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A full-scale prediction method for wind turbine rotor noise by using wind tunnel test data

Jaeha Ryi [a], Jong-Soo Choi [a,*], Seunghoon Lee [b], Soogab Lee [c]

[a] Department of Aerospace Engineering, Chungnam National University, Daejeon 305-764, Republic of Korea
[b] School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-744, Republic of Korea
[c] Center for Environmental Noise and Vibration Research, Engineering Research Institute, School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-744, Republic of Korea

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ABSTRACT

The development of a low-noise wind turbine rotor and propeller is often cost-effective and is in fact a race against time to those who wish to build and test a small-scale rotor instead of an expensive full-scale rotor. The issue of this approach has to do with the interpretation of wind tunnel model test data in terms of both the frequency band and sound pressure level information for the noise scaling effect.

This paper discusses a prediction method for the estimation of the noise generated from a full-scale wind turbine rotor using wind tunnel test data measured with both a small-scale rotor and a 2D section of the blade. The 2D airfoil self-noise and the scaled rotor noise were investigated with a series of wind tunnel experiments. Wind tunnel data post-processing considered four aspects: removal of the test condition effect, scaling to full scale, consideration of the wind turbine rotor operating conditions, and the most important terms of full-scale rotor noise as adjustments to address the differences between the wind tunnel test conditions and the full-scale operating conditions.

A full-scale rotor noise prediction results comparison was performed by initially dividing the test conditions into the condition of a 2D section noise test and the condition of a small-scale rotor noise test. Based on an airfoil section, the rotor was selected from a blade section at $r/R = 0.75$. The small-scale rotor was scaled down by a factor of 5.71 for the wind tunnel test.

Finally, the full-scale rotor noise data was compared with the wind tunnel test data using a scaling estimation method.

1. Introduction

In recent years, the sudden inflation of the oil price has brought much attention regarding the use of wind energy to produce electricity. Industrialized countries at present produce about 65% of their electricity from fossil fuels. If the entire world continues to use fossil fuels at the same rate of 65% as is done now, a dramatic rise in the greenhouse effect and polluting emissions can certainly be expected, even if the fuel price remains within a manageable range. Hence, it would be beneficial if wind energy, a promising renewable energy source, can somehow replace, even in a supplementary role, fossil fuels. To develop rotor blades that offer effective high efficiency and low noise, a numerical method that considers theoretical approaches for air pressure and noise has been developed. In particular, regarding air pressure designs, various approaches are in use, such as blade element theory, lifting surface theory, and computational fluid dynamics. These are widely used to predict the capacity of a full-scale rotor. However, in the case of noise, it has proven to be difficult to obtain a correct estimation for a full-scale rotor test despite the use of numerous empirical formulas according to various design parameters of wind rotors. One method can check results through a wind tunnel experiment at the development stage of the wind rotor to assess this problem. The wind tunnel test is an effective means of verifying the capacity of a developing product, incurring only a small cost in the process of developing actual products, which often incurs a large cost when developing wind rotors or airplanes.

This paper analyzed earlier studies and related regulations related to the development process of the low-noise rotor blades used in wind turbines and performed noise measurement tests both at the wind tunnel test stage and in the operation condition of a full-scale rotor [1,2]. In particular, we considered how to estimate the noise of a full-scale wind rotor using the wind tunnel test result. We also compared the acquired noise data with the full-scale wind

* Corresponding author. Tel.: +82 42 821 6683; fax: +82 42 825 9225.
E-mail address: jchoi@cnu.ac.kr (J.-S. Choi).

