

TECHNICAL REPORT

Horizontal directivity of sound emitted from wind turbines

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Abstract: Field measurements of noise generated from two different wind turbines, one with an upwind rotor and one with a downwind rotor, have been performed. To examine the radiation characteristics of wind turbine noise, some receiving points were set around each wind turbine and the apparent A-weighted sound power levels were calculated from the obtained data at 200 ms intervals under various wind conditions. Wind turbine operational data were collected at 1 s intervals along with corresponding acoustic data. Additionally, a simple empirical formula for the sound directivity was proposed, assuming the directivity pattern of aerodynamic and mechanical sound to be bi- and omnidirectional, respectively. The results showed that the horizontal directivity of the A-weighted sound pressure level at the ground level for the two different wind turbines is almost the same, whereas the frequency dependence of the sound directivity is different for the individual wind turbines. Furthermore, obtaining data of the rotor rotational speed, output power, and nacelle direction is strongly recommended to assess the characteristics of noise emission, such as the changes in the sound power level, sound directivity, and tonal components of wind turbine noise.

Keywords: Radiation characteristic, Rotor rotational speed, Output power, Wind speed, Tonal components

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1. INTRODUCTION

The noise generated from operating wind turbines is classifiable as aerodynamic or mechanical sound as a whole. Aerodynamic sound is generated from the blade passing through the air, and mechanical sound is emitted by some equipment in the nacelle. Wind turbine noise is typically dominated by aerodynamic broadband sound but often has discrete tonal components which are included in mechanical sound [1,2].

Regarding the directional characteristics of wind turbine noise, some studies based on aerodynamic sound theories and experiments have been carried out [2–7]. Oerlemans and Schepers [3] and Friman [4] focused on the directivity of the trailing edge noise from the blade and evaluated the horizontal distributions of the overall A-

weighted sound pressure levels L_A in 1/3-octave bands at frequencies from 250 Hz to 800 Hz, respectively. Although the measurement data were collected under limited wind conditions, it was demonstrated that the overall levels L_A of the trailing edge noise in the crosswind direction are 4–6 dB lower than those in the up- and downwind directions. Evans and Cooper [5] presented the differences in the sound level ($L_{A90,1\text{ min}}$) with the measurement direction while operating a wind turbine, to assess the impact of noise on the environment around wind farms.

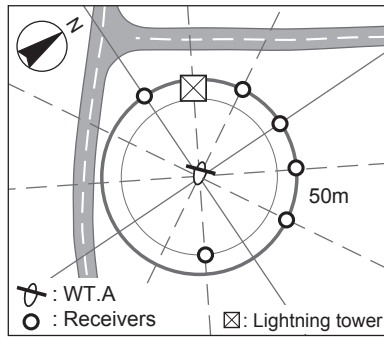
We have also examined the radiation characteristics of wind turbine noise under various wind conditions [8,9]. Field measurements of noise around a wind turbine with an upwind rotor have been performed to investigate the horizontal directivity of the A-weighted sound pressure level in 1/1-octave bands. In addition, a simple empirical formula for the directivity correction was applied to the measurement results. In the present work, to validate the sound directional characteristics revealed from the previous study, noise measurements around a different wind turbine

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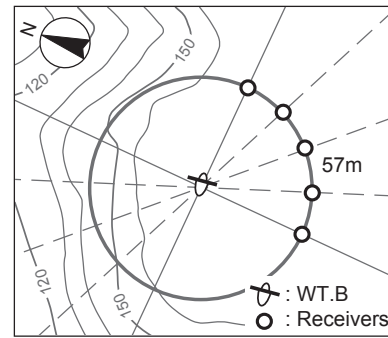
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(a) wind turbine A

Type of rotor	Upwind rotor		
Measurement period	8 days in 2011		
Rated power	1.5 MW	Rated rotor speed	20.0 rpm
Hub height	65.0 m	Cut-in wind speed	3.0 m/s
Rotor diameter	70.5 m	Rated wind speed	12.0 m/s



(b) wind turbine B

Type of rotor	Downwind rotor		
Measurement period	3 days in 2013		
Rated power	2.0 MW	Rated rotor speed	17.5 rpm
Hub height	80.4 m	Cut-in wind speed	4.0 m/s
Rotor diameter	80.0 m	Rated wind speed	13.0 m/s

Fig. 1 Arrangement of receiving points around each wind turbine (WT.A and WT.B).

with a downwind rotor were carried out [10] and the directivity patterns calculated by the empirical formula were compared with those obtained at a different site.

