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Wind Tunnel Study on Wind and Turbulence Intensity Profiles in Wind Turbine Wake

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In recent years, there has been a rapid development of the wind farms in Japan. It becomes very important to investigate the wind turbine arrangement in wind farm, in order that the wake of one wind turbine does not to interfere with the flow in other wind turbines. In such a case, in order to achieve the highest possible efficiency from the wind, and to install as many as possible wind turbines within a limited area, it becomes a necessity to study the mutual interference of the wake developed by wind turbines. However, there is no report related to the effect of the turbulence intensity of the external flow on the wake behind a wind turbine generated in the wind tunnel. In this paper, the measurement results of the averaged wind profile and turbulence intensity profile in the wake in the wind tunnel are shown when the turbulence intensity of the external wind was changed. The wind tunnel experiment is performed with 500mm-diameter two-bladed horizontal axis wind turbine and the wind velocity in wake is measured by an I-type hot wire probe. As a result, it is clarified that high turbulence intensities enable to the entrainment of the main flow and the wake and to recover quickly the velocity in the wake.

Keywords: Horizontal axis wind turbine, Wake, Wind profile, Turbulence intensity, Power output

Introduction

Recently, wind power generation has become popular as one of the solutions for the global warming issue and exhaustion of fossil fuel. Therefore, installations of new wind farms are expected to increase. A wind farm is a wind power generation plant comprising many wind turbines. The wind passed through a wind turbine has lower velocity and higher turbulence, which would cause power loss in downstream side wind turbine. In previous works, the power reduction of the wind turbine operating in wake is reported [1]. For these reasons, the layout of wind turbines should be determined with consideration of the interference with each other. There is recommended wind turbine spacing by rotor diameter. The spacing is $10D$ in the prevailing wind direction and $3D$ in lateral direction [2]. In Japan, a lot of good potential wind sites are located in mountainous regions. The topography becomes interference for design of wind turbine layout in wind farm. Therefore, it is difficult to keep the recommended distance.

The research that has been conducting up to now has been dealing with simple observation of the wake flow in the wind tunnel and in the field. However, there is no report related to the effect of the turbulence intensity of the external flow on the wake behind a wind turbine generated in the wind tunnel. The purpose of this paper is to obtain basic data to estimate wind turbines interference in

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Nomenclature

D	rotor diameter (m)	x	longitudinal coordinate (m)
L	longitudinal distance from nozzle (m)	y	lateral coordinate (m)
TI	turbulence intensity	z	vertical coordinate (m)
U_{local}	mean longitudinal velocity with wind turbine (m/s)	**Greek letter**	
U'_{local}	mean longitudinal velocity without wind turbine (m/s)	σ	standard deviation of wind velocity
U_{main}	main flow wind velocity		

wind farms. In this paper, measurements of the velocity field in wake were performed for different turbulence intensities in the main flow in a wind tunnel.

Experimental Method

Experimental apparatus

Figure 1 shows the experimental apparatus. The wind tunnel has a 3600mm-diameter nozzle and a 6200mm length open test section. A two-bladed horizontal axis wind turbine of diameter D = 500 [mm] is used (Fig. 2). When the main wind velocity is 7m/s, the optimal tip speed ratio of the turbine is 3.4. The pitch angle of the wind turbine is fixed at 4 degrees, which is the optimal pitch angle. The upstream wind turbine was set at 750mm downstream from the nozzle center. The coordinate system is defined for the measurements, in which the x-axis, the y-axis and the z-axis are set in the streamwise, the lateral and the vertical directions, respectively. The origin is taken at the center of wind turbine rotor. The hub height is set at 2500mm from the floor. The wind profile in wake is measured by using an I-type hot wire probe attached on a positioning device as shown in Fig. 1.