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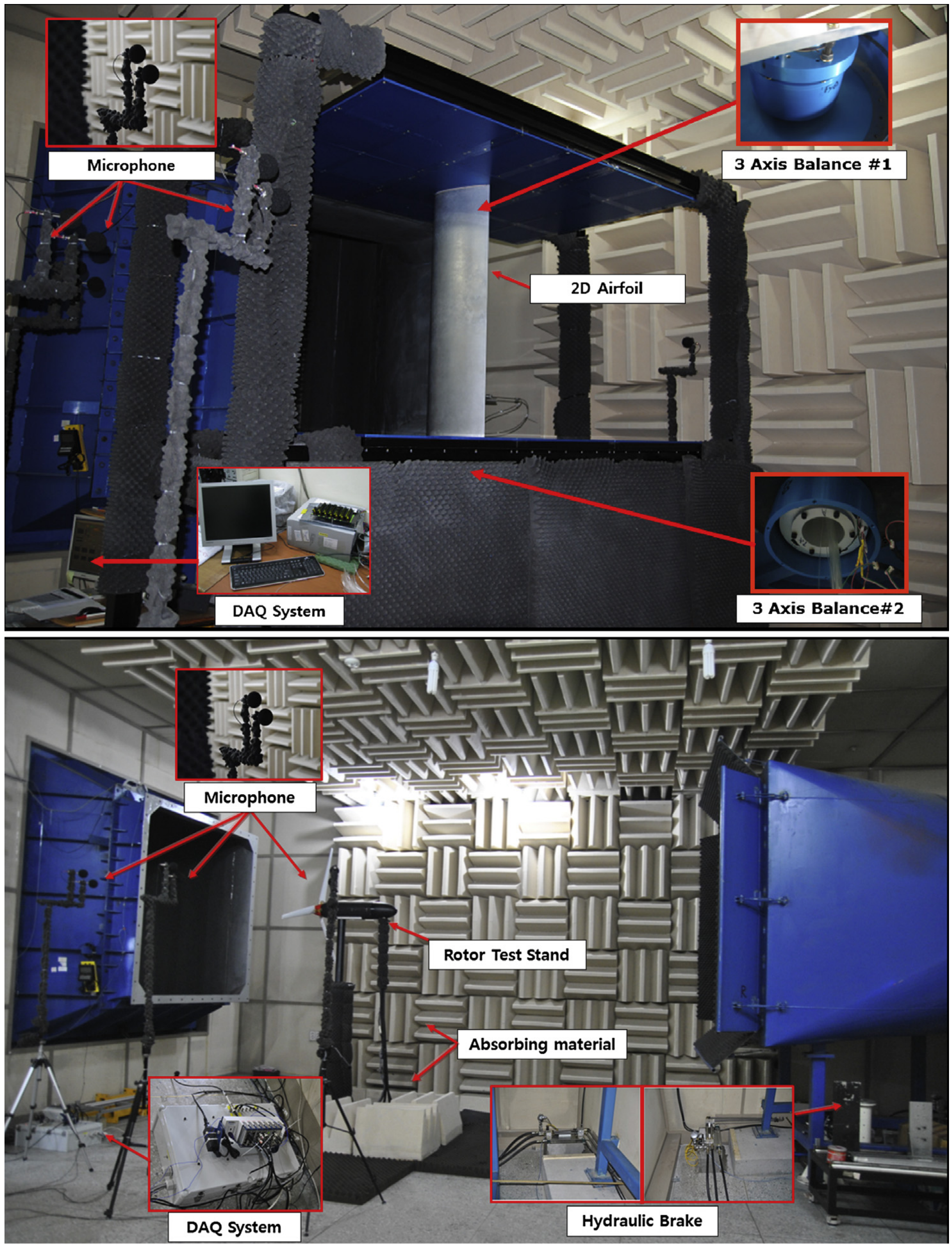

Fig. 1. Configuration of wind tunnel test stand for airfoil experiment and the small-scale rotor test at Chungnam National University.

rotor test result through a post-treatment during the testing stage by performing a test with full-size wind rotor blades. From these results, we reviewed the possibility of estimating the noise capacity of a full-scale rotor in a wind tunnel test stage that uses a small scale rotor and a 2D airfoil wing.

