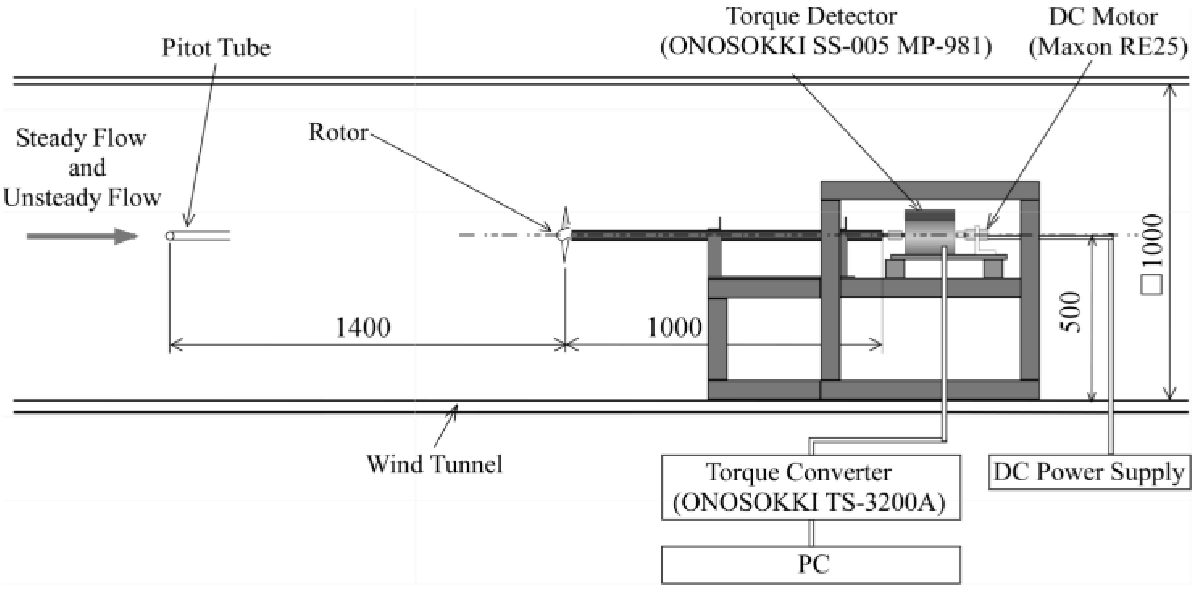

Fig. 1 Schematics of experimental system to measure wind turbine performance.

Table 1 Design condition of rotor

Rotor	U_D [m/s]	λ_D	AOA [deg.]	POT (x_e/c)	MOI [kgm^2]	Mass [g]
NACA1	10	5.0	-	50%	1.52×10^{-4}	120
NACA2	6.5	3.5	8	35%	8.65×10^{-5}	102
MEL1	6	5.0	10	33%	2.81×10^{-5}	67
MEL2	6	4.0	15	33%	3.95×10^{-5}	71
MEL3	6	2.5	15	33%	1.42×10^{-4}	104

λ_D =Designed Tip speed ratio, AOA=Angle of attack, POT=Position of torsional axis from leading edge, MOI=Moment of inertia.

Experimental Procedure

Experimental apparatus

Figure 1 shows the measuring system of experiment. The wind turbine type is a horizontal axis with three blades. The cross section of the wind tunnel is 1m×1m. The flow is generated by the 66 fans which are actively controlled. The system is consisted of the torque detector, the rotational speed sensor, the torque converter (Ono-sokki, SS-005, MP-981), the DC motor (Maxon, RE25, 20W) and the DC electric power supply. The DC motor works as a power generator to control the rotor load and the rotational speed.

Wind Turbine Models

Table 1 and Figure 2 show the design conditions of rotors, its schematic and photo respectively. The rotors of NACA are designed on the basis of NACA 632xx series blade at Reynold number Re=3.0×10^6. The rotor NACA1 is designed by Furukawa et al. for a long type wind lens turbine [4], which the profile is formed from NACA63218 at root to NACA63212 at tip along a span. The characteristic and performance for steady and sinusoidally oscillating velocity wind have been studied in the authors' previous papers [5, 6]. The rotor NACA2 and MEL1-3 are newly designed on the basis of NACA63218 at Re=3.0×10^6 and MEL002 at Re=9.0×10^4 respectively. Here, the MEL series blade (MEL002) was developed by National Institute of Advanced Industrial Science and Technology (AIST) for wind turbine in Japan.

