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Integrated numerical method for the prediction of wind turbine noise and the long range propagation

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ABSTRACT

Characteristics of noise propagation from wind turbine have been studied by using the integrated numerical methods based on Ray theory. There are two numerical approaches in this paper. Those are constructing noise sources of wind turbine and computing the noise level on the ground. First of all, the flow fields around the wind turbine blade are calculated using Wind Turbine Flow, Aeroacoustics and Structure analysis (WINFAS). WINFAS is an unsteady vortex lattice methods based on potential flow. The results of flow analysis are used for predicting tonal noise, turbulence ingestion noise, and airfoil self noise. Tonal noise is induced by the displacement of fluid and loading fluctuation of the blade and those are predicted by Farassat 1A equation. Moreover, semi-empirical formulas are used for the prediction of broadband noise such as the airfoil self noise and turbulence ingestion noise. Before the beginning of the next step, the acoustic pressure is integrated at the each point of virtual acoustic sphere considering retarded time. It also represents the noise directivity on wind turbine. Then, the noise level on the ground has been predicted including the effects of air absorption, ground reflection and diffraction.

1. Introduction

1.1. Research background

Wind turbine has two major noise components, mechanical and aerodynamic noise. The mechanical noise became no longer critical issue because of many efforts for dropping its level. However, the noise aerodynamically generated from blades is still important issue and moreover, it is a barrier to the development of the wind turbine industry. Since aerodynamic noise from the wind turbine can be easily propagated even the location at a long distance and it is radiating during 24 h a day, inhabitants around the wind turbine have been suffered. Therefore, the efforts for classifying noise generations and developing noise prediction method at a receiver are needed for a local community as a clean renewable energy.

Aerodynamic noise on wind turbine is divided by three categories according to its generation, low frequency noise, turbulent inflow noise, and airfoil self noise. Low frequency noise is caused by pressure fluctuations and loading distributions around the blades. These noise levels can be obtained by using Farassat 1A formula which is broadly used for helicopter noise predictions. Turbulent inflow noise is from turbulent inflow that causes unsteady loading distribution around the blades. Spectrum of turbulent inflow noise depends on eddy size. If the eddy size is larger than airfoil chord length, it generates the low frequency noise, and in another case, when the eddy size is much smaller than the chord length, it makes the high frequency noise. Airfoil self noise is also a major source on the wind turbine noise. Its generation is due to the interaction between the blades and its boundary layer. There are several types in airfoil self noise and those are turbulent boundary layer trailing edge noise (TBLTE), laminar boundary layer vortex shedding noise (LBLVS), tip vortex noise (TIP), separated/stalled flow noise (SEP), and trailing edge bluntness vortex shedding noise (TEBVS).

Before the prediction of a noise on a ground, aerodynamic analysis and noise prediction on the blades have been analyzed by Wind Turbine Flow, Aeroacoustics and Structure analysis (WINFAS). WINFAS based on potential flow has used an unsteady vortex lattice methods and vortex ring method for wake considerations. Tone noise of blades can be obtained using acoustic analogy with the results of aerodynamic analysis and broadband noise is determined by empirical formulations suggested by Brooks et al. [1]. To develop a long range noise propagation method of the wind turbine noise, noise database is constructed with the tone and broadband noise. This noise database is called acoustic sphere. Next, propagation algorithm based on Ray theory has been developed with the acoustic sphere. Noise levels on the ground can be

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determined by considering effects of an atmospheric attenuation, a reflected wave and a diffracted wave. In this paper, we have integrated these numerical approaches step by step and we also simulate the noise propagation on the complicated ground from GIS terrain data.

2. Numerical methods

2.1. Wind turbine flow analysis

Aerodynamic loading distributions around the wind turbine blades have been analyzed by using the unsteady vortex lattice methods and vortex ring model. The results of the aerodynamic analysis will be used for a noise prediction, especially a tone noise.