2. Overview of the noise data scaling and estimation method

This paper performed the wind tunnel test using the 2D airfoil, representing 75% of the full-scale rotor radius with a small-scale rotor. We considered the changes of test atmosphere conditions such as moisture, temperature, and air pressure together with acquiring the noise data during the wind tunnel test. We also considered the rotating speed of the rotor, the tip speed ratio, and the wind speed. For the noise data, we acquired the raw data of the sound pressure level to obtain the narrowband spectrum or the 1/3-octave band spectrum. To compare this wind tunnel test result with the full-scale rotor test result, we needed to consider a weighting method to eliminate effects of the test environment and the noise result on the full-scale rotor. Considering these, this paper achieved a weighted noise result via the wind tunnel test using the post-treatment program LabVIEW2011™ to assign weights to the wind tunnel noise test results.

2.1. *Removal of the test condition effect*

A device installed in a wind tunnel should consider the microphone and set the test condition considering the regular distance from the wind tunnel test model and the measuring angle. When measuring the noise at the test device, as shown in Figs. 1 and 2, it was necessary to consider the atmospheric absorption rate of the noise and the emitting distance between the positions of the actual noise source and measurement. We weighted the distance between the noise source and measuring position considering the Doppler

Effect by the speed (M) using Eq. (1) when we performed the test (Figs. 3,4).

$$R' = \frac{R}{M\cos\theta + \sqrt{M^2\cos^2\theta - M + 1}} \quad (1)$$

$$\theta' = \cos^{-1}\left(\mathrm{M}\cos^2\theta + \cos\theta\sqrt{1 - \mathrm{M}^2\cos^2\theta}\right) \quad (2)$$

$$f_{ss}^{D} = \frac{f_{ss}}{1 - \mathrm{M}\cos\theta'} \quad (3)$$

$$\widehat{L}_P(f_{ss}, \theta')_{ss} = L_P^*(f_{ss}, \theta)_{ss} + 20\log R' + \alpha_{td}\left(f_{ss}^{D}\right)R' \quad (4)$$

To do this, "α_{td}" in Eq. (4) can be obtained through the test conditions, as in an earlier paper [3], of the atmospheric absorption rate correction coefficient. With Eqs. (2) and (3), we determined the Doppler frequency (f_{ss}^{D}) of the noise source considering the emitting angle of the noise source (θ') and the small-scale model. We calculated the sound pressure level of the noise source while weighting the test condition with Eq. (4) considering these values.

2.2. Scaling from small scale to full scale

To weight the noise data acquired from the wind tunnel test using the small-scale model to the actually size data, we adjusted the frequency of the sound wave and sound pressure level.

$$\mathrm{St} = \frac{f_{fs}D_{fs}}{V_{j,fs}} = \frac{f_{ss}D_{ss}}{V_{j,ss}} \quad (5)$$

$$f_{fs} = f_{ss}\frac{D_{ss}}{D_{fs}} = f_{ss}\sqrt{\frac{A_{ss}}{A_{fs}}} \quad (6)$$

The frequency of the measured sound wave can be weighted using Eq. (6) considering the Strouhal-Number, which is defined by Eq. (5). Using the small-scale model rotor diameter, the full-scale rotor diameter, or the area of the rotor, we can convert it within the frequency range of the full-scale rotor. Next, the sound pressure level of the result can be weighted using Eqs. (7) or (8).

$$\widehat{L}_P\left(f_{fs}, \theta'\right)_{fs} = \widehat{L}_P(f_{ss}, \theta')_{ss} + 10\log\left(\frac{A_{fs}}{A_{ss}}\right) + +10\log\left(\frac{\Delta f_{fs,\neq\omega}}{\Delta f_{fs}}\right) \quad (7)$$

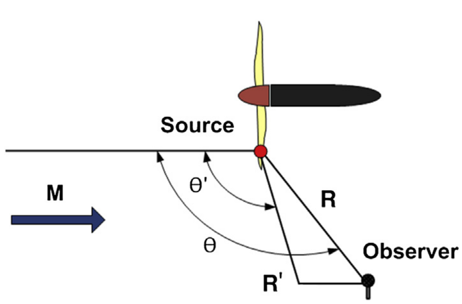

Fig. 2. Layout of the sound propagation path and angle in a moving stream for the Doppler-Effect.

