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Numerical and experimental study of aerodynamic noise by a small wind turbine

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ABSTRACT

To examine the aerodynamic noise produced by small wind turbines, this study predicts and measures the aerodynamic noise from a 10 kW wind turbine. The numerical predictions include the turbulence ingestion noise, turbulent-boundary-layer trailing edge noise, and trailing edge bluntness noise. The noise measurement is carried out with free-field microphones at a reference position according to the IEC 61400-11 standard. Although the trailing edge bluntness noise is under-predicted at low wind speeds, the spectral trends of the prediction results generally agree well with those of the experimental data. It is also found that for small wind turbines, the trailing edge bluntness noise can be an important noise source.

1. Introduction

Wind turbines transform wind energy into electric energy without producing any waste. However, they make noise due to the rotational motion of the wind turbine blades. This noise can exert a negative influence on people near wind turbines. Accordingly, it is important to evaluate the noise generated from wind turbines.

Several previous studies have numerically and experimentally examined the noise produced by wind turbines. Zhu et al. modeled the aerodynamic noise from a 300 kW wind turbine using a semi-empirical model, and they compared the predicted results with measurement data [1]. Although the semi-empirical model that they used was in terms of NACA0012 airfoil, they successfully calculated the wind turbine noise by altering the input data of the boundary layer displacement thickness so that it matched the data pertaining to the actual airfoil shape of the wind turbine blade. Oerlemans and Schepers predicted the noise from two large wind turbines using the same empirical model [2]. They measured the wind turbine noise using a microphone array and then validated the prediction results with experimental data. These previous studies found that the main source of wind turbine noise is the aerodynamic noise from the wind turbine blades, also showing that this noise has a broadband spectrum.

However, while many studies have focused on the noise from large wind turbines, noise from small wind turbines has not been thoroughly investigated thus far. The Reynolds number of the flow around small wind turbine blades is generally smaller than that around large wind turbine blades. Due to this difference, the aerodynamic noise made by small wind turbines can differ from that of large wind turbines. In addition, small wind turbines are typically installed close to residences compared to large wind turbines. As a result, people can be more annoyed by the noise from a small wind turbine as compared to a more distant large wind turbine. Thus, it is necessary to examine the aerodynamic noise from small wind turbines.

The purpose of this study is to evaluate the aerodynamic noise generated from a small wind turbine. Based on a 10 kW small wind turbine, the aerodynamic noise is predicted using empirical models proposed by Lowson [3] and Brooks et al. [4]. Noise measurements are also carried out to validate the results of the numerical predictions. Using these results, we assess the noise characteristics of the small wind turbine.

2. Numerical method

The aerodynamic noise that is generated from wind turbine blades is composed of turbulence ingestion noise and airfoil self-noise [3]. The turbulence ingestion noise occurs when

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Nomenclature

Latin letters

C	chord length (m)
c_0	speed of sound (m/s)
$\overline{D_h}$	high frequency directivity function
$\overline{D_l}$	low frequency directivity function
h	height from the ground (m)
h_e	trailing edge thickness (m)
h_{min}	minimum trailing edge height (mm)
K_{lc}	low-frequency correction factor
$\hat{k}$	normalized wave number
l_T	atmospheric turbulence length scale (m)
l	span (m)
M	Mach number
r_e	distance from source to observer (m)
SPL	sound pressure level (dB)
St	Strouhal number
$\overline{w}$	turbulence intensity
z	ground roughness

Greek letters

δ^*	boundary layer displacement thickness (m)
ρ	air density (kg/m^3)

Subscripts

TEBN	trailing edge bluntness noise
TEN	trailing edge noise
TIN	turbulence ingestion noise
α	angle of attack effect
p	pressure side
s	suction side

atmospheric turbulence is ingested into the wind turbine rotor, while the airfoil self-noise is generated regardless of the atmospheric turbulence. The airfoil self-noise is composed of turbulent-boundary-layer trailing edge noise, laminar-boundary-layer vortex shedding noise, trailing edge bluntness noise, and tip noise [4]. Because wind turbines operate in an open environment, the boundary layers on the blades are typically turbulent at the trailing edge. This leads to the generation of turbulent-boundary-layer trailing edge noise. Moreover, trailing edge bluntness noise can be produced by the blades unless the blades have sharp trailing edges. Thus, the turbulence ingestion noise, the turbulent-boundary-layer trailing edge noise, and the trailing edge bluntness noise are modeled by a numerical prediction method.

In addition, because steady loading is applied to the rotating blade as it operates, low-frequency loading noise can be generated from the wind turbine rotor. This loading noise is one of the main noise sources of rotating machinery, such as helicopter rotors, turbo-machinery, and fans. However, for a wind turbine rotor, this low-frequency loading noise is inaudible in most situations, as the rotational speed of a wind turbine is very low. Accordingly, the low frequency loading noise is not calculated in the numerical prediction.

The turbulence ingestion noise is predicted by an empirical model proposed by Lowson [3,5]. According to this model, the frequency spectrum can be expressed as

$$\mathrm{SPL_{TIN}} = \mathrm{SPL_{H,TIN}} + 10\log_{10}\left(\frac{K_{lc}}{1+K_{lc}}\right), \tag{1}$$

with

$$\mathrm{SPL_{H,TIN}} = 10\log_{10}\left\{\rho^2 c_0^2 l_T \frac{l}{r_e^2} M^3 \overline{D_l}\,\overline{w}^2 \hat{k}^3 \left(1+\hat{k}^2\right)^{-7/3}\right\} + 58.4, \tag{2}$$

where K_{lc} is the low-frequency correction factor, l_T is the atmospheric turbulence length scale, $\overline{w}$ is the turbulence intensity, and $\hat{k}$ is the normalized wave number. The atmospheric turbulence length scale and the turbulence intensity are determined from an empirical model using the ground roughness [6]. These are determined as follows:

$$l_T = 25h^{0.35}z^{-0.063} \tag{3}$$

and

$$\overline{w} = \left\{0.24 + 0.096\log_{10}z + 0.016(\log_{10}z)^2\right\}\frac{\log(30/z)}{\log(h/z)}, \tag{4}$$

where z is the ground roughness and h is the height from the ground.

A semi-empirical model proposed by Brooks et al. is used to calculate the turbulent-boundary-layer trailing edge noise and trailing edge bluntness noise [4]. This model is made based on wind tunnel experiments using a NACA0012 airfoil. With this semi-empirical model, the 1/3 octave band sound pressure levels of the trailing edge noise and trailing edge bluntness noise are calculated as Eqs. (5)–(9).

$$\mathrm{SPL_{TEN}} = 10\log\left(10^{\mathrm{SPL}_\alpha/10} + 10^{\mathrm{SPL_s}/10} + 10^{\mathrm{SPL_p}/10}\right), \tag{5}$$

with

$$\mathrm{SPL_p} = 10\log\left(\frac{\delta_p^* M^5 l \overline{D_h}}{r_e^2}\right) + A\left(\frac{\mathrm{St_p}}{\mathrm{St_1}}\right) + (K_1 - 3) + \Delta K_1, \tag{6}$$

$$\mathrm{SPL_s} = 10\log\left(\frac{\delta_s^* M^5 l \overline{D_h}}{r_e^2}\right) + A\left(\frac{\mathrm{St_s}}{\mathrm{St_1}}\right) + (K_1 - 3), \tag{7}$$

$$\mathrm{SPL}_\alpha = 10\log\left(\frac{\delta_s^* M^5 l \overline{D_h}}{r_e^2}\right) + B\left(\frac{\mathrm{St_s}}{\mathrm{St_2}}\right) + K_2, \tag{8}$$

and

$$\mathrm{SPL_{TEBN}} = 10\log\left(\frac{h_e M^{5.5} l \overline{D_h}}{r_e^2}\right) + G_4\left(\frac{h_e}{\delta_{avg}^*}, \psi\right) + G_5\left(\frac{h_e}{\delta_{avg}^*}, \psi, \frac{\mathrm{St'''}}{\mathrm{St'''_{peak}}}\right). \tag{9}$$

Detailed descriptions of the functions and the parameters in Eqs. (5)–(9) are explained in the literature [4].

A strip theory approach is used to apply the two-dimensional empirical models to rotating wind turbine blades. Each blade is divided into a number of segments of equal lengths, and the prediction models are then applied to the segments. Moreover, a cardioid-type directivity pattern is used for the prediction of the