In order to change the turbulence intensity, two turbulence grids which have different blockage ratios are applied. Figure 3 shows setting positions and photographs of these grids. As shown in Fig. 3, the coarse grid was set at honeycomb section of the wind tunnel. The fine grid was set at the nozzle outlet. The blockage rates of these grids are 0.391 and 0.438, respectively. Turbulent flows without grid, with the coarse one and with the coarse and fine ones were described as “Low turbulence”, “Medium turbulence” and “High turbulence”, in increasing order of averaged turbulence intensity. Figure 4 shows the change of turbulence intensities in the main flow generated by the grids. The horizontal axis represents the longitudinal distance from the nozzle outlet, L. The vertical axis represents the turbulence intensity, TI, which is defined as:

$$TI = \frac{\sigma}{U_{\mathrm{main}}} \tag{1}$$

where U_{main} and σ are the main flow wind velocity and the standard deviation of local wind velocity, respectively. In general, the local mean wind velocity is used as the denominator in definition (1) for the wind assessment. However, here the main flow wind velocity is used as the denominator in order to figure out not the wind velocity deficit but only the wind velocity variance in wake. As shown in Fig. 4, the turbulence intensity in “Low turbulence” remains about 0.5%. The one in “Medium turbulence” remains about 3%. The one in “High turbulence” decreases from 21% to 4% with increase of L.

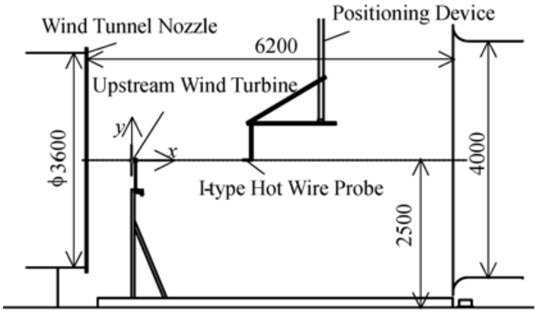


Fig. 1 Experimental apparatus for wind profile measurement.

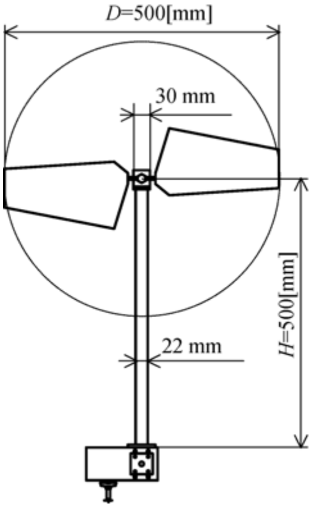
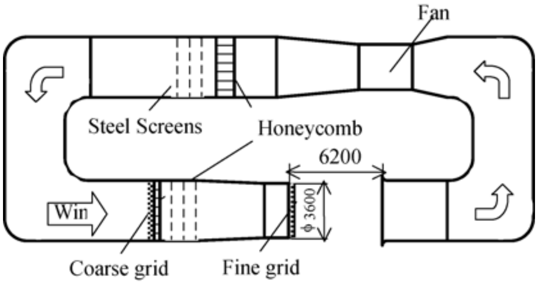
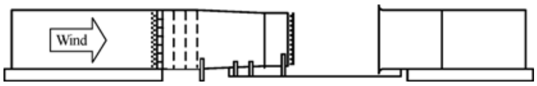


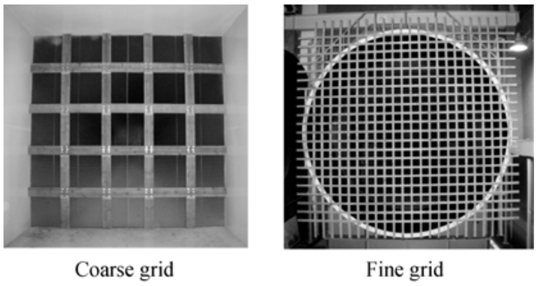
Fig. 2 Geometry of test wind turbine.



(a) Attachment positions of grids (Top view)



(b) Attachment positions of grids (Side view)



(c) Photographs of grids

Fig. 3 Turbulence grids.