In this experiment, two kinds of Reynolds number should be considered. One is Rotor Reynolds Number, Re=9.0×10^4, which is calculated by steady velocity 7m/s and rotor diameter 0.194m as a characteristic length. Another is local blade Reynolds number. For example, when inflow velocity of the blade is assumed as 2m/s, it is determined as Re= 1.8×10^4～3.7×10^4 with tip speed ratio λ=2～4 and blade chord length 2cm as a characteristic length. Then, the local blade Reynolds number is as same order as one of MEL002.

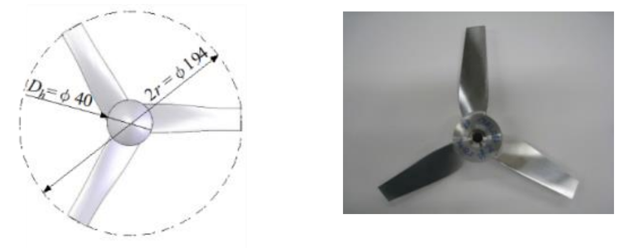

Fig. 2 Schematic and photograph of the wind turbine model, MEL3.

Definition of Power and Torque Coefficients

The power and torque coefficients of wind turbines are defined by following equations;

$$C_w = \frac{P}{\frac{1}{2}\rho A \overline{U}^3}\,, \qquad (1)$$

,

$$\lambda = \frac{r\omega}{\overline{U}}\,. \qquad (2)$$

Here, P , T, ρ , A and $\overline{U}$ denote generated power and torque of a wind turbine, fluid density, rotor swept area and the upstream time averaged flow velocity, respectively.

Performance in Natural Wind

The simulated natural wind with fluctuating velocity is made through Karman's power spectrum density function (PSD) of Eq. (3) and (4).

$$S_u(f) = 4I^2 L\overline{U}\frac{1}{\left[1+70.8\left(\frac{fL}{\overline{U}}\right)^2\right]^{5/6}}\,, \qquad (3)$$

$$I = \frac{\sigma}{\overline{U}}\,. \qquad (4)$$

Where, I and L mean turbulent intensity and vortex scale respectively. One generates the velocity data of time history through inverse Fourier transformation with random phase in this study.

Wind conditions

Table 2 shows the conditions of the simulated natural wind to examine the effect of I and L on power coefficient. The experimental duration time is 10 minutes for each case. The mean velocity, I and L of the wind do not accurately correspond to target conditions. Hence they are monitored during measurement by hot-wire anemometer. The data show the column of "Measurement" in Table 2.

Figure 3 presents the comparison between theoretical data and experimental result of Karman's PSD [$S_u(f)$] at target conditions $\overline{U}$ =6.5m/s, I=5.0% and L=6m. The theoretical and experimental data are almost same for the frequency $0.03 < f < 1.0$. It means that the simulated wind is appropriately generated on the basis of Karman's PSD of Eq. (5). Figure 4 shows the example of the velocity data of time history at $\overline{U}$ =6.5m/s, *I*=5% and *L*=6m. Here we should mention that the vortex scale *L* doesn't present the real vortex size since it means probabilistic parameter of vortex scale.

Experimental results and discussions

Figures 5 and 6 show the effect of vortex scale *L* on the power coefficients of NACA1 and MEL3 with the target turbulent intensity *I*=10% in Table 2. In addition, power coefficient in steady wind of 7m/s is also presented in the figures as reference. The gray region of "resonance" show that the rotor axis rotationally resonates. Hence, the data of resonance region are omitted.

Table 2 Conditions of turbulent wind.

Target			Measurement	
$\overline{U}$ [m/s]	*I* [%]	*L* [m]	$\overline{U}$ [m/s]	*I* [%]
6.5	5	3	6.5	5.1
		6	6.4, 6.7	5.2, 5.1
		10	6.6	5.1
	10	3	6.5	9.9
		6	6.4, 6.5	9.9, 10.6
		10	6.5	10.1
	15	3	6.6	15.8
		6	6.4, 6.6	15.8, 15.8
		10	6.7	15.1

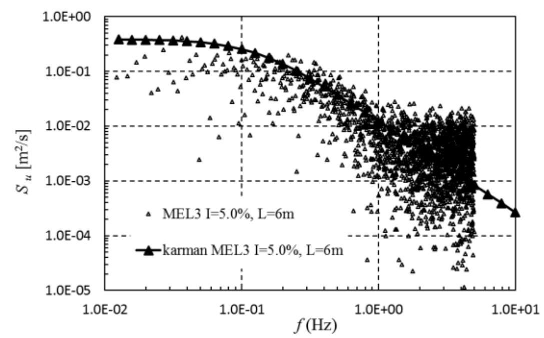

Fig. 3 Comparison of power spectrum between theory and experiment for fluctuating wind velocity.