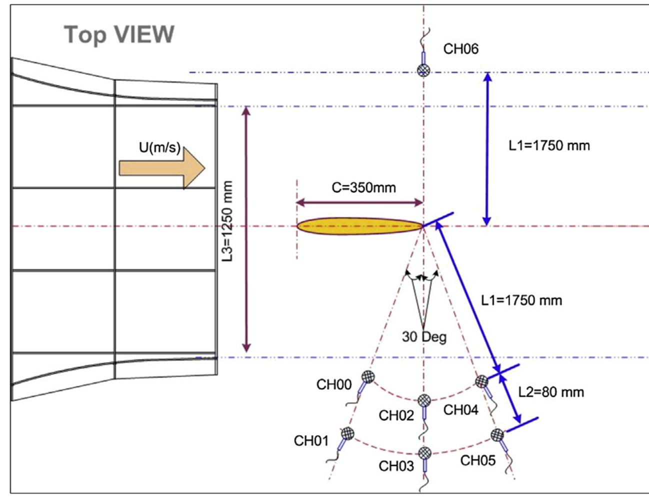

Fig. 3. Layout of the microphone array for the 2D airfoil noise test in the open-jet wind tunnel.

$$\widehat{L}_P\left(f_{fs}, \theta'\right)_{fs} = \widehat{L}_P(f_{ss}, \theta')_{ss} + 20\log\left(\frac{D_{fs}}{D_{ss}}\right) + +10\log\left(\frac{\Delta f_{fs,\neq\omega}}{\Delta f_{fs}}\right) \quad (8)$$

Here, "$\Delta f_{fs,\neq\omega}$" and "Δf_{fs}" denote the difference in the resolution limit of the desired spectrum; if there is a difference in the resolution limit between the desired spectrum and the measured spectrum, we apply the narrowband spectrum to converted to 1/3-octave spectrum [5,7].

2.3. Adjustment of the simulation distance from small scale to full scale

The difference between the small-scale rotor test and the sound pressure level of the full-scale rotor which that arose in the test conditions was weighted with the data post-treatment program. To match the position of the noise measurement under the conditions of the full-scale rotor and the wind tunnel test, we can use a weighting method which considers the sound pressure according to the distance or the Doppler Effect.

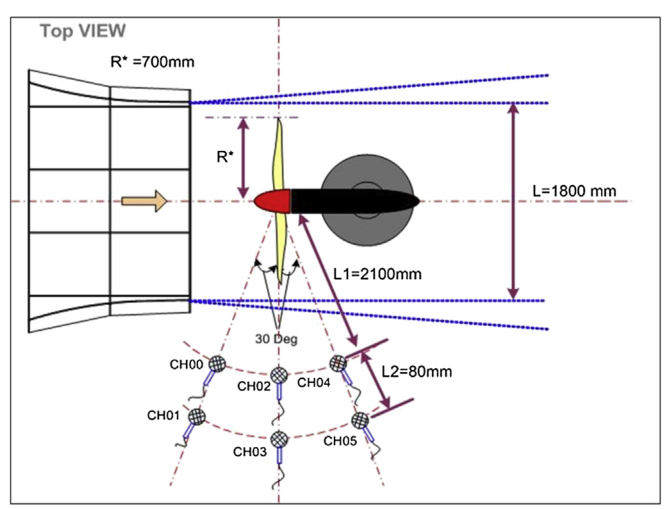

Fig. 4. Layout of the microphone array for the small-scale rotor noise test in the wind tunnel.

To compare the noise result of the full-scale rotor, we weighted while assuming that the noise source of the wind rotor has a sufficient far-field condition for