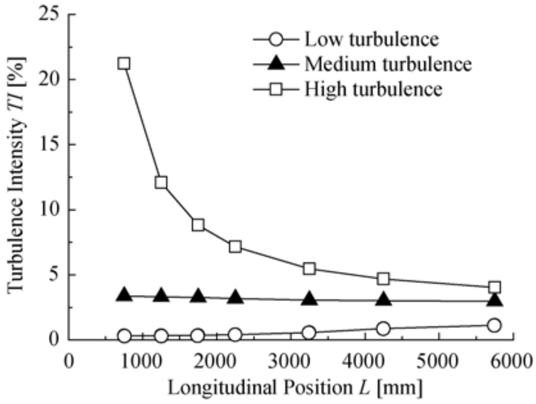


Fig. 4 Turbulence intensity in main flow.

Experimental conditions

The main flow velocity is fixed at 7m/s at x=5000 [mm]. In the measurements, the upstream wind turbine was operated with the optimal tip speed ratio. The velocity and turbulence intensity distributions were measured by I-type hot wire anemometer at 6 positions in the longitudinal direction x/D=1, 2, 3, 5, 7 and 10 in the lateral range of -1000mm<y<1000mm with 40mm interval. The number of sampling data was 16384 at every measurement position with a sampling frequency of 1 kHz. In this experiment, the averaged x-axial velocity is used in the following discussions. The y-axial and z-axial velocities are not considered because these values are much lower than x-axial one.

Experimental Results and Discussions

Wind profiles in wake

Figure 5 shows the wind velocity profiles in wake generated by the upstream wind turbine for various turbulence intensities in main flow. The vertical and horizontal axes represent the non-dimensional longitudinal coordinate, x/D, and the non-dimensional lateral coordinate, y/D. One division of scale in the horizontal axis corresponds to a non-dimensional x-axial velocity of U_N=1, which is defined by:

$$U_{\mathrm{N}} = \frac{U_{\mathrm{local}}}{U'_{\mathrm{local}}} \tag{2}$$

where U_{local} and U'_{local} are mean local x-axial velocities respectively with and without the upstream wind turbine. As shown in Fig. 5, the velocity in wake increases and the deficit area expands symmetrically with increase of x/D. Near the wind turbine ((x/D)≤3), the velocity distribution shows a small peak around the y-axis because the wind energy isn't extracted inside of the blade root. For each condition of turbulent in main flow, slight differences are found in the velocity recovery. It seems that the turbulence enables a quick recovery of the wake velocity. These effects are caused by the high turbulence intensity promoting the entrainment of the main flow and wake.

Turbulence intensity profiles in wake

Figure 6 shows the turbulence intensity profiles in the wake generated by the upstream wind turbine. One division of scale in horizontal axis corresponds to the turbulence intensity of TI=20[%]. As for x/D=1, the turbulence intensity reaches a maximum value, about 20% at $|y/D|$=0.56 where the blade tip lies in all conditions. It seems that the result is due to large fluctuations of the tip vortex velocity which exist there. Comparing with Fig. 5 and Fig. 6, the region of the velocity deficit is roughly equivalent to the inside of the lateral positions of high turbulence intensity ($|y/D|\leq 0.56$). Therefore a tip vortex produces the highest turbulence in wake and separates the wake from the main flow. Near the wind turbine ($x/D\leq 3$), the turbulence intensity distribution also shows a small peak around y-axis because of the root vortices produced by the blade roots.