2. METHODS FOR MEASUREMENT AND ANALYSIS

Noise measurements were carried out around two different wind turbines, one over eight days in 2011 and the other over three days in 2013. Figure 1 shows the arrangement of the receiving points around the upwind and downwind turbines [9]. The upwind turbine (hereinafter referred to as WT.A) has been operated since 2003 and its rated output power, rotor rotational speed, and wind speed are 1.5 MW, 20 rpm, and 12 m/s, respectively. The specifications for the downwind turbine (hereinafter, WT.B), operated since 2012, are 2.0 MW, 17.5 rpm, and 13 m/s, respectively. These wind turbines were manufactured by different companies.

To examine the horizontal directivity of the sound generated from the wind turbines, six receiving points (○, sound level meter: ONOSOKKI LA-1440) were set circularly around WT.A at 30° intervals. These points were placed at a horizontal distance of 50 m except for one point (distance of 40 m). In the case of WT.B, five receiving points at 22.5° intervals were set at a distance of 57 m, considering the geographical features at the site. An all-weather-type windscreen with a diameter of 20 cm was installed on each microphone at a height of 1.2 m. 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 (e.g., road vehicles and aircraft) 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, the residual noise levels ($L_{A95,10\text{min}}$ in 1/3-octave bands) under various wind speeds were obtained and the influence of the residual noise on the measurements was checked.

To compare the characteristics of the sound generated from both wind turbines, the apparent A-weighted sound power levels (L_{WA}) were calculated using the time-averaged sound pressure levels over 10 s ($L_{peq,10\text{s}}$) and the attenuation of geometrical spreading from a point source set at the rotor center to each receiving point, in accordance with IEC 61400-11:2012 [11].

3. MEASUREMENT RESULTS

3.1. 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 synchronized with the acoustic data were calculated over 10 s periods. Figure 2 shows the operational conditions of the wind turbines during the measurements [9]. The solid line in the figure represents the power curve for each wind turbine. The

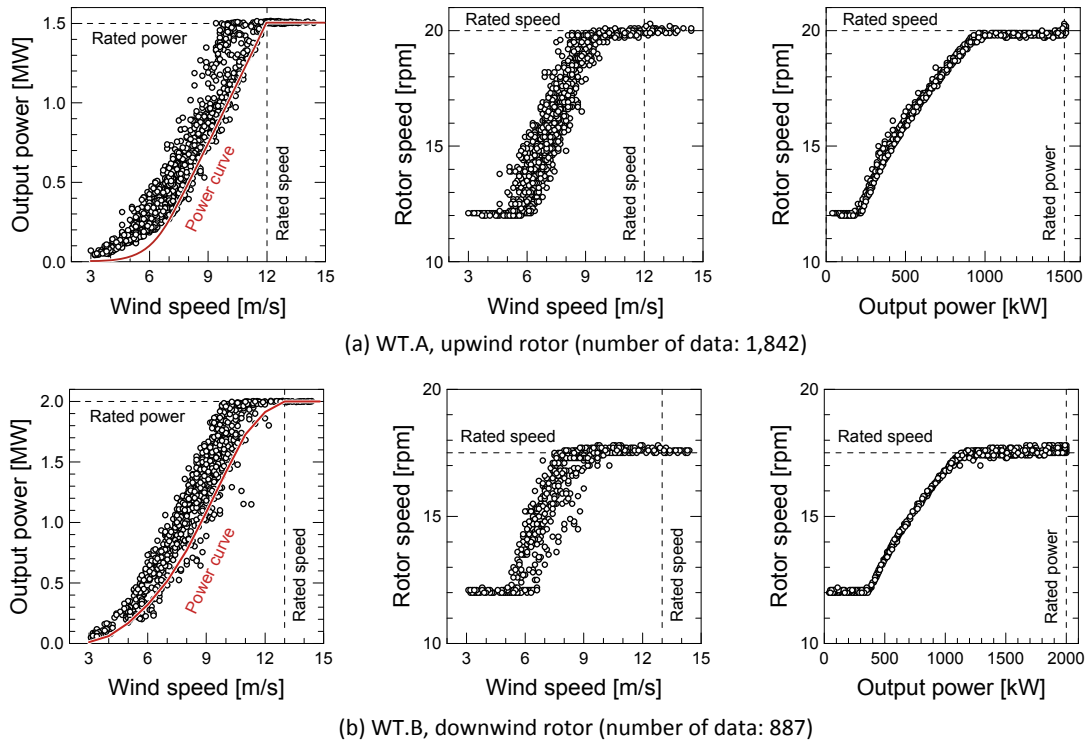


Fig. 2 Operational conditions of the wind turbines during noise measurements.

