

PAPER

Radiation characteristics of noise generated from a wind turbine

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Abstract: In Japan, the development of large-scale wind power generation facilities has been promoted since about 2000. Nationwide investigations of the acoustic characteristics of wind turbine noise have been conducted at various wind farms. In this study, to examine the horizontal and vertical radiation characteristics of noise generated from wind turbines, field measurements of noise from a single wind turbine with a rated power of 1.5 MW have been performed. Some receiving points were set circularly around the wind turbine and mounted on a nearby lightning tower. Meteorological and associated wind turbine operational data were collected at 1 s intervals along with corresponding acoustic data. In addition, the sound pressure level distributions at distances of 50 m to 200 m from the wind turbine were investigated. Results revealed distinguishable horizontal directivity of wind turbine noise. The A-weighted sound pressure levels in the crosswind direction are almost 5 dB lower than those in the up- and downwind directions. Furthermore, it has been found that the sound directivity around the wind turbine could be expressed by a simple empirical formula, assuming the wind turbine to be a point source with combined bi- and omnidirectional patterns.

Keywords: Wind turbine noise, Sound directivity, Output power, Rotor rotational speed, Noise propagation

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1. INTRODUCTION

The noise generated from wind turbines is classifiable as aerodynamic or mechanical sound as a whole [1–3]. Aerodynamic sound is generated when the rotor blade passes through the air, and mechanical sound is emitted by some equipment in the nacelle, such as the gearbox, generator, and cooling fan. Wind turbine noise has affected nearby residents and has often been perceived as annoying. For this reason, wind power generation facilities were added to the projects subject to the Environmental Impact Assessment Law in Japan in October 2012.

Various investigations of wind turbine noise including low-frequency components have been conducted in Japan [4–8], as in many other countries. Tachibana *et al.* [4,5] performed nationwide noise measurements and a questionnaire survey at residential areas around wind farms. The results showed that almost all wind turbine noise has a similar spectral characteristic, whereas tonal components are seen in some data.

Regarding the directivity of the emitted noise, some studies based on aerodynamic sound theories and experiments have been carried out [2,6,8–14]. Oerlemans, Boorsma and Schepers [9,10] have demonstrated that the A-weighted sound pressure levels in the crosswind direction are lower than those in the up- or downwind direction; however, these results were obtained by noise measurement under limited wind conditions. In addition, few studies have focused on the frequency dependence of the sound directivity [2,13].

In this study, to assess the horizontal and vertical radiation characteristics of noise generated from wind turbines under various wind conditions, field measurements of noise around a single wind turbine have been performed over eight days in three months [15,16]. The directivities of the dominant frequency components of wind turbine noise

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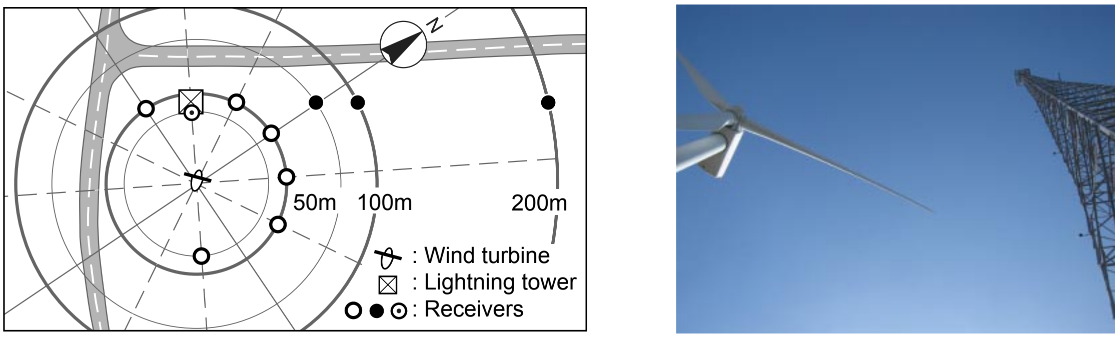

Fig. 1 Arrangement of receiving points around a wind turbine and a lightning tower used for vertical noise measurements.

were examined. In addition, we investigated temporal variations in wind turbine noise and the dependences of the increase in the sound pressure level on the wind speed at the hub height, the output power, and the rotor rotational speed. Moreover, the sound pressure level distributions at distances of up to 200 m were investigated in consideration of the horizontal directivity of wind turbine noise.

2. METHODS FOR MEASUREMENT AND ANALYSIS

Measurements were performed around a single wind turbine installed on flat hard soil over eight days in Nov. and Dec. 2010 and Mar. 2011. The turbine has an upwind rotor diameter of 70.5 m and a hub height of 65 m. Its rated wind speed, output power, and rotor rotational speed are 12 m/s, 1.5 MW, and 20 rpm, respectively. This turbine has been operated since Nov. 2003 and is periodically inspected once a year. To assess the directional characteristics of wind turbine noise, six receiving points (○, sound level meter: ONOSOKKI LA-1440) were set circularly around the wind turbine at 30° intervals, as shown in Fig. 1. These points at a height of 1.2 m were placed at a horizontal distance of 50 m except for one point (distance of 40 m). To examine noise propagation from the wind turbine, three receiving points (●) were additionally placed at distances of 80 m, 100 m, and 200 m for two days. We also mounted four microphones (⊙) at 2.5 m, 30 m, 45 m, and 65 m heights on a nearby lightning tower to measure the vertical distribution of wind turbine noise, as presented in Fig. 1. An all-weather-type windscreen with a diameter of 20 cm was installed on each microphone. All acoustic signals measured using the A-frequency weighting were recorded on PCM recorders (SONY PCM-M10, 48 kHz sampling, 16 bits).