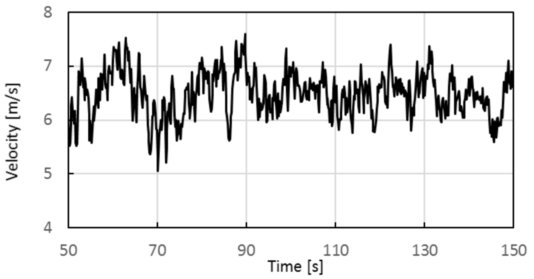

Fig. 4 Example of the time history velocity data at $\overline{U}$ =6.5m/s, *I*=5% and *L*=6m.

The maximum power coefficient of MEL3 is larger than one of NACA1. The maximum power coefficient ratios (C_{wu}/C_{ws}) of MEL3 is almost same as one of NACA1 at 1.2. The maximum power coefficients C_{wu} NACA1 and MEL3 are occurred with *L*=6m, 10m and 10m, respectively. Thus the effect of vortex scale is large at *I*=10%.

Figures 7 to 10 show the effect of turbulent intensity *I*. Its effect depends on vortex scale. The effect is small on the coefficients of NACA1 and MEL3 at L=3m, however its effect is large at L=6m. It seemed that the effect of turbulent intensity on the power coefficient increase with increasing vortex scale. In other words, the wind turbines can pick up the turbulent wind power with large vortex scale and small turbulent frequency.

According to the results, MEL3 shows the highest performance for the natural winds.

Conclusions

The paper presents the performances of the five prototype wind turbines for simulated natural wind. The rotors are newly designed, which are based on NACA five number series and MEL002 blades.

According to the experimental results, the conclusions are as follows.

1. The rotor MEL3 shows the highest performance in the five rotors for three kind of winds - steady and simulated natural winds. In particular, the maximum power coefficient in the simulated natural wind is as 130% large as one in the steady wind.
2. The effect of vortex scale on the power coefficient is large at vortex scale I=10%. The largest coefficient 0.4 occurs at tip-speed-ratio 2.3 with turbulent intensity I=10% and vortex scale L=10m.
3. The effect of turbulent intensity is small with small vortex scale L=3m.
4. The effect of turbulent intensity increases with increasing vortex scale. In the experiment, the MEL3-turbine could most gain the turbulent energy at I=10% and L=10m.
5. One can make large output power of the wind turbine through tailoring wind rotor design to turbulent character of installing location wind.

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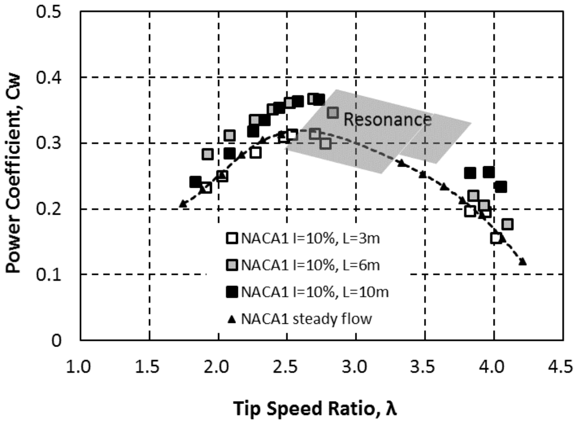

Fig. 5 Effect of vortex scale on power coefficient of NACA1 at I = 10%.