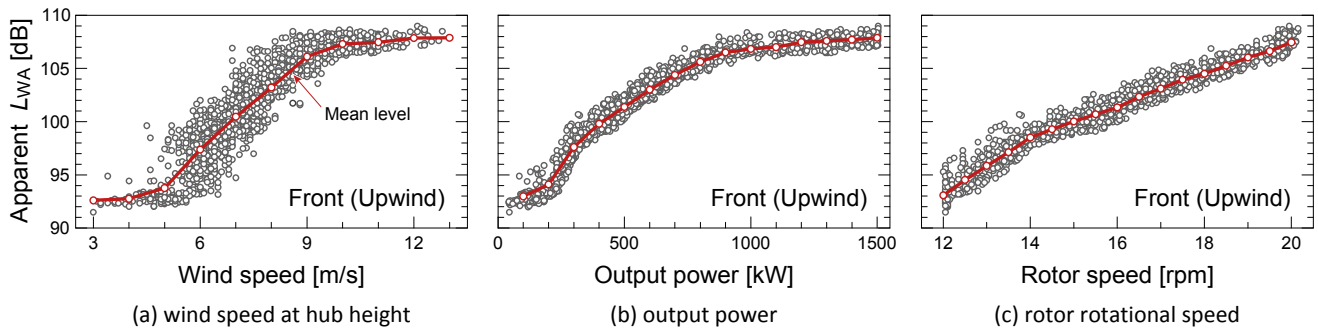


Fig. 3 Changes in apparent A-weighted sound power level with operational conditions. Measuring positions are within $\pm 30^\circ$ relative to the upwind direction of the wind turbine (WT.A, —: mean level, number of data: 1,976).

number of data was 1,842 for WT.A and 887 for WT.B. The noise measurements were made over the range from the cut-in wind speed to the rated wind speed. The rotor rotational speed reaches the rated speed (20/17.5 rpm) at a mean wind speed of approximately 9 m/s, whereas the rated wind speed is 12 m/s or 13 m/s. Then, at the rated rotor speed, the output power is respectively 900 kW or 1.1 MW, which is less than the rated power (1.5/2.0 MW). Thus, the changes in the operational conditions of both wind turbines exhibit similar behavior, despite their being manufactured by different companies.

3.2. Radiation Characteristics

Figure 3 shows examples of the apparent A-weighted sound power levels for WT.A plotted against the wind

speed at hub height, output power, and rotor rotational speed. The circles in the figures represent the measured L_{WA} within $\pm 30^\circ$ relative to the upwind direction, which is in front of the wind turbine. The measuring position was determined from the angle between each receiving point and the nacelle direction. The solid lines indicate the calculated arithmetic mean levels at 1 m/s, 100 kW, and 0.5 rpm intervals, respectively.

The A-weighted sound power level of wind turbine noise increases with increasing wind speed, as presented in Fig. 3(a). However, the correlation between L_{WA} and the wind speed at hub height is only moderate, because the change in the wind speed is rapid as well as irregular under actual meteorological conditions, as mentioned in a previous study [9]. On the other hand, the correlation