After field measurements, the A-weighted sound pressure levels in 1/3 octave bands for the frequency range from 50 Hz to 5 kHz were analyzed at 200 ms intervals ($L_{p,200\text{ms}}$) from the recordings. These instantaneous levels were stored through the FAST time-weighting characteristic of a signal analyzer (RION SA-01A4). In this analysis, periods with intruding intermittent background noise such as road vehicle noise, aircraft noise, and wind-induced noise at a microphone were omitted through hearing checks. In particular, to eliminate data including wind-induced noise as accurately as possible, instantaneous changes in the 1/3 octave band spectrum due to wind were checked carefully while reproducing the sound. In addition, with the wind turbine stopped forcibly during noise measurements, background noise was measured under various wind speeds, and the residual noise levels ($L_{\text{A95,10min}}$ in 1/3 octave bands) were checked.

In this study, to grasp general patterns of the sound directivity around the wind turbine, the time-averaged sound pressure levels in 1/1 octave bands over 10 s ($L_{p\text{eq,10s}}$) were calculated using the analyzed results. All data measured at a distance of 40 m were converted to those at a distance of 50 m in consideration of the difference in the attenuation of geometrical spreading for a point source set at the rotor center.

3. MEASUREMENT RESULTS

3.1. Meteorological and Wind Turbine Operational Conditions

Meteorological and associated wind turbine operational data (wind speed at hub height, nacelle direction, output power, and rotor rotational speed) were also collected at 1 s intervals. These mean values were calculated over 10 s periods, synchronized with acoustic data. Wind is measured with an anemometer mounted on the nacelle behind the upwind rotor. The effect of the rotating blades could be included in the measurement data of wind direction and speed.

The distributions of the mean wind speed and direction during noise measurements are presented in Fig. 2. The wind directions were predominantly from the west (W) to east-southeast (ESE). Therefore, almost all acoustic data were obtained in front of the wind turbine (in the upwind direction).

Figure 3 shows wind turbine operational conditions during measurements. The solid line in Fig. 3(a) represents

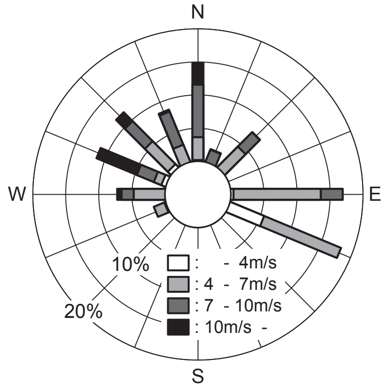

Fig. 2 Wind rose measured at hub height during noise measurements.

the power curve for this wind turbine. The noise measurements were performed over the range from the cut-in wind speed of 3 m/s to the rated wind speed. The rotor speed increases linearly with increasing wind speed and reaches the rated rotor speed at a mean wind speed of approximately 9 m/s (see Fig. 3(b)). Then, at the rated rotor speed, the output power is within the range from 900 kW to the rated output power (see Fig. 3(c)).

3.2. Temporal Variations in Wind Turbine Noise

Figure 4 shows an example of measured A-weighted sound pressure levels in 1/1 octave bands at 200 ms intervals and wind turbine operational data at 1 s intervals when the wind speed at hub height varied strongly for almost 3 min. The receiving point was −30° relative to north (see Fig. 1) and the nacelle direction (D_{nac}) was 45°, that is, the direction of the measuring position was −75° relative to the upwind direction of the wind turbine.

The wind speed (V_{nac}) varied rapidly between 5 m/s and 10 m/s. In response to the wind speed, the magnitude of changes in the A-weighted sound pressure level was almost 10 dB in only a few minutes. Additionally, the changes in the sound pressure level appear to depend not only on the wind speed but also on the output power (P_m) and rotor speed (V_R).

Figure 5 shows examples of wind turbine noise plotted against the wind speed at hub height. The circles in the figure represent measured $L_{Aeq,10s}$ within ±30° relative to the up- and crosswind directions. The level of wind turbine noise increases concomitantly with increasing wind speed. For this wind turbine, the increase in the level was about 15 dB within the range of the cut-in to rated wind speed. However, the correlation between $L_{Aeq,10s}$ and wind speed is not so strong. The scatter of $L_{Aeq,10s}$ was up to almost 8 dB in each wind speed interval from 5 m/s to 8 m/s, because the change in the wind speed is rapid as well as irregular under actual meteorological conditions, as presented in Fig. 4.