Effects of turbulence on wake flow

Figures 7, 8 and 9 show the fluctuations of wind velocity in wake at longitudinal position x/D=1.0 at several lateral positions in conditions of low, midium and high turbulence, respectively. The vertical and horizontal axes

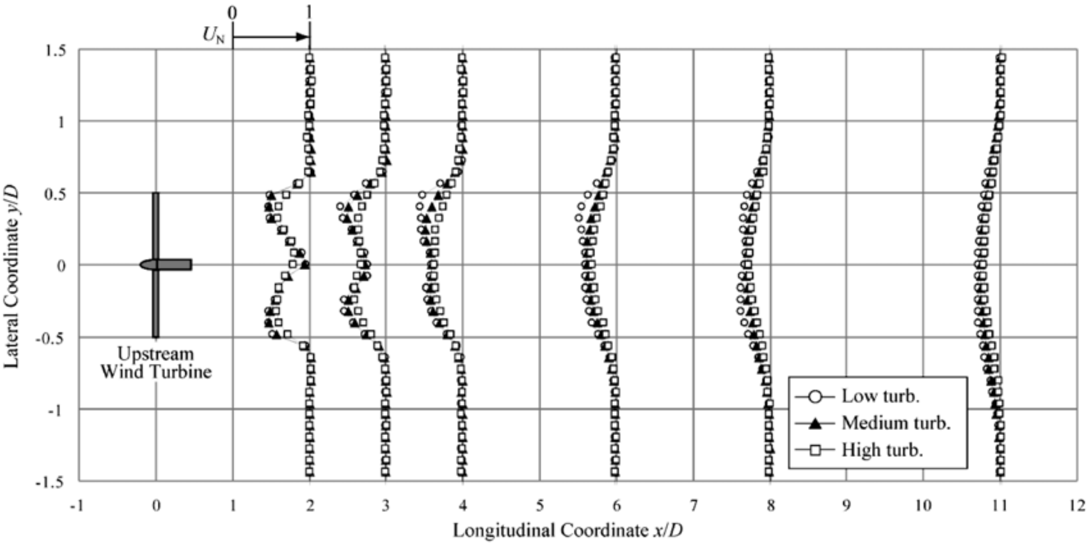


Fig. 5 Wind profiles in wake.

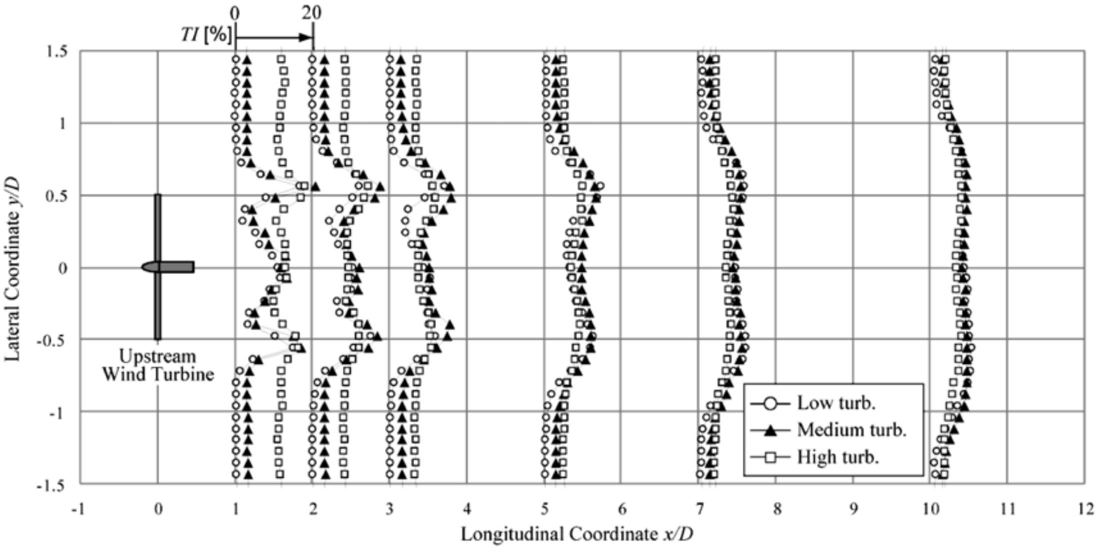


Fig. 6 Turbulence intensity distribution in wake.