2.2. Noise prediction

Tone noise can be calculated by using Farassat 1A formula. Farassat 1A formula regards the rotor blade noise as thickness and loading noise. [2] Thickness noise is induced by the displacement of fluid and loading noise is caused from the pressure fluctuation around the blades surface. These noise sources are due to the rotating motion of blades, therefore; those are related to a blade passage frequency. Since RPM of the wind turbine is lower than other common rotating machinery such as a helicopter or a compressor, the peak noise values occur at low frequency bands.

$$4\pi p'_T(\vec{x},t) = \int_{f=0}\left[\frac{\rho_0 \dot{v}_n}{r(1-M_r)^2}\right]_{ret} dS + \int_{f=0}\left[\frac{\rho_0 v_n(r\dot{M}_i\hat{r}_i + c_0 M_r - c_0 M^2)}{r^2(1-M_r)^3}\right]_{ret} dS \quad (1)$$

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

$p'_T(\vec{x},t)$ and $p'_L(\vec{x},t)$ represent the acoustic pressure due to thickness and loading in Eqs. (1) and (2) respectively. $\dot{v}_n$ denotes the rate of variation of a velocity above the blade surface with respect to time. $\dot{M}_i\ \hat{r}_i$ also denote the time variation of mach number and distance in radiation direction.

There are two types in broadband noise, turbulent inflow noise (TIN) and airfoil self noise (ASN). Both broadband noise can be determined by semi-empirical formulations. At first, TIN is considered by the model suggested by Lowson [3]. For the prediction of noise from the interaction between the blades and the turbulence near the boundary layer, empirical formulations proposed by Brooks et al. have been adjusted in this paper [2]. In ASN, the boundary layer displacement thickness, δ^* of the airfoil is the important parameter and it has been obtained from the results of flow analysis.

2.3. Long range noise propagation

A large amount of calculation time and results of flow analysis are needed to predict noise level for a receiver at a distance from wind turbine if we follow whole previous mentioned numerical methods. For the lesser calculation time and reducing number of data file, noise database is constructed. Noise database means the storage of noise information at specific time and location to the rotating blades. Its shape is a sphere because each data point is equally located by a constant distance from the center of wind turbine hub.

After the determination of the sphere, noise prediction on a ground can be calculated by the method based on Ray theory. If there is no wind speed variations and no temperature variations, a ray path from a source to a receiver might be a straight line. With this assumption, we can develop a long range noise propagation method on the wind turbine.

There are several reasons why the noise level varies during its propagation and those are atmospheric attenuation and terrain effects. Noise emitted from the wind turbine is attenuated by air molecules while it propagates in the air. Atmospheric attenuation can be considered using ISO 9613-2. Terrain effects are divided into two main components, reflected wave and diffracted wave. The reflected wave can be considered using the imaginary source having the same distance from the ground as the height of real sources. Ground impedance is the main role to decide reflection coefficients and it has governed by inherent property of the ground material, a flow resistivity. Attenborough's impedance model has been used for the calculation and then we can also get reflection coefficient. Finally, relative sound pressure level can be calculated by following Eq. (3). [4].

$$\Delta L_{ref} = 10\ \log\left|1 + Q\frac{R_1}{R_2}e^{ik(R_2-R_1)}\right|^2 \quad (3)$$

ΔL_{ref} is an increment of sound pressure level in dB due to the reflected wave. R_1, R_2 denotes the distance from a source to receiver direct path and reflected path, respectively. Also Q is a reflected wave coefficient calculated by ground impedance.

If a ray cannot directly arrive in the receiver location because of an obstruction between the receiver and the source, that receiver

Table 1
Turbine geometry factors and operation conditions.