Figure 6 shows the same measured data $L_{Aeq,10s}$ as those presented in Fig. 5 but plotted as a function of the output power. The correlation between them is extremely strong compared with the result using the wind speed. The A-weighted sound pressure levels in the crosswind direction tend to be lower than those in the up- and downwind directions. For this wind turbine, the noise increases slightly as the output power rises beyond 900 kW, at which point the rotor speed reaches the rated speed (see Fig. 3(c)). Moreover, the A-weighted sound pressure levels in all directions increase almost linearly up to the rated rotor speed, as shown in Fig. 7.

Thus, the acoustic characteristics of wind turbine noise can be explained adequately in terms of the output power or rotor rotational speed. In this study, the sound directivities around the wind turbine have been examined, focusing on the output power and rotor speed.

3.3. Changes in Sound Pressure Level

The dependences of the increase in the sound pressure level of wind turbine noise on the output power and rotor speed were examined. The 1/1 octave band sound pressure

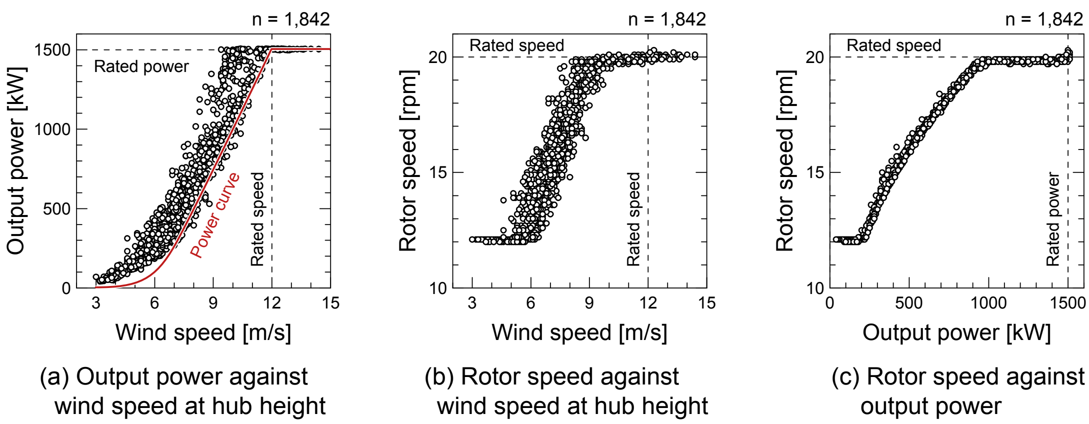

Fig. 3 Operational conditions of the wind turbine during noise measurements (n: number of data).

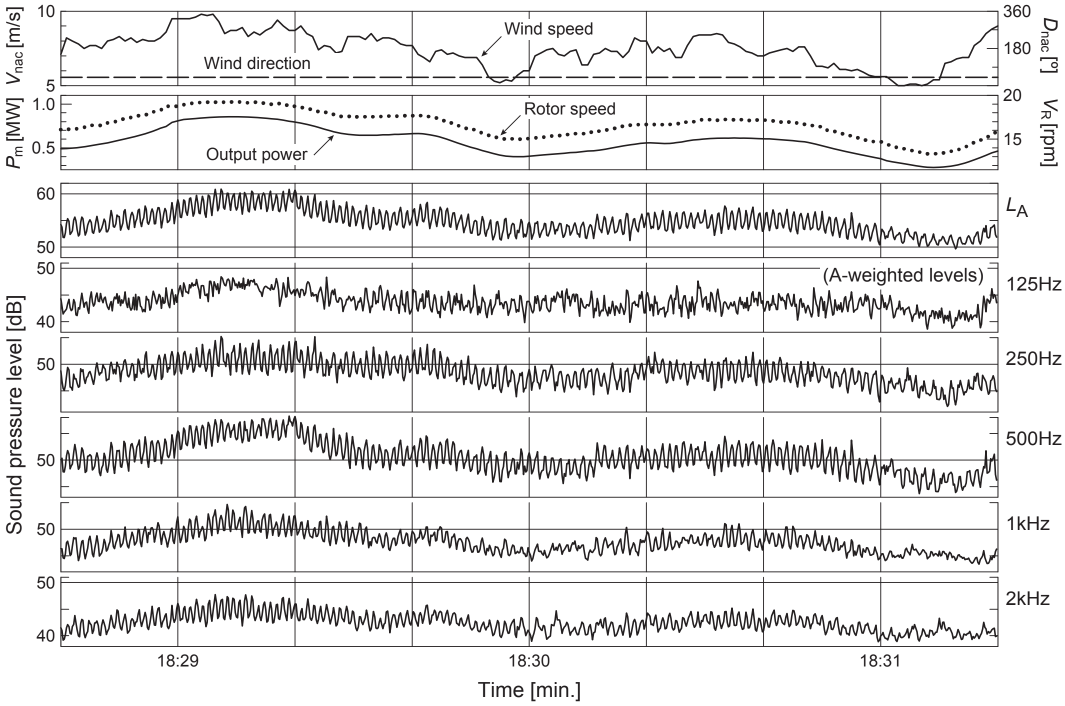

Fig. 4 Example of A-weighted sound pressure levels in 1/1 octave bands at 200 ms intervals and the wind turbine operational data at 1 s intervals. The direction of the measuring position was $-75°$ relative to the upwind direction.