represent the BIN averaged non-dimensional wind velocity U_N and the azimuth angle of upstream wind turbine. It must be noted that the anemometer are placed at 90 degrees azimuthal position so the blades at 90 and 270 degrees azimuth angle pass in front of the measurement point. In the condition of low turbulence (Fig. 7), two cycle fluctuation can be found in one rotor revolution. The fluctuation amplitudes are large around y/D=-0.5 downstream where the blade tips pass. The fluctuations show opposite peaks at inner (y/D>-0.5) and outer (y/D<-0.5) regions of the rotor. It is because of the approach and passage of tip vortices generated by two blades. For medium turbulence (Fig. 8), almost the same fluctuation can be seen, however the fluctuation amplitude is smaller than that for low turbulence. Furthermore, clear fluctuation does not appear in high turbulence condition during rotor rotation (Fig. 9).

In order to clarify the effect of turbulence on wake vortex structure, frequency analysis is performed for the fluctuation of wind velocity. Figures 10, 11 and 12 show the power spectrum densities of wind velocity fluctuation in wake at x/D=1.0, y/D=-0.56 with that measured in main flow without the upstream wind turbine. At any turbulence conditions, the power spectrum densities are higher than that in main flow. In low turbulence condition (Fig. 10), the spectrum peaks are found at integral multiples of 15.8Hz, and the highest peak is at 31.6Hz. They correspond to the rotational frequency of wind turbine (950r/min, that is, 15.8Hz) and the blade passage frequency (15.8×2=31.6[Hz]), respectively. For medium

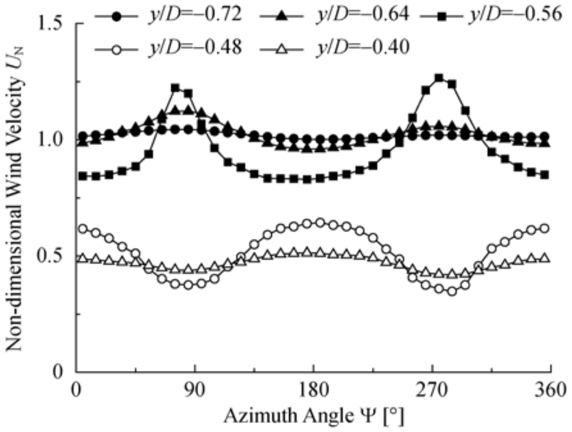


Fig. 7 Fluctuation of wind velocity in wake. (x/D=1.0, Low turbulence)

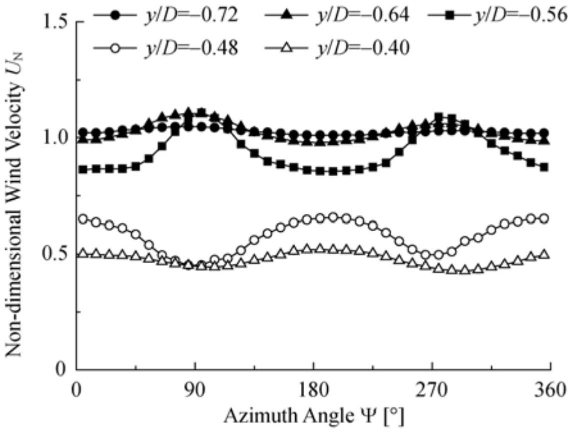


Fig. 8 Fluctuation of wind velocity in wake. (x/D=1.0, Medium turbulence)

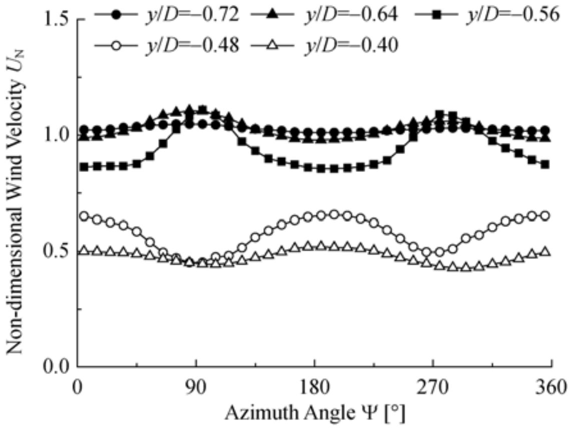


Fig. 9 Fluctuation of wind velocity in wake. (x/D=1.0, High turbulence)

