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Numerical prediction of acoustic pressure radiated from large wind turbines

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ABSTRACT

This paper presents a numerical study to model acoustic pressure radiated from a generic 2.5MW wind turbine. The acoustic pressure is calculated by using the formulation 1A of Farassat. An unsteady surface pressure distribution is analytically derived from the model proposed by Amiet. Using these numerical methods, not only the frequency spectrum or the sound pressure level of trailing edge noise, but also its acoustic pressure is successfully predicted in this study. The result clearly showed that the amplitude modulation of wind turbine noise exists even at far distances from large wind turbines, which implies that the wind turbine noise may be perceived when the background noise level is very low.

Keywords: Wind turbine noise, Time domain modeling, Trailing edge noise

1. INTRODUCTION

Although the noise level of a large wind turbine is relatively low, this noise is sometimes perceived even far from a wind turbine (e.g. 1km from wind turbines) [1, 2]. This is known to be due to the amplitude modulation characteristic of wind turbine noise. Several studies have investigated this amplitude modulation characteristic [3], but only few studies have been performed to predict the amplitude modulation of wind turbine noise [4, 5]. To investigate the reason why wind turbine noise is heard even at far distances, this study predicts the acoustic pressure radiated from large wind turbine blades.

2. METHODOLOGY

2.1 Trailing edge noise model

In this study, unsteady pressure on blade surfaces is obtained analytically by using the trailing edge noise model proposed by Amiet [6, 7]. By assuming that the turbulence in the boundary layer convects as a frozen pattern, the surface pressure jump on the moving surface of a flat-plate can be expressed as Eq. (1).

$$\Delta p_c(y_1,t)=\int_{\infty}^{\infty} p_0 e^{-ik_c(y_1-U_c t)}\{e^{\varepsilon k_c y_1}-1+(1+i)E^*[-y_1\{k_c+\mu(1+M)\}]\}dk_c \qquad (1)$$

where, k_c : chordwise convective wave number ($k_c=\omega/U_c$)
U_c : convection velocity
$E^*[\,]$: complex conjugate of Fresnel integral
$\mu=M\omega/\beta^2 U \qquad \beta=\sqrt{1-M^2}$

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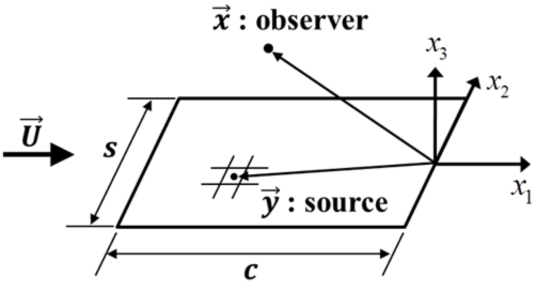

Figure 1 – Schematic for a flat-plate model problem

The detail descriptions of this equation can be found in Ref. [5, 7]. In the present study, this equation is numerically calculated by using the method proposed by Ref. [5, 8].

2.2 Acoustic analogy

Formulation 1A of Farassat [9] is used to calculate the acoustic pressure radiated from blade surfaces. We only considered loading noise for the calculation, because thickness noise is negligible for low Mach number flow. The loading term of Formulation 1A is described as Eq. (2).

$$\begin{aligned} 4\pi p'(\vec{x},t) = {} & \frac{1}{c_0}\int_{f=0}\left[\frac{\dot{l}_i\hat{r}_i}{r(1-M_r)^2}\right]_{ret} ds + \int_{f=0}\left[\frac{l_r - l_i M_i}{r^2(1-M_r)^2}\right]_{ret} ds \\ & + \frac{1}{c_0}\int_{f=0}\left[\frac{l_r(r\dot{M}_i\hat{r}_i + c_0 M_r - c_0 M^2)}{r^2(1-M_r)^3}\right]_{ret} ds \end{aligned} \tag{2}$$

where, $\vec{l}$: unsteady surface pressure vector ($\vec{l} = \Re[-\Delta p_c]\,\hat{n}$)
$f = 0$: the surface of the plate

2.3 Rotor noise prediction

Using the numerical prediction method, this study predicts the trailing edge noise from a wind turbine. The wind turbine model is a 2.5MW upwind wind turbine. The rotor diameter and the hub height are 93m and 82m, respectively. Its rated rotational speed is 15.4RPM.

To apply the two-dimensional trailing edge noise model to the rotating wind turbine blades, a strip theory approach is applied, as shown in Fig. 2. Each blade is divided into 20 segments, and the segments are modeled as rectangular flat-plates. Next, the numerical method was applied to each segment.

The calculation is performed for a duration of 1/3 revolution of the wind turbine. The lower and the upper frequency bound are 10 Hz and 5,000 Hz, respectively. In order to reduce the computational time, parallel computing technique (message passing interface, MPI) is used.

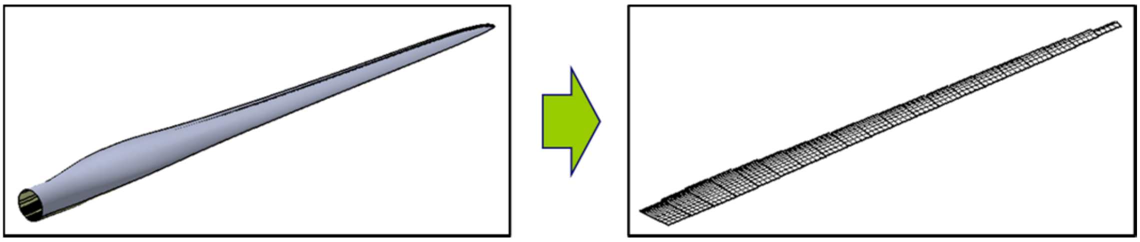

Figure 2 – wind turbine blade

3. RESULT

First, we predict the acoustic pressure at four reference positions according to IEC 61400-11 [10]. Figure 3 demonstrates the predicted acoustic pressures and its predicted positions. The figure also shows the overall sound pressure levels and the A-weighted sound levels of each sound. It can be found that the shapes and the sound levels of the acoustic pressures at position one and two are similar to those of the acoustic pressures at position three and four, respectively. The overall sound pressure level of the sounds at position one and three is about 3dB higher than that of the sound at position two and four, but the A-weighted sound levels of the four sounds are almost the same. Moreover, the predicted result shows that the amplitude modulation of wind turbine noise exists at all of the four positions.

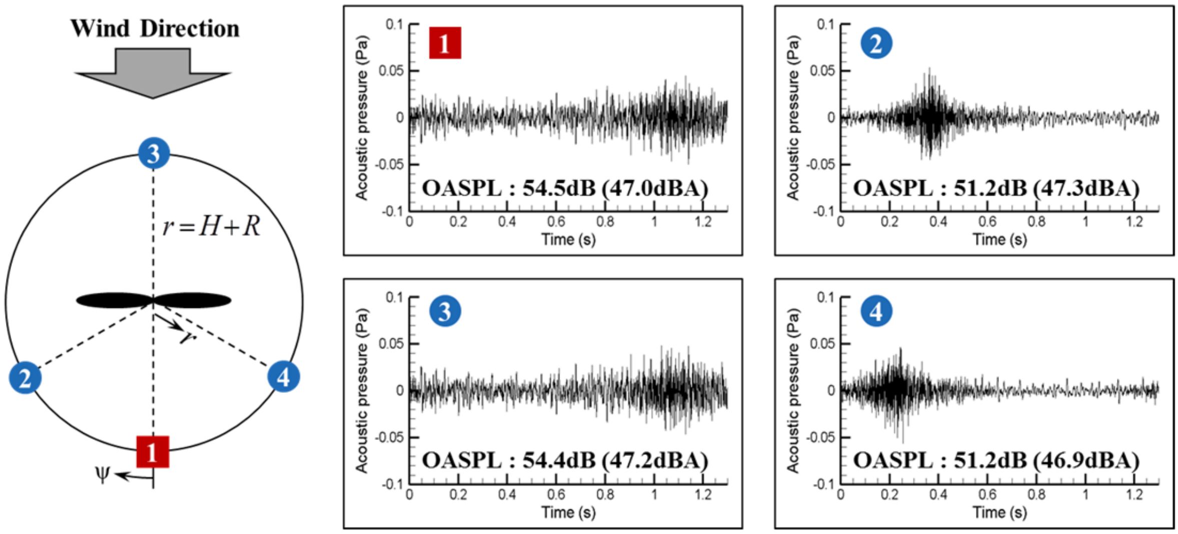

Figure 3 – Result (1): IEC 61400-11 reference positions

Next, to evaluate the wind turbine noise at far distances from the wind turbine, the acoustic pressure is predicted at a distance of 1 km from the wind turbine. Figure 4 presents the predicted acoustic pressures and its predicted positions. The result shows that the sound pressure level is maximum at position one, and it decreases as the azimuth angle moves to 90°. On the other hand, the amplitude modulation characteristic can hardly be seen at position one, but the amplitude modulation is large near the rotation plane.

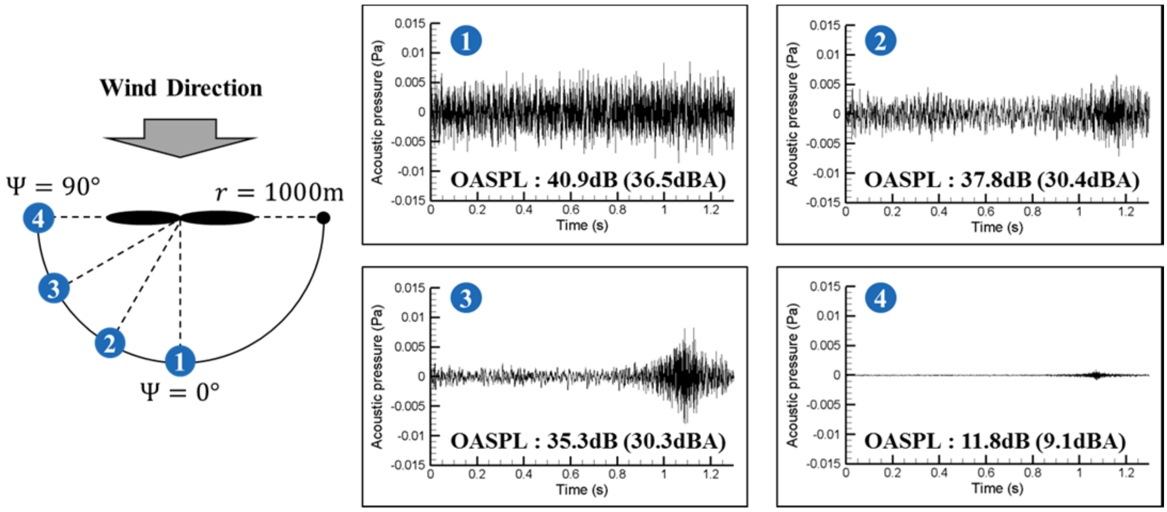

Figure 4 – Result (2): At 1km from the wind turbine

Furthermore, by expanding the previous result, the acoustic pressure is calculated at a distance of

250, 500, 750, and 1000m from the wind turbine. Figure 5 shows the overall sound pressure level and the modulation depth of the predicted sound. As can be seen from the figure, the overall sound pressure level is a maximum at downwind direction, while the modulation depth is a maximum at crosswind direction. Moreover, it is worthy of notice that the overall sound pressure level decreases as increasing the distances, but the modulation depth is consistent with the distance. This is because even though the distances increase, the variation of the directivity between the observer and the wind turbine blades remains the same.

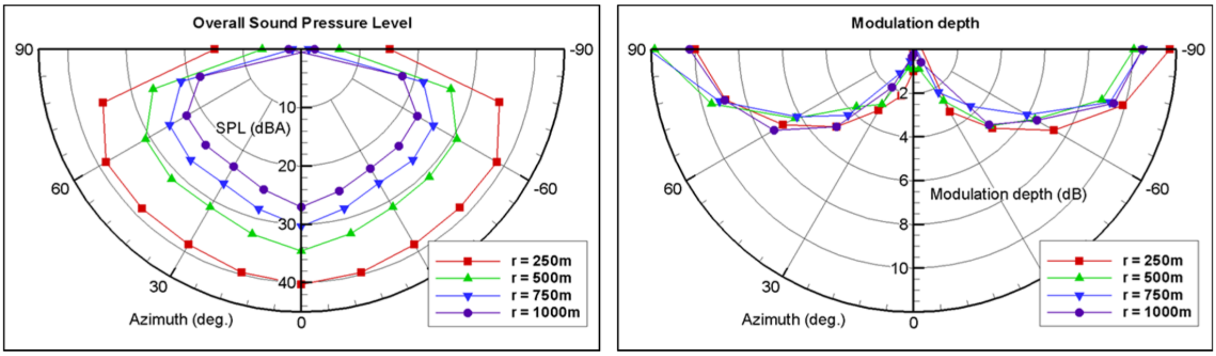

Figure 5 – Result (3): Overall sound pressure level and modulation depth

4. CONCLUSIONS

This study predicted the acoustic pressure of trailing edge noise from a large wind turbine. Using the proposed numerical method, this study successfully modeled the acoustic pressure radiated from the wind turbine blades. Since parallel computing technique was applied for the numerical computation, we could obtain the acoustic pressure up to 5 kHz more effectively. The result showed that the amplitude modulation exists even at far distances from the wind turbine, which implies that the wind turbine noise may be perceived when the background noise level is very low.

ACKNOWLEDGEMENTS

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