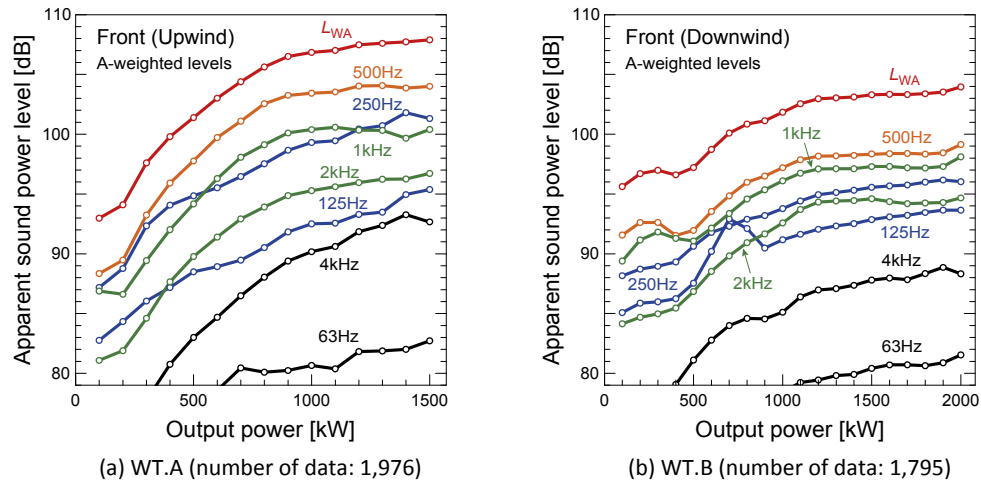


Fig. 4 Output power dependence of mean A-weighted sound power level in 1/1-octave bands (WT.A and WT.B).

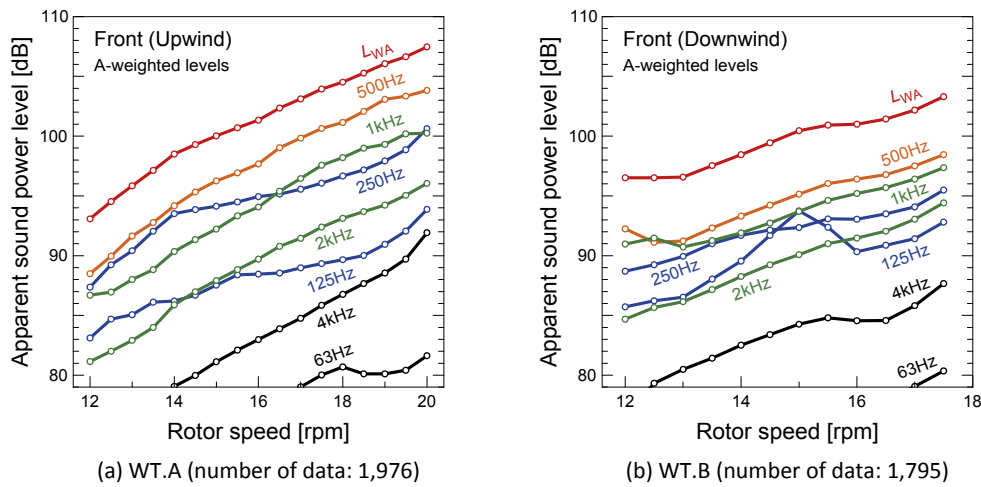


Fig. 5 Rotor speed dependence of mean A-weighted sound power level in 1/1-octave bands (WT.A and WT.B).

between L_{WA} and the output power or rotor speed is extremely strong compared with that with the wind speed at hub height, as presented in Figs. 3(b) and 3(c). In the case of WT.A, the power level increases almost linearly up to the rated rotor speed.

Next, to examine the dependence of the output power or rotor speed on the sound pressure level of wind turbine noise, the mean 1/1-octave band sound power levels with the A-frequency weighting were calculated, as shown in Figs. 4 and 5. For WT.B, the results in Figs. 4(b) and 5(b) represent the apparent sound power levels calculated using the measured data within $\pm 30^\circ$ relative to the downwind direction. The sound levels under the upwind conditions could not be obtained because the wind directions during the measurements over three days were predominantly from west-northwest (WNW) to northwest (NW) (refer to Fig. 1(b)).

The apparent A-weighted sound power levels L_{WA} for both wind turbines increase slightly as the output power

rises beyond 900 kW or 1.1 MW, at which point the rotor reaches the rated speed. The increases in L_{WA} above the rotor rated speed were 1.5 dB. As a reference, comparing the power level L_{WA} at the rated rotor speed or rated output power between both wind turbines, the power level for WT.A was almost 4 dB larger than that for WT.B. In addition, the sound pressure level at a frequency of 500 Hz or more appears to increase monotonically with increasing rotor speed, whereas sharp tonal components were seen in the sound levels at a frequency of 125 Hz for WT.B, as shown in Figs. 4(b) and 5(b).

3.3. Tonal Components

To preliminarily assess the tonal components included in wind turbine noise for WT.B, the changes in the 1/3-octave band sound power levels at frequencies from 100 Hz to 200 Hz with the wind speed, output power, and rotor speed are illustrated in Fig. 6. The circles and solid lines indicate their calculated apparent power levels and the

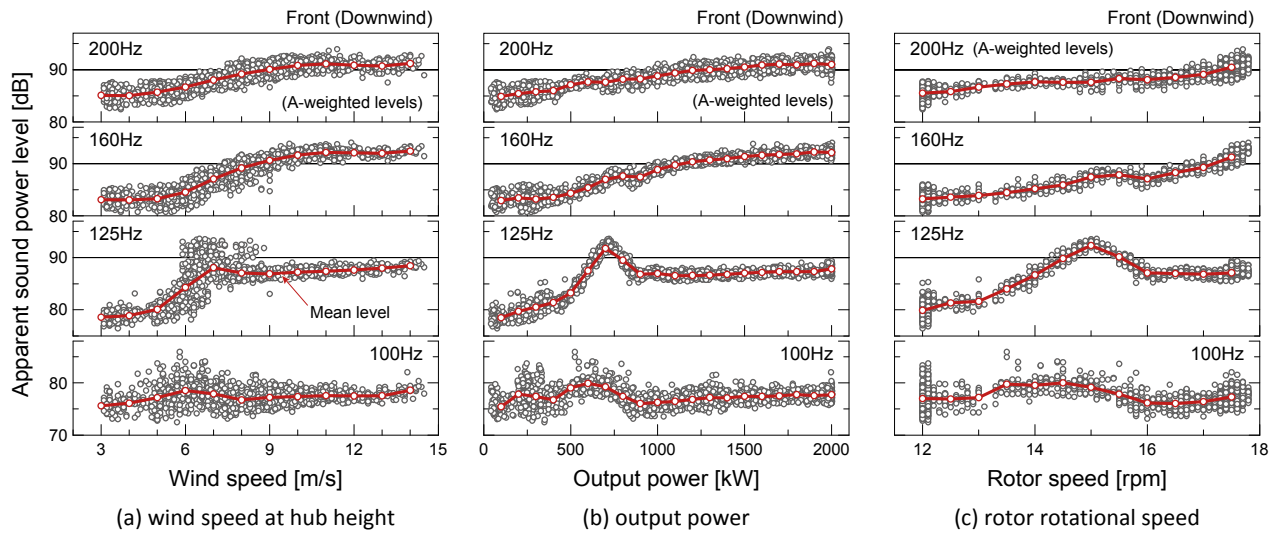


Fig. 6 Changes in 1/3-octave band sound power levels at frequencies from 100 Hz to 200 Hz with operational conditions (WT.B, —: mean level, number of data: 1,795).

arithmetic mean levels, respectively, which are the same data as those presented in Figs. 4(b) and 5(b).

From the results obtained using the output power or rotor speed, tonal components can be clearly confirmed in the mean levels at a frequency of 125 Hz. The mean levels at 700 kW or 15 rpm exceeded those at adjacent frequency bands by 5 dB or more. On the other hand, according to the result obtained using the wind speed, the sound levels at 125 Hz varied widely and the increases in the mean level at speeds of around 7 m/s were smaller than those indicated in Figs. 6(b) and 6(c). Consequently, obtaining the operational data of the output power and rotor rotational speed should be necessary to assess the characteristics of the noise emission. Note that the wind speed is one of the required factors to measure or predict the sound level in residential areas at long distances from wind turbines.

The mean 1/3-octave band sound power spectra at different rotor rotational speeds are shown in Fig. 7. These results were averaged using data within ± 0.25 rpm relative to each rotor speed. The symbol n represents the number of measured data at each rotor speed. For WT.A, tonal components were seen in the sound levels at frequencies of 200 Hz and 500 Hz under the operation condition of 14 rpm. The differences in the mean levels from those at adjacent frequency bands were 5 dB. For both wind turbines, no marked tonal components were found in the 1/3-octave band sound spectra at rotor speeds of 16 rpm and above. Thus, the tonal components included in wind turbine noise depend on the operational conditions. It will also be necessary to examine in detail these tonal components by performing the narrow-band analysis described in IEC 61400-11:2012 [11].

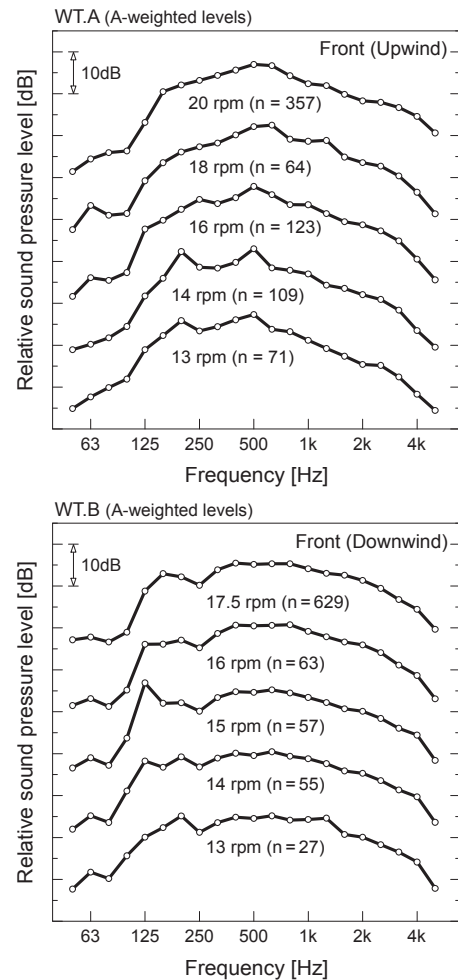


Fig. 7 Mean 1/3-octave band sound power spectra for different rotor speeds (WT.A and WT.B, n : number of data).

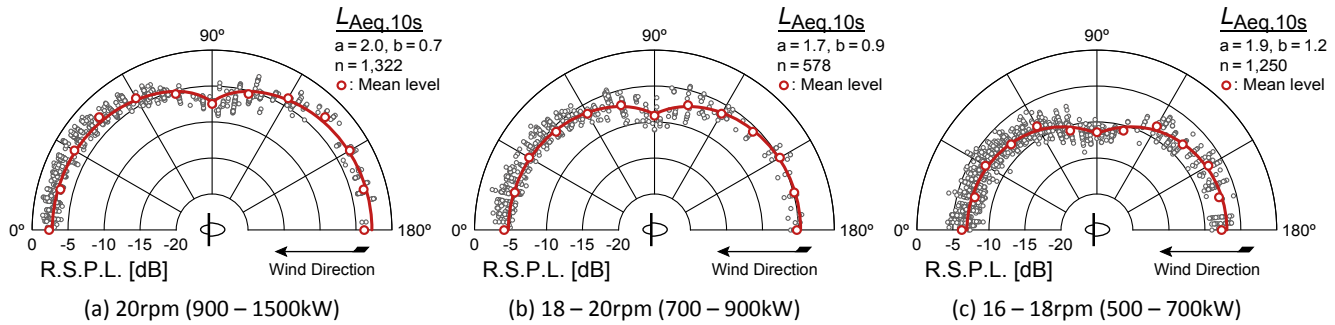


Fig. 8 Horizontal distribution of relative sound pressure level and calculated mean level at 15° intervals for three rotor speed ranges (WT.A, ○: mean level, —: $\Delta L_{dir,\theta}$ calculated by Eq. (1), a, b : coefficients for $\Delta L_{dir,\theta}$, n : number of data).

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

Rotor speed [rpm]	$L_{Aeq,10s}$			250 Hz			500 Hz			1 kHz			Number of data
	a	b	r	a	b	r	a	b	r	a	b	r	
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	1,322
18–20	1.7	0.9	0.98	2.7	1.0	0.99	2.6	0.9	0.99	1.3	0.7	0.90	578
16–18	1.9	1.2	0.95	2.9	1.5	0.98	3.1	1.2	0.96	1.4	1.2	0.86	1,250
Average	1.9	0.9	0.93	3.0	1.1	0.92	3.0	1.0	0.96	1.2	0.9	0.82	—

3.4. Horizontal Directivity

Several calculation methods for the horizontal sound directivity around a wind turbine have been proposed on the basis of aerodynamic sound theories or semi-empirical prediction methods [3,4,6,7]. To simplify the modeling of the directivity pattern of wind turbine noise at the ground level, 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 [9]. A simple regression formula was applied, assuming the directivity pattern of aerodynamic and mechanical sound to be bi- and omnidirectional, respectively. The directivity correction $\Delta L_{dir,\theta}$ is expressed by combining both directional patterns as follows:

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

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 measured at the ground level around the wind turbine.

First, the sound directivity was examined using the measured A-weighted sound pressure levels in 1/1-octave bands at the receiving points set circularly around WT.A [9]. The measured data were divided into three groups in consideration of the rotor speed dependence of the emitted noise. Figure 8 shows the measured A-weighted sound pressure levels (○) and the mean values (○) calculated at

15° intervals using data within $\pm 7.5^\circ$ relative to each direction, assuming the sound radiation to be symmetrical with the nacelle direction [4]. The direction of the measuring position was determined from the angle between each receiving point and the nacelle direction. The solid line indicates the directivity correction $\Delta L_{dir,\theta}$ derived from the results under three operational conditions at rotor speeds of 20 rpm, 18–20 rpm, and 16–18 rpm. Table 1 shows the coefficients a and b obtained for the A-weighted sound pressure level in 1/1-octave bands, which are the dominant frequency components of wind turbine noise (see Fig. 5).

All values of the correlation coefficient r are more than 0.86, and the calculated $\Delta L_{dir,\theta}$ agrees reasonably well with the measured sound pressure levels. The calculated differences in the sound pressure level $\Delta L_{dir,90^\circ}$ in the crosswind direction compared with those in the up- and downwind directions are presented in Table 2. The differences in $L_{Aeq,10s}$ are within 4–5 dB and the level differences at 250 Hz and 500 Hz are within 6–7 dB and almost 4 dB at 1 kHz, respectively.

The coefficients a and b depend on the frequency band as well as the rotor rotational speed. Therefore, to grasp the average directivity of wind turbine noise from an engineering perspective, the average $\Delta L_{dir,\theta}$ was derived using the mean level differences under each operational condition. Figure 9 and Table 1 present the average directivities $\Delta L_{dir,\theta}$ of the A-weighted sound pressure level in 1/1-octave bands at rotor speeds of 16–20 rpm. The coefficients

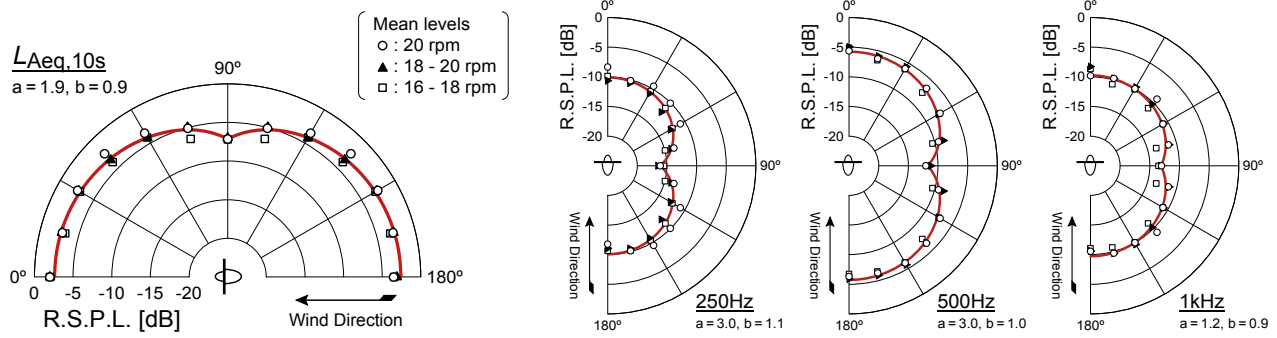


Fig. 9 Average horizontal directivity of the A-weighted sound pressure level in 1/1-octave bands for three rotor speed ranges (WT.A, —: average $\Delta L_{\text{dir},\theta}$ in the range of 16–20 rpm, a, b : coefficients for average $\Delta L_{\text{dir},\theta}$).

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

Rotor speed [rpm]	$\Delta L_{\text{dir},90^\circ}$ [dB]			
	$L_{\text{Aeq},10\text{s}}$	250 Hz	500 Hz	1 kHz
20	−4.8	−6.7	−6.3	−3.4
18–20	−4.3	−5.7	−5.6	−3.6
16–18	−4.6	−5.9	−6.1	−3.8
Average	−4.6	−6.0	−6.0	−3.4

a and b for the A-weighted sound pressure level $L_{\text{Aeq},10\text{s}}$ are 1.9 and 0.9, respectively. In addition, the average $L_{\text{Aeq},10\text{s}}$ in the crosswind direction is 4.6 dB lower than those in the up- and downwind directions, as shown in Table 2.

3.5. Validation of Average Sound Directivity

To validate the average directivity correction $\Delta L_{\text{dir},\theta}$ at the ground level, the directivity pattern of the A-weighted sound pressure level obtained around WT.A was compared with that around WT.B. For WT.B, the sound pressure levels at the rated rotor speed of 17.5 rpm within -30° to 120° relative to the downwind direction (0°) were used in this examination, because the sound levels could not be obtained in the upwind directions, tonal components were clearly seen at rotor speeds of around 15 rpm and the sound levels reached almost their upper limits at the rated speed, as mentioned in Sects. 3.2 and 3.3.

Figure 10 shows a comparison between the directivity patterns of the A-weighted sound pressure level in 1/1-octave bands (250 Hz, 500 Hz, and 1 kHz) for WT.A and those for WT.B. The solid lines indicate the average $\Delta L_{\text{dir},\theta}$ suggested on the basis of the results around WT.A, as presented in Fig. 9. The symbol r represents the correlation coefficient between the calculated $\Delta L_{\text{dir},\theta}$ and the measured data for WT.B. The number of measured data ($n = 1,312$) is sufficient for the validation. As a reference, the corrections $\Delta L_{\text{dir},\theta}$ derived from the mean levels at the rated speed of 17.5 rpm (± 0.25 rpm) for WT.B are illustrated by broken lines in the figure.

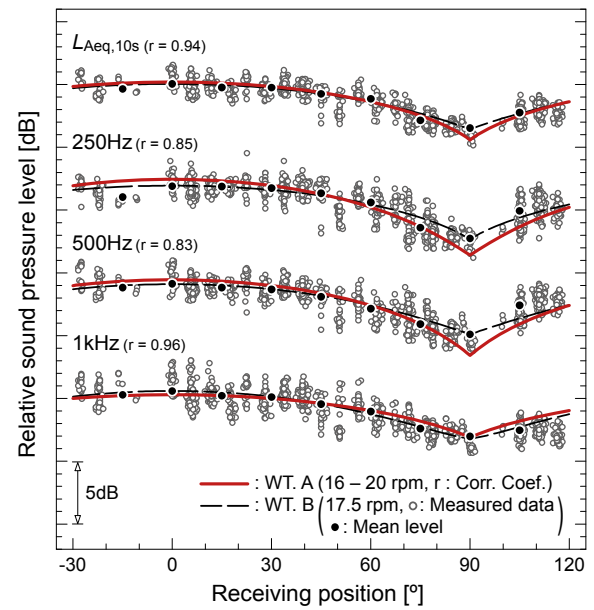


Fig. 10 Comparison of horizontal directivity of the A-weighted sound pressure level in 1/1-octave bands for different wind turbines (number of data: 1,312).

The average sound directivity pattern $\Delta L_{\text{dir},\theta}$ for the A-weighted sound pressure level for WT.A is qualitatively similar to that for WT.B, whereas the frequency dependence of the decrease in the sound level in the crosswind direction is different for the two wind turbines. In the case of WT.B, the mean A-weighted sound pressure level in the crosswind direction was almost 4 dB lower than that in the downwind direction.

Consequently, the apparent A-weighted sound power level can be estimated by using the empirical formula $\Delta L_{\text{dir},\theta}$ and the sound levels measured in any direction relative to the wind turbine. In addition, if the sound pressure levels can be obtained at some circular points around individual wind turbines, the regression formula (Eq. (1)) is applicable to express their horizontal directivity. It should be noted that these results were obtained using data measured at the ground level around the wind turbines,

and the investigation of the sound directivity at long distances is necessary to predict noise propagation [9].

4. CONCLUSIONS

Noise emitted from wind turbines is composed of aerodynamic and mechanical sound and has directional radiation characteristics. In order to investigate the horizontal sound directivity at the ground level under various wind conditions, field measurements around different wind turbines were performed over long periods. The distinguishable sound directivity was revealed by the noise measurement at both wind turbine sites. The mean A-weighted sound pressure levels in the crosswind direction are 4–5 dB lower than those in the up- and downwind directions. This tendency is similar to the results at other wind turbine sites, although the target frequency of the sound was limited within the range of 250 Hz to 800 Hz in the previous measurements [3,4].

An empirical formula for the average directivity correction was proposed to estimate the apparent A-weighted sound power level by using measured sound levels in any direction relative to the wind turbine, and the reliability of the formula was confirmed. Furthermore, obtaining associated wind turbine operational data such as the rotor rotational speed, output power, and nacelle direction is strongly recommended to assess the acoustic characteristics of wind turbine noise more accurately.

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