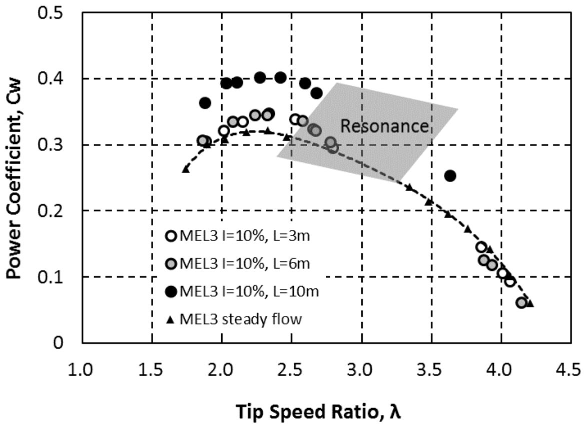

Fig. 6 Effect of vortex scale on power coefficient of MEL3 at I = 10%.

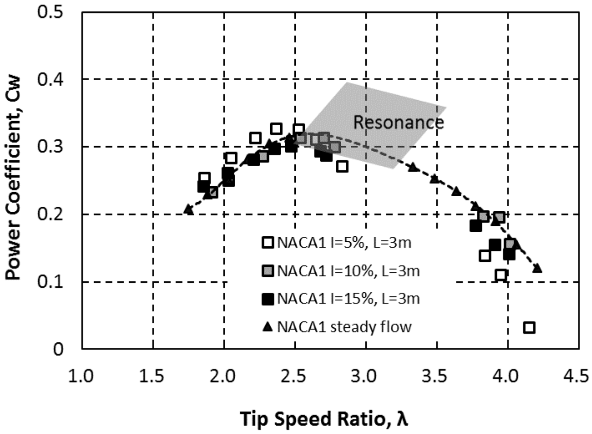

Fig. 7 Effect of turbulent intensity on power coefficient of NACA1 at L = 3m.

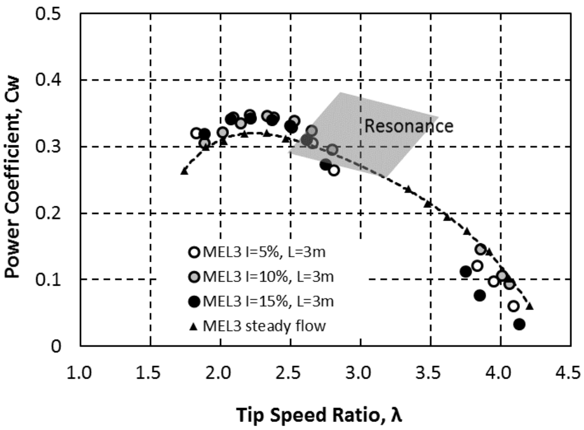

Fig. 8 Effect of turbulent intensity on power coefficient of MEL3 at L=3m.

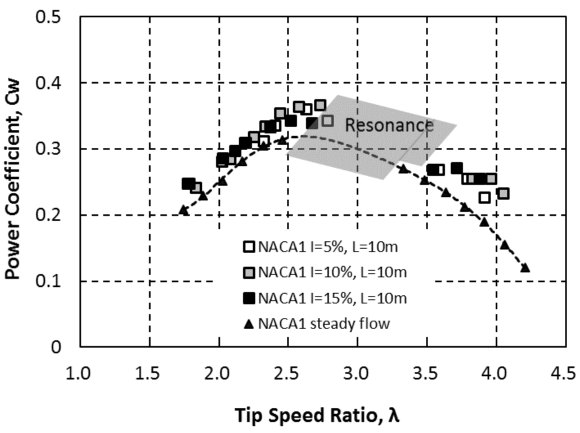

Fig. 9 Effect of turbulent intensity on power coefficient of NACA1 at L = 10m

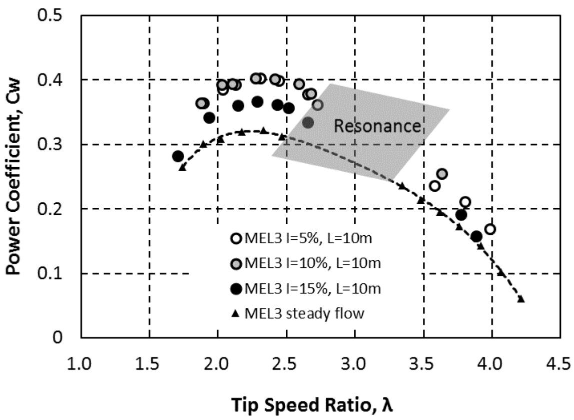

Fig. 10 Effect of turbulent intensity on power coefficient of MEL3 at L=10m.

Industrial Science and Technology of Japan) for providing MEL blade data.

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