	NEG-Micon
Blade radius	36 m
Hub height	62 m
Section airfoil	NACA 63.4XX, NACA 63.2XX
Inflow wind speed	10 m/s
RPM	17.3

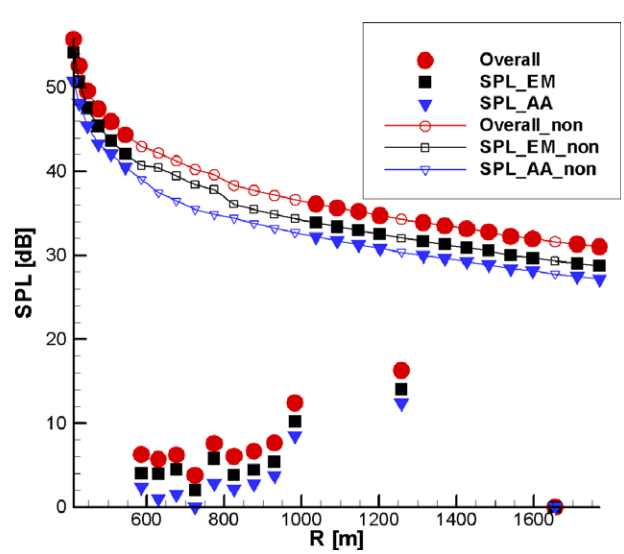
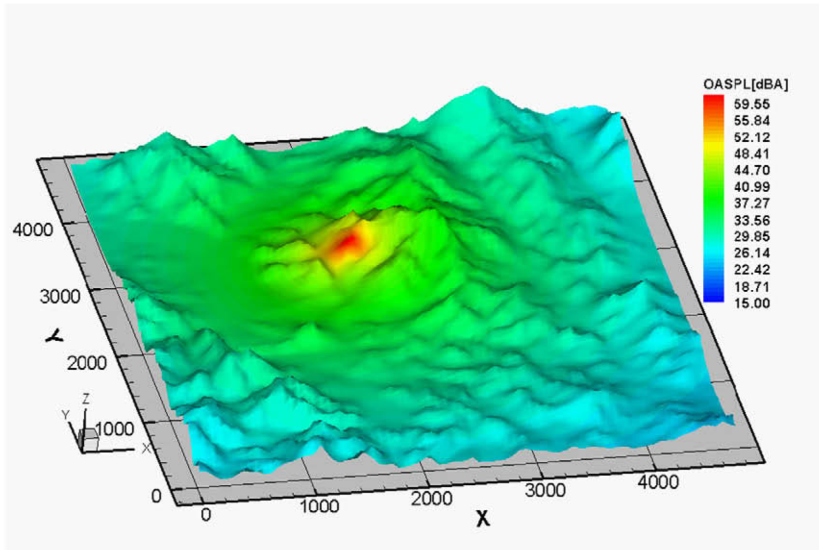
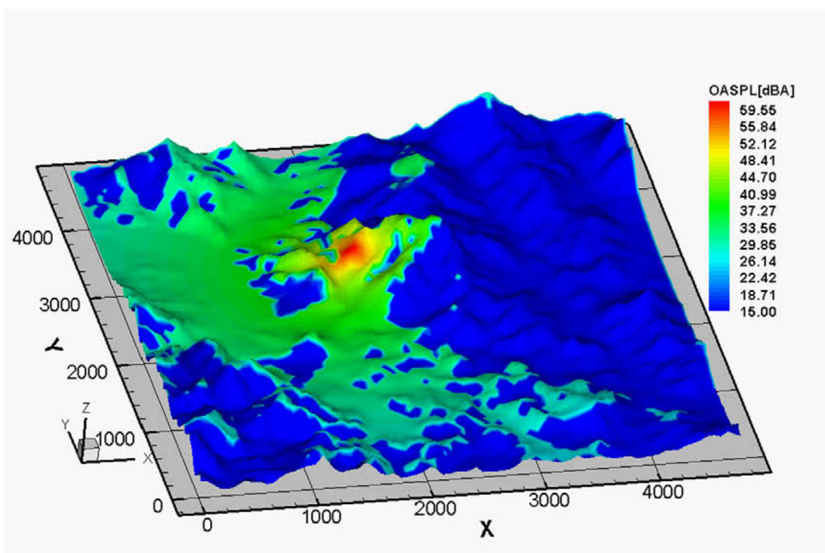


Fig. 1. Noise level at each receiver position.



