Study on empirical formula for the sound directivity around a wind turbine

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ABSTRACT
Noise emitted from wind turbines is composed of aerodynamic and mechanical sound and has directional radiation characteristics. To investigate the horizontal sound directivity around a wind turbine under various wind conditions, field measurements of noise emitted from two different wind turbines have been performed. Wind turbine operational data were collected at 1 s intervals along with corresponding acoustic data. An empirical formula for the average directivity correction was proposed on the basis of the measured A-weighted sound pressure levels in 1/1-octave bands at the receiving points set circularly around the wind turbine. The results showed that the directivity pattern of the A-weighted sound pressure level for two different wind turbines is almost the same, whereas the frequency dependence of the sound directivity is different for the individual wind turbines. The correlation between wind turbine noise and the rotor rotational speed is extremely strong compared with that with the wind speed at hub height. Additionally, the preliminary results of comparison between the rotor speed estimated by using the analyzed amplitude modulation sound and that actual value are presented.

Keywords: Radiation characteristic, Rotor rotational speed, Amplitude modulation

I-INCE Classification of Subjects Number(s): 14.5.4

1. INTRODUCTION

Regarding the directional characteristics of wind turbine noise (WTN), some studies based on aerodynamic sound theories and experiments have been carried out (1-6). According to several studies, it was demonstrated that the overall sound pressure 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, although those measurement data were collected under limited wind conditions. Furthermore, few studies have focused on the frequency dependence of the sound directivity.

We have also performed field measurements of noise generated from two different wind turbines, one with an upwind rotor and one with a downwind rotor, to examine the dependences of wind turbine operational conditions on radiation characteristics of WTN, the horizontal directivity for estimating the noise emission levels from wind turbines, and the tonal components included WTN (7, 8). In this study, the results of the rotor speed dependence of the apparent A-weighted sound power level and a simple empirical formula for the directivity correction derived from the measured sound levels of dominant frequency components of WTN are presented. Additionally, the rotor rotational speed estimated by using the amplitude modulation (AM) components contained in WTN was compared with the actual mean speed and the strength of the AM depth in emission areas was calculated. The F-S method proposed by Fukushima and Tachibana (9, 10) was used as a reference for determining the AM components.

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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. Table 1 shows the specifications for two wind turbines. The upwind turbine (hereinafter, WT.A) has been operated since 2003 and its rated output power, rotor speed and wind speed are 1.5 MW, 20 rpm, and 12 m/s, respectively. Those for the downwind turbine (WT.B), operated since 2012, are 2.0 MW, 17.5 rpm, and 13 m/s.

To examine the horizontal directivity of WTN, six receiving points were set circularly around WT.A at 30º intervals. These points were placed at a distance of 50 m except for one point (distance of 40 m) (7). In the case of WT.B, five receiving points at 22.5º intervals were set a distance of 57 m, considering the geographical features at the site (8). 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 (48 kHz sampling, 16 bit).

### Table 1 – Specifications for wind turbines

<table>
<thead>
<tr>
<th></th>
<th>WT. A</th>
<th>WT. B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of rotor</td>
<td>Upwind rotor</td>
<td>Downwind rotor</td>
</tr>
<tr>
<td>Rated output power</td>
<td>1.5 MW</td>
<td>2.0 MW</td>
</tr>
<tr>
<td>Rated rotor speed</td>
<td>20 rpm</td>
<td>17.5 rpm</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>12.0 m/s</td>
<td>13.0 m/s</td>
</tr>
<tr>
<td>Measurement period</td>
<td>8 days in 2011</td>
<td>3 days in 2013</td>
</tr>
<tr>
<td>First year of operation</td>
<td>2003</td>
<td>2012</td>
</tr>
</tbody>
</table>

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 ($L_{pA, 200ms}$) from the recordings. In this analysis, to eliminate periods with including intermittent back-ground noise (e.g., road vehicles, aircraft, and birdsong) and wind-induced noise at a microphone, instantaneous changes in the 1/3-octave band spectrum owing to them were checked carefully while reproducing the sound. In addition, with the wind turbine stopped forcibly, the residual noise levels ($L_{WA95, 10min}$ 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-average sound pressure levels over 10 s ($L_{peq,10s}$) 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).

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 acoustic data ($L_{Leq,10s}$, $L_{WA}$) were calculated over 10 s periods.

3. MEASUREMENT RESULTS

3.1 Temporal Variations in Wind Turbine Noise

Figure 1 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 for WT.A, when the wind speed at hub height varied strongly for almost 3 min. The direction of the measuring position was $-75^\circ$ relative to the upwind direction (receiving point: $-30^\circ$, nacelle direction $D_{nac}$: $45^\circ$). The hub height 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 $L_A$ 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 rotational speed $V_R$.

Figure 2 shows the apparent $L_{WA}$ for WT.A plotted against the operational data (hub height wind speed, output power, and rotor rotational speed). These data represent the measured $L_{WA}$ within $\pm 30^\circ$ relative to the up- and crosswind direction, which are in front and side of the wind turbine. The measuring position was determined from the angle between each receiving point and the nacelle direction. The apparent $L_{WA}$ increases concomitantly with increasing wind speed at hub height. However, the correlation between $L_{WA}$ and wind speed is only moderate, because the change in the wind speed is rapid as well as irregular under actual meteorological conditions, as shown in Fig. 1.
Figure 1 – Example of A-weighted sound pressure levels in 1/1-octave bands at 200 ms intervals and the turbine operational data at 1 s intervals (WT.A, measuring position: –75° relative to the upwind direction).

Figure 2 – Changes in apparent A-weighted sound power level with operational conditions. Measuring positions are within ±30° relative to the up- and crosswind direction (WT.A, n: number of data).

On the other hands, the correlation between $L_{WA}$ and the output power or rotor speed is extremely strong compared with that with the wind speed at hub height. In the case of WT.A, the WTN increases almost linearly up to the rated rotor speed of 20 rpm. Moreover, the apparent $L_{WA}$ in the crosswind direction tends to be lower than those in the upwind direction.

3.2 Changes in Sound Pressure Level

To examine the rotor speed dependence of the sound pressure level of WTN, the mean 1/1-octave band sound power levels with A-frequency weighting were calculated at 0.5 rpm intervals, as presented in Fig. 3. The result for WT.B represents $L_{WA}$ calculated using the measured data within ±30° relative to the downwind direction. The sound levels under the upwind conditions could not be
obtained because of prevailing wind direction during noise measurements over three days (8). The noise generated from both wind turbines was dominated by middle-frequency components of 250 Hz, 500 Hz, and 1 kHz. It is apparent that the sound pressure levels at a frequency of 500 Hz or more 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 a reference, comparing the apparent $L_{WA}$ at the rated rotor speed between both wind turbines, the power level for WT.A was almost 4 dB larger than that for WT.B.

Figure 4 shows the mean 1/3-octave band sound power spectra at different rotor rotational speeds. These results were averaged using data within ±0.25 rpm relative to each rotor speed. The symbol $n$ represents the number of measured data. For WT.B, sharp tonal components can be clearly confirmed in the mean levels at a frequency of 125 Hz. The mean level at a rotor speed of 15 rpm exceeded those at adjacent frequency bands by 5 dB or more. In the case of WT.A, tonal components were seen in the sound levels at frequencies of 200 Hz and 500 Hz under the operation conditions of 14 rpm. The differences in the mean levels from those at adjacent frequency bands were 5 dB. On the other hand, 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 WTN 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 (11).

Figure 3 – Rotor speed dependence of mean A-weighted sound power level in 1/1-octave bands.

(a) WT.A (number of data: 1,976)           (b) WT.B (number of data: 1,795)

Figure 4 – Mean 1/3-octave band sound power spectra for different rotor speeds ($n$: number of data).
3.3 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 (3-6). To simplify the modeling of the directivity pattern of WTN 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. A simple regression formula was applied, assuming the directivity pattern of aerodynamic and mechanical sound to be bi- and omnidirectional, respectively. The directivity correction $\Delta L_{\text{dir,} \theta}$ is expressed by combining both directional patterns as follows:

$$\Delta L_{\text{dir,} \theta} = 10 \log \left( \frac{1 + a \cos^b \theta}{1 + a} \right) \quad 0 \leq \theta \leq 360^\circ,$$

where $\theta$ is the direction of the measuring position relative to the wind turbine and $a$ and $b$ are coefficients for the sound directivity.

First, the coefficients $a$ and $b$ were derived from the A-weighted sound pressure levels in 1/1-octave bands measured at the receiving points set circularly around WT.A (7). The measured data were divided into three groups in consideration of the rotor speed dependence of the emitted noise.

Figure 5 shows the horizontal distribution of the A-weighted sound pressure levels ($\circ$) and the mean values (○) calculated at 15º intervals, 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 $\Delta L_{\text{dir,} \theta}$ derived from the results under three operational conditions at rotor speeds of 20 rpm, 18 – 20 rpm, and 16 – 18 rpm. Table 2 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 WTN (see Fig. 3).

All values of the correlation coefficient $r$ are more than 0.86, and the calculated $\Delta L_{\text{dir,} \theta}$ agrees reasonably well with the measured sound pressure levels. The differences $\Delta L_{\text{dir,} 90^\circ}$ between sound levels in up-/ downwind direction and those in crosswind direction are within 4 – 5 dB for $L_{\text{Aeq,10s}}$, within 6 – 7 dB at 250 Hz and 500 Hz, and almost 4 dB at 1 kHz, respectively (8).

![Figure 5](image-url)

Figure 5 – Horizontal distribution of relative sound pressure level and calculated mean level at 15º intervals for three rotor ranges (W.T.A, –: $\Delta L_{\text{dir,} \theta}$ calculated by Eq.(1), $a$, $b$: coefficients, $n$: number of data).

<table>
<thead>
<tr>
<th>Rotor speed [rpm]</th>
<th>$L_{\text{Aeq,10s}}$</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>Num. data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a$</td>
<td>$b$</td>
<td>$r$</td>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>20</td>
<td>2.0</td>
<td>0.7</td>
<td>.94</td>
<td>3.7</td>
<td>0.8</td>
</tr>
<tr>
<td>18 – 20</td>
<td>1.7</td>
<td>0.9</td>
<td>.98</td>
<td>2.7</td>
<td>1.0</td>
</tr>
<tr>
<td>16 – 18</td>
<td>1.9</td>
<td>1.2</td>
<td>.95</td>
<td>2.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Average</td>
<td>1.9</td>
<td>0.9</td>
<td>.93</td>
<td>3.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 2 – Coefficients $a$, $b$ for directivity correction $\Delta L_{\text{dir,} \theta}$ and correlation coefficient $r$ (WT.A)
3.3.1 Average Sound Directivity

The coefficients \(a\) and \(b\) depend on the frequency band as well as the rotor rotational speed. Therefore, to grasp the average directivity of WTN from an engineering perspective, the average \(\Delta L_{\text{dir},\theta}\) was derived using the mean level differences under each operational condition, as presented in Fig. 5. Figure 6 and Table 2 show the average directivities \(\Delta L_{\text{dir},\theta}\) of the A-weighted sound pressure level in 1/1-octave bands at rotor speeds of 16 – 20 rpm. The coefficients \(a\) and \(b\) for \(L_{\text{Aeq,10s}}\) are 1.9 and 0.9, respectively. In addition, the average \(L_{\text{Aeq,10s}}\) in the crosswind direction (\(\Delta L_{\text{dir,90^\circ}}\)) is 4.6 dB lower than those in the up-/ downwind directions (8).

Figure 6 – Average horizontal directivity of A-weighted sound pressure level in 1/1-octave bands (WT. A, -: average \(\Delta L_{\text{dir},\theta}\) in the range of 16 –20 rpm, \(a\), \(b\): coefficients for average \(\Delta L_{\text{dir},\theta}\)).

Figure 7 – Comparison of horizontal directivity of A-weighted sound pressure level in 1/1-octave bands for different wind turbines (number of data for WT.B: 1,312).

To validate the average directivity \(\Delta L_{\text{dir},\theta}\) 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 (±0.25 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 direction and tonal components were clearly seen at speeds of around 15 rpm, as mentioned in Sect. 3.2. Figure 7 shows a comparison between the directivity patterns of the A-weighted sound pressure level in 1/1-octave bands (250 Hz – 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. 6. The symbol \(r\) represents the correlation coefficient between the calculated \(\Delta L_{\text{dir},\theta}\) and the measured data for WT.B. As a reference, the corrections \(\Delta L_{\text{dir},\theta}\) derived from the mean levels obtained around WT.B are illustrated by broken lines in the figure.
The average sound directivity $\Delta L_{\text{dir,} \theta}$ 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 both 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 sound power level $L_{WA}$ can be estimated by using the empirical formula $\Delta L_{\text{dir,} \theta}$ and the sound pressure levels measured in any direction relative to the wind turbine. Additionally, the effectiveness of the directivity $\Delta L_{\text{dir,} \theta}$ which can be applied at horizontal distances of up to 100 m (reference point described in IEC 61400-11), was confirmed (7).

4. EXAMINATION FOCUSED ON AMPLITUDE MODULATION

As mentioned above, the radiation characteristics of WTN depend strongly on the rotor rotational speed. However, it is generally difficult to obtain the actual rotor speed at several seconds intervals during noise measurements. Thus, we focused on the periodic fluctuations (amplitude modulation; AM) of sound generated from blades of a wind turbine and the rotor speed was estimated from the blade-passing-frequency (BPF), which can be detected by calculating fourier spectrum of the AM components contained in WTN. Then the estimated rotor speeds by using the measured sound levels were compared with actual values. As a reference, the AM depths $D_{\text{AM}}$ (9, 10), which evaluate the strength of the AM components, in emission areas under various operational conditions were calculated. In this preliminary examination, the measurement data at one receiving point around WT.A were used.

4.1 Estimation of Rotor Rotational Speed

Regarding the assessment of the AM components contained in WTN, several methods have been proposed. In this study, the F-S method (9, 10) was used as a reference, in which the difference $\Delta L_{\text{A}}$ between the A-weighted sound pressure level with the FAST time-weighting ($L_{WA}$) and that with the SLOW time-weighting ($L_{WA,S}$) is calculated to extract the short-term fluctuation of AM by removing the long-term fluctuation (trend), and then the AM depth $D_{\text{AM}}$ is obtained by calculating the 90 % range of $\Delta L_{\text{A}}$. The effectiveness of this method has been theoretically proved (10), while we used a moving average of $L_{WA,F}$ instead of $L_{WA,S}$ to simplify the calculation procedure, as follows:

\[
\Delta L_{\text{A}} = L_{\text{A,100ms}} - L_{\text{A,3s}} ,
\]

(2)

\[
D_{\text{AM}} = \Delta L_{\text{A,5}} - \Delta L_{\text{A,95}} ,
\]

(3)

where $L_{\text{A,100ms}}$ is the reanalyzed A-weighted sound pressure levels with the FAST time-weighting at 100 ms intervals and $L_{\text{A,3s}}$ is the 3-seconds moving average of $L_{\text{A,100ms}}$ (blade-passing-interval for WT.A: 1.7 – 1.0 s).

Figure 8 shows the time-traces of $L_{\text{A,100ms}}$, $L_{\text{A,3s}}$, and level difference $\Delta L_{\text{A}}$ between them, when the wind turbine operated at around the rated speed (CASE1: 17 – 20 rpm) and low speeds (CASE2: 13 – 17 rpm). In addition, the fourier spectrum and auto-correlation function of $\Delta L_{\text{A}}$ in the first 30 s was presented in the figure, respectively. The long-term fluctuations (trend) in accordance with the rotor rotational speed $\dot{V}_R$ were seen in the AM components of WTN and the changes in the moving average $L_{\text{A,3s}}$ were similar to those in the rotor speed. The extent of the level difference $\Delta L_{\text{A}}$ which represents the short-term fluctuation of AM without the trend, tended to increase with increasing rotor speed. Additionally, it can be seen that the BPF of $\Delta L_{\text{A}}$ in 30 s is apparently detected as a fundamental frequency of 0.98 Hz or 0.82 Hz, corresponding to a periodicity of 1.0 s or 1.2 s, and the estimated rotor speeds (19.53/ 16.41 rpm) were within actual speed ranges of 19 – 20 or 16 – 17 rpm, respectively.

Next, the BPF and rotor speed were estimated by using $\Delta L_{\text{A}}$ calculated from all of the A-weighted sound pressure levels obtained in a measuring period of eight days, and then the estimated BPF and rotor speed were compared with actual mean values of them. Figure 9 shows comparison results in the case of using $\Delta L_{\text{A}}$ for 30 s and 1 min. The number of data were 557 and 233, respectively. The BPFs for WT.A are within 0.6 – 1.0 Hz (12 – 20 rpm) and the estimated BPFs agree reasonably well with the actual mean values, whereas the differences of almost 0.1 Hz between them are seen in a few cases. The 98 % of the all estimated rotor speeds are within ±0.5 rpm of the actual mean speed for 30 s. Therefore, the rotor rotational speed can be identified with a certain amount of accuracy by using the sound levels measured around a wind turbine.
(a) CASE 1 (rotor speed: 17 – 20 rpm, measuring time: 18:19 – 18:22)

(b) CASE 2 (rotor speed: 13 – 17 rpm, measuring time: 18:49 – 18:52)

Figure 8 – Examples of A-weighted sound pressure level $L_{A, 100ms}$, moving average $L_{Ave, 3s}$, level difference $\Delta L_A$, and the fourier and auto-correlation coefficients of $\Delta L_A$ in 30 s (WT.A, $V_R$: rotor rotational speed at 1 s intervals).

(a) blade-passing-frequency (b) rotor rotational speed

Figure 9 – Comparison between BPF and rotor speed estimated by using acoustic data and actual mean values of them for WT.A (Analysis time: 30, 60 s, $n$: number of data).

4.2 AM Depth in Emission Areas

The procedure mentioned above was applied to the A-weighted sound pressure levels obtained at one receiving point in WT.A site and the AM depths $D_{AM}$ in emission areas were calculated from the level differences $\Delta L_A$ for 30 s and 1 min., as shown in Fig. 10. The strengths of $D_{AM}$ in 30 s and 1 min. were almost the same and distributed primarily within a range of 2 – 4 dB. In the future, we intend to investigate the dependence of wind turbine operational conditions (rotor speed, output power, and wind speed) on the strength of the AM components and the horizontal directivity of them on the basis of noise measurements around a wind turbine.
5. CONCLUSIONS

Field measurements have been performed at different wind turbine sites over long periods to examine the directional radiation characteristics of WTN at the ground level under various operational conditions. The distinguishable sound directivity is revealed and the A-weighted sound pressure levels in the crosswind direction are 4 – 5 dB lower than those in the up- and downwind directions. The tendency is similar to the results at other wind turbine sites in the previous measurements (3-5). 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 this formula was confirmed. Furthermore, it was found that the radiation characteristics of WTN depend strongly on the rotor rotational speed, which can be estimated from the AM components contained in WTN.

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