turbulence (Fig. 11), the spectrum peaks exist only at the integral multiples of double rotational frequency. Although the general level of spectrum increases with turbulence, the value of double rotational frequency peak is lower than that for the low turbulence. In high turbulence condition (Fig. 12), there are no spectrum peaks. It means that the tip vortex structure is scattered by turbulence, and it isn't preserved with high turbulence.

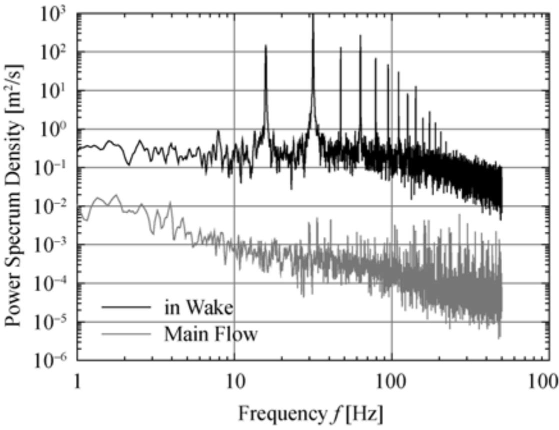


Fig. 10 Power spectrum density of wind velocity. (x/D=1.0, y/D=–0.56, Low turbulence)

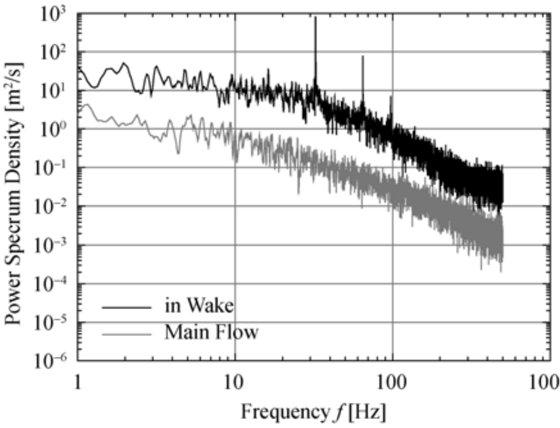


Fig. 11 Power spectrum density of wind velocity. (x/D=1.0, y/D=–0.56, Medium turbulence)

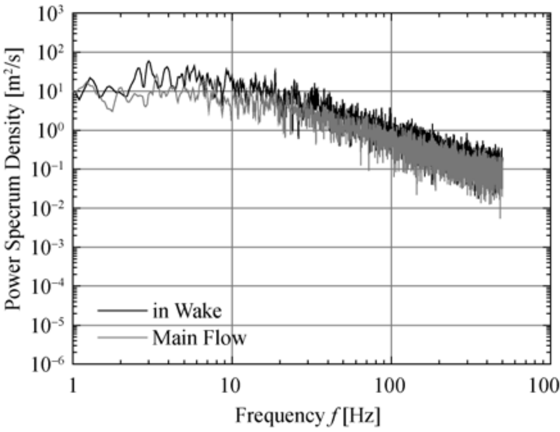


Fig. 12 Power spectrum density of wind velocity. (x/D=1.0, y/D=–0.56, High turbulence)

Conclusions

Using a hot wire anemometer, the velocity distribution was measured in the wake generated by a wind turbine. The following were clarified by these measurements.

The turbulence of main flow influences the profile of wind turbine wake. High turbulence intensities enable to entrainment of the main flow and the wake and to recover quickly the velocity in the wake.

The maximum values of turbulence intensity in the wake are generated at near the blade tips and almost the same as in any turbulent condition.

The tip vortex structure is scattered by turbulence, and it isn't preserved with high turbulence.

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