(a) Without terrain effects



(b) With terrain effects

Fig. 2. Wind turbine noise contour.

regions are called shadow zone. In this shadow zone, the sound pressure levels are governed by diffracted wave field. The effects of the diffracted wave can be considered by using Salomons's empirical formula which calculates a transfer function, attenuation level due to a barrier, Eq. (4), and next considers additional absorption on the wedge surface, Eq. (5). [5].

$$D_{barrier} = 10\ \log\left(\Gamma\cos^2\left(\frac{\phi_s - \phi_r}{2}\right)\right) \quad (4)$$

$$\Delta D = -\frac{H}{(\pi-\gamma)^{1.2}}\begin{bmatrix} \frac{6}{f^{0.4}}\ min\left(1, B + \frac{6}{f^{0.5}}\right) \\ +4f^{0.15}\ max(0, \phi_s - \phi_r - \pi) \\ min\left(1, B + \frac{18}{f^{0.5}}\right) \end{bmatrix} \quad (5)$$

$D_{barrier}$ and ΔD denotes the attenuation level due to a barrier and additional surface of wedge. H is an efficiency factor in Ref. [5]. γ, ϕ_s, ϕ_r are geometric angles of wedge, source and receiver from the center of wedge.

At first, the shadow zones have to be determined by a relation of source and receiver positions because those regions could hear the noise due to diffracted waves. Next, the geometric parameters are decided by information on grid data, i.e. complex terrain. At this stage, the geometric shape is simplified by a triangle. With these parameter, transfer functions in Eq. (4). can be obtained in each spectrum.

Therefore, the final noise level can be expressed as shown by the following Eq. (6). The noise value of the receiver is sum of a sound pressure level of the source, atmospheric attenuation, relative sound pressure level and the absorption due to the diffracted wave.

$$L_R = L_{p_{free}} + \Delta L_a + \Delta L_{ref} + \Delta L_{diff} \quad (6)$$

L_R is the sum of all values of source power, absorption due to air, reflected waves and diffracted waves.

3. Results

The results of aerodynamic analysis are validated with power curve over uniform wind speed which varies from 4 m/s to 12 m/s. Noise level from wind turbine blade is also validated with the measurement data of AOC 15/50 and VS-45 generators. Each noise source data is generated by using WINFAS and it has the same characteristics as the previous study. [6] and, now with these numerical methods, noise level on a ground for a near field and far field is predicted. Predicted sound pressure level is generated from NEG-Micon 1.5 MW wind turbine and its geometry factors and operation conditions are shown by Table 1.

Wind turbine is located at $S_0 = (2000, 3000, 400)m$ and noise level is predicted under a constant sound speed and without wind speed variations.

Fig. 1 shows the calculated noise levels caused by aerodynamic loading distributions and the interaction between the blades and the turbulent flow and those are represented SPL_AA, SPL_EM, respectively. Noise level on the ground from the wind turbine is more affected by the sum of TIN and ASN, as shown by fig. 1. In Fig. 1, 'non' means the value without considering the effects of terrain. There are large amount of reduced noise values attenuated by the obstacles so that the noise level is being totally different value unless the noise calculation contains the effects of terrain. These differences are clearly shown by following Fig. 2.

Fig. 2(a) and (b) shows different noise contour caused by terrain effects. Since Fig. 2(a) does not contain one of the most important effects such as diffraction, noise has been only decreased with 1/r. However, Fig. 2(b) shows an irregular noise distribution according to terrain height between the source and the receiver.

Many of wind turbines have been located at top of mountain and its noise can propagate everywhere and arrive in a long distance. However, as shown in Fig. 2(b), noise exposed from wind turbine can be minimized for far field if the noise path is properly intercepted.

4. Conclusions

Noise generated from wind turbine has been predicted by integrated numerical methods. Aerodynamic loadings and aerodynamically generated sound have been predicted and adjusted to further numerical method. Almost receiver regions have been affected by broadband noise even in far field. For more accurate predictions, terrain effects are confirmed to be most important factors. The effects of the refracted wave occur in the temperature gradient and wind speed variation and it will be considered in the next study.

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