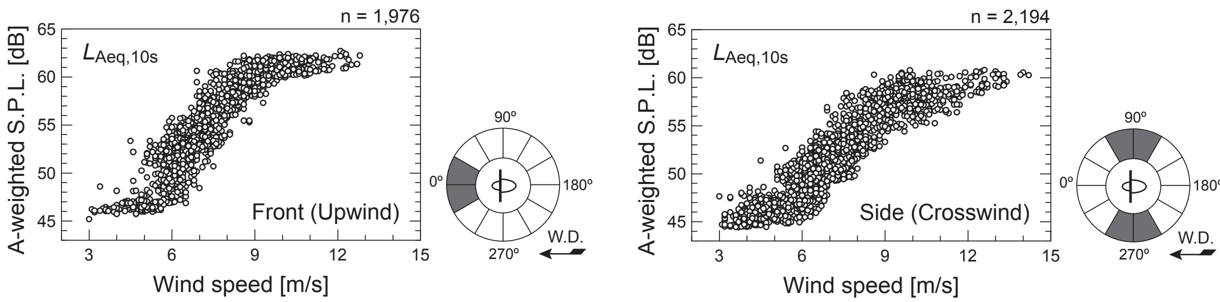

Fig. 5 Wind speed dependence of A-weighted sound pressure level (*n*: number of data, measuring positions are within $\pm 30°$ relative to the up- and crosswind directions of the wind turbine).

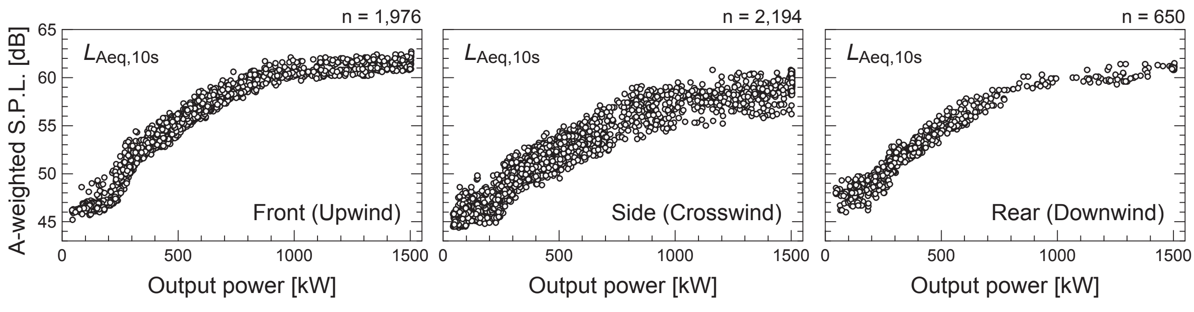

Fig. 6 Output power dependence of A-weighted sound pressure level (*n*: number of data, up-, cross-, and downwind directions).

levels with A-frequency weighting were averaged arithmetically at 100 kW and 0.5 rpm intervals, respectively. Figure 8 shows the mean values within $\pm 30°$ relative to the upwind direction. It is apparent that the sound pressure levels at a frequency of 500 Hz or more increase monotonically with increasing output power as well as rotor speed. The noise generated from this wind turbine was dominated by middle-frequency components of 250 Hz, 500 Hz, and

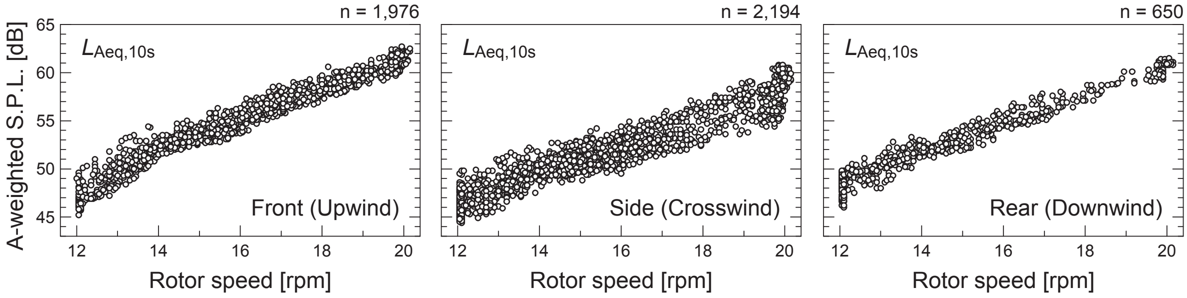

Fig. 7 Rotor speed dependence of A-weighted sound pressure level (n: number of data, up-, cross-, and downwind directions).

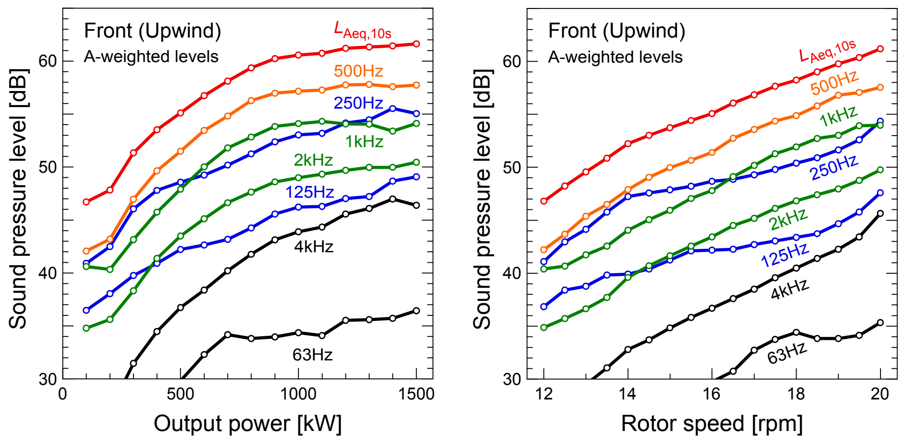

Fig. 8 Mean A-weighted sound pressure level in 1/1 octave bands plotted against output power and rotor speed. Measuring positions are within ±30° relative to the upwind direction.

1 kHz, even if the generated electrical power is low at hub height wind speeds of below about 6 m/s.

3.4. Horizontal Radiation Characteristics of Wind Turbine Noise

In order to examine the horizontal radiation characteristics of wind turbine noise, the A-weighted sound pressure levels in 1/1 octave bands were averaged arithmetically at 15° intervals using measured data within ±7.5° relative to each direction. The direction of the measuring position was determined from each receiving point and the nacelle direction. In addition, the measured data were divided into three groups in consideration of the dependence of the emitted noise on the output power or rotor speed.

Figure 9 shows these results under three operational conditions at output powers of 400–600 kW (15–17 rpm), 600–900 kW (17–20 rpm), and 900–1,500 kW (20 rpm), assuming the sound radiation to be symmetrical with the nacelle direction [11]. The A-weighted sound pressure levels $L_{\mathrm{Aeq,10s}}$ in the up- and downwind directions are almost the same, although the total number of obtained data in the upwind direction was lower than that in the downwind direction. The A-weighted sound pressure levels in the crosswind direction of the nacelle tend to be almost 5 dB lower than those in the up- or downwind directions.

Furthermore, similar sound directivity for $L_{\mathrm{Aeq,10s}}$ can be recognized at dominant components of 250 Hz, 500 Hz, and 1 kHz, regardless of the wind turbine operational conditions. As a result, distinguishable horizontal directivity of wind turbine noise was found. To assess the emitted noise more accurately, the direction of the measuring position relative to the wind turbine should be taken into consideration.

3.4.1. Empirical formula for directivity correction

Several calculation methods for the sound directivity around a wind turbine have been proposed on the basis of aerodynamic sound theories or semi-empirical prediction methods [2,9–12]. To simplify the modeling of the directivity pattern of wind turbine noise, we have focused on the difference between the sound pressure levels in the up- or downwind direction and those in the other directions, which was obtained through field measurements. A simple regression formula was applied, assuming the directivity pattern of aerodynamic and mechanical sound to be bi- and omnidirectional, respectively. The directivity correction $\Delta L_{\mathrm{dir},\theta}$ is expressed by combining both directional patterns as follows:

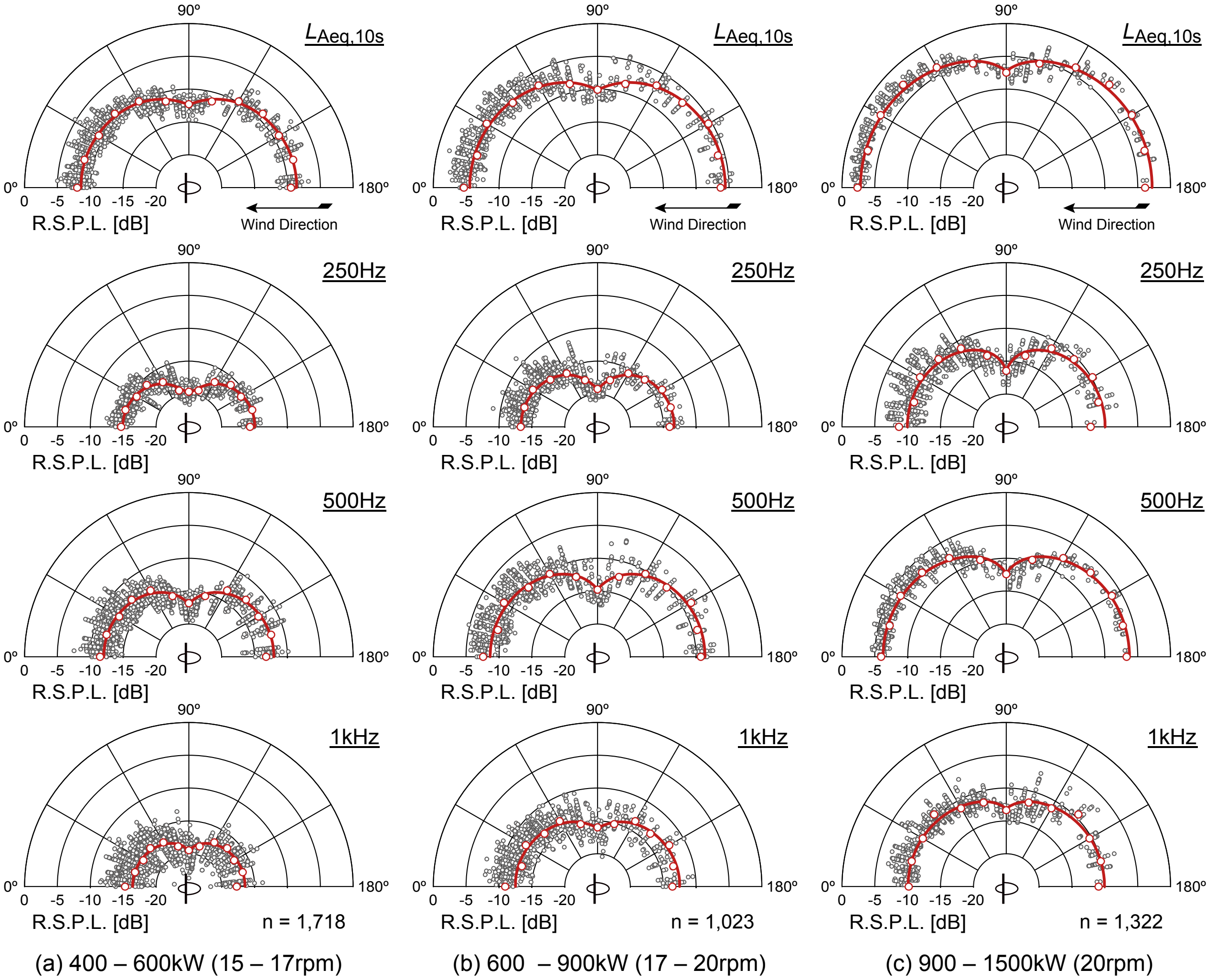

Fig. 9 Horizontal distribution of relative sound pressure level of wind turbine noise and calculated mean level at 15° intervals for three output power ranges (○: arithmetically averaged levels, –: $\Delta L_{\mathrm{dir},\theta}$ calculated using Eq. (1) and Table 1, n: number of data).

Table 1 Coefficients a, b for empirical sound directivity formula and correlation coefficient r.

Output power [kW]	Rotor speed [rpm]	$L_{\mathrm{Aeq,10s}}$			250 Hz			500 Hz			1 kHz		
		a	b	r	a	b	r	a	b	r	a	b	r
900–1,500	20	2.0	0.7	0.94	3.7	0.8	0.91	3.3	0.8	0.98	1.2	0.6	0.88
600–900	17–20	1.9	1.0	0.96	2.9	1.3	0.99	3.1	1.0	0.96	1.3	1.0	0.86
400–600	15–17	1.4	1.0	0.95	2.1	1.5	0.98	2.1	1.0	0.95	1.1	0.8	0.86

$$\Delta L_{\mathrm{dir},\theta} = 10\,\mathrm{lg}\left(\frac{1 + a|\cos^b \theta|}{1 + a}\right), \qquad (1)$$

where θ is the direction of the measuring position relative to the wind turbine ($0^\circ \leq \theta \leq 360^\circ$) and a and b are coefficients for the sound directivity.

The coefficients a and b were derived from the A-weighted sound pressure levels in 1/1 octave bands, as presented in Fig. 9. Table 1 shows the coefficients obtained for each dominant frequency component and the correlation coefficient r. The solid lines in Fig. 9 indicate the calculated directivity correction $\Delta L_{\mathrm{dir},\theta}$ using the coefficients a and b for each wind turbine operational condition.

All values of the correlation coefficient r are more than 0.86, and the calculated $\Delta L_{\mathrm{dir},\theta}$ agree reasonably well with the measured sound pressure levels. The coefficients a and b depend on the frequency band and output power. For example, the coefficients a and b for the A-weighted sound pressure level $L_{\mathrm{Aeq,10s}}$ are within 1.4–2.0 and 0.7–1.0, respectively.

Table 2 Calculated level difference $\Delta L_{dir,90^\circ}$ relative to the up- or downwind direction of the wind turbine.

Output power [kW]	Rotor speed [rpm]	$\Delta L_{dir,90^\circ}$ [dB]			
		$L_{Aeq,10s}$	250 Hz	500 Hz	1 kHz
900–1,500	20	−4.8	−6.7	−6.3	−3.4
600–900	17–20	−4.6	−5.9	−6.1	−3.6
400–600	15–17	−3.8	−4.9	−4.9	−3.2

Table 2 shows the calculated differences in the sound pressure level $\Delta L_{dir,90^\circ}$ in the crosswind direction compared with that in the up- or downwind direction. The level difference tends to increase slightly with increasing output power. The magnitude of the level difference also depends on the frequency band. At an output power of above 900 kW, at which the rated rotational speed is achieved, the difference in $L_{Aeq,10s}$ is almost 5 dB and the level differences at 250 Hz and 500 Hz are 6–7 dB and almost 3 dB at 1 kHz.

3.5. Vertical Radiation Characteristics of Wind Turbine Noise

To examine the vertical radiation characteristics of noise generated from the wind turbine, the mean A-weighted sound pressure levels in 1/1 octave bands were calculated using data measured by four microphones mounted at heights of 65 m, 45 m, 30 m, and 2.5 m on a nearby lightning tower. The horizontal distances from the wind turbine to the receiving points were 40–45 m and the rotor blade radius was about 35 m, as presented in Fig. 1. To avoid the influence of wind-induced noise at the microphones or the steel columns of the lightning tower, instantaneous changes in the 1/3 octave band spectrum due to wind were checked carefully during analysis, as mentioned in Sect. 2.

Figure 10 shows examples of the vertical distribution of wind turbine noise measured within ±30° relative to the downwind direction, which is to the rear of the wind turbine. These results represent the mean and standard deviation of the A-weighted sound pressure levels in 1/1 octave bands at a wind speed of lower than 7 m/s (at which the output power is in the range of 50–600 kW). Because the effect of wind-induced noise on the measurement was greater at a high position than near the ground, the numbers of data at the above heights from the hub (65 m) to near the ground (2.5 m) were 83, 84, 85, and 254, respectively.

The differences between the mean levels at heights from the hub (65 m) to the rotor tip (35 m) and those near the ground (2.5 m) were almost 2 dB. Note that the effects of the difference in distance between the sources (e.g., rotor blades and nacelle) and each receiver as well as reflections by obstacles such as the ground are included in these results. No marked difference was found in the vertical distribution of the sound pressure levels of the wind turbine from an engineering perspective.

3.6. Noise Propagation from the Wind Turbine

Measurement of the noise propagating from the wind turbine was carried out at the same site over two days. The receiving points at a height of 1.2 m were additionally set at horizontal distances of 80 m, 100 m, and 200 m from the wind turbine (see Fig. 1). The distance of the receiving point at 100 m is equal to the reference distance, as described in IEC 61400-11:2012 [17].

Figure 11 shows comparisons between the distributions of the relative sound pressure levels $L_{Aeq,10s}$ at distances of 80 m and 100 m and the calculated mean values $L_{Aeq,10s}$ at a

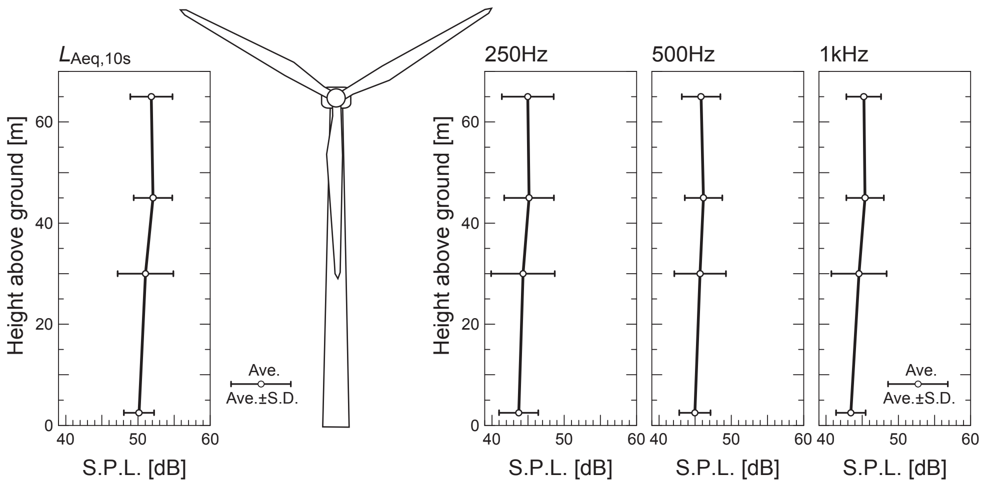

Fig. 10 Vertical distribution of mean and standard deviation of the A-weighted sound pressure levels in 1/1 octave bands measured within ±30° relative to the downwind direction (output power of 50–600 kW, hub height wind speed of 3–7 m/s).

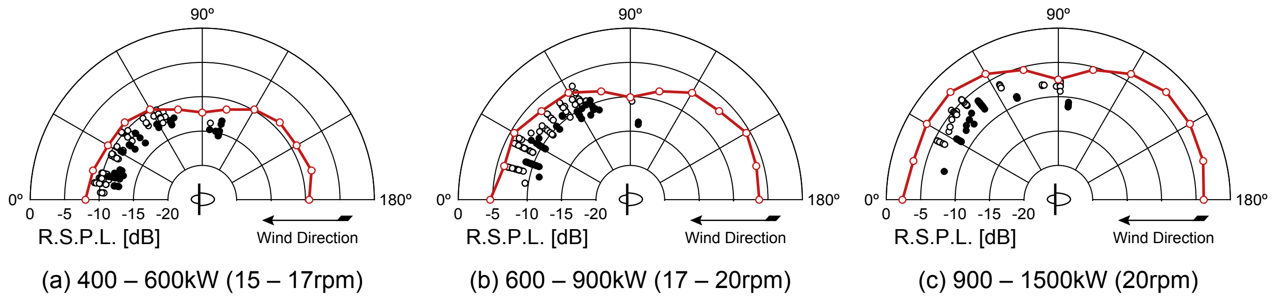

Fig. 11 Comparison between relative sound pressure levels of wind turbine noise at horizontal distances of 80 m and 100 m and the mean level at 50 m for three output power ranges (–: 50 m, ○: 80 m, ●: 100 m).

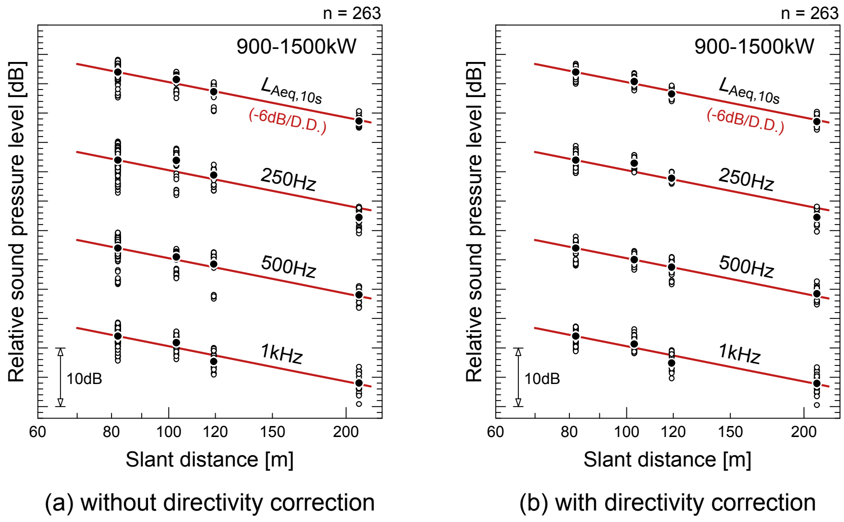

Fig. 12 Distributions of the A-weighted sound pressure levels in 1/1 octave bands at horizontal distances of up to 200 m shown against slant distance (●: mean sound pressure levels, –: calculated attenuations for a point source, n: number of data).

distance of 50 m (see Fig. 9). The A-weighted sound pressure levels at horizontal distances of 80 m and 100 m in the crosswind direction tend to be lower than those in the other directions, as seen in the measurement results around the wind turbine. Consequently, attention should be paid to the nacelle direction during noise measurement for determining the apparent sound power level of wind turbines, as mentioned in IEC 61400-11.

Next, the sound pressure levels considering the sound directivity were compared with those without it. The directivity corrections $\Delta L_{\mathrm{dir},\theta}$ were calculated using the direction of the measuring positions relative to the wind turbine and added to the measurement data.

Figure 12 shows results at an output power of 900 kW or more plotted against the slant distance (D_{slant}) from the rotor center to the receiver. Filled circles in the figure indicate the mean A-weighted sound pressure levels in 1/1 octave bands at horizontal distances of 50–200 m ($D_{\mathrm{slant}} = 82.0 - 210.3$ m). Solid lines show values calculated from the attenuation of geometrical spreading for a point source set at the rotor center. These lines were fitted to the mean levels (●) at a horizontal distance of 50 m ($D_{\mathrm{slant}} = 82.0$ m).

The attenuations at some distance from the wind turbine are almost the same as those for a point source as a whole. At horizontal distances of up to 100 m (D_{slant}: 119.3 m), the scattering of sound pressure levels with the directivity correction tends to be smaller than that without it. However, at a horizontal distance of 200 m, no marked difference was found in the sound pressure level distributions with and without the directivity correction. The principal reason for this is that the hub height wind speed was more than 9 m/s and the sound pressure level was considered to vary widely due to the influence of wind on sound propagation, as mentioned in previous studies [6,18]. However, it is necessary to examine detailed differences between the sound directivity at distant locations and that around wind turbines.

4. CONCLUSIONS

Noise emitted from wind turbines is divisible into aerodynamic sound generated at the blades and mechanical sound from the nacelle components. In this experimental study, to investigate the horizontal and vertical radiation characteristics of wind turbine noise under various wind conditions, field measurements have been performed around a large-scale single wind turbine over eight days in three months. Results show distinguishable horizontal directivity of wind turbine noise, whose pattern can be expressed by a simple empirical formula, assuming the wind turbine to be a point source with combined bi- and omnidirectional patterns. The A-weighted sound pressure levels in the crosswind direction are almost 5 dB lower than those in the up- and downwind directions. In addition, no marked differences in the vertical distribution of the sound pressure levels of the wind turbine are apparent from an engineering perspective. Furthermore, obtaining associated wind turbine operational data such as the output power, rotor rotational speed, and nacelle direction is strongly recommended to assess the acoustic characteristics of wind turbine noise more accurately.

In the future, to validate the horizontal radiation characteristics of the emitted noise obtained in this experiment, the authors intend to conduct noise measurements at another wind turbine site. In addition, it is necessary to examine the tonal components included in mechanical sound emitted from wind turbines to evaluate noise annoyance as well as the directivity of wind turbine noise at long distances to predict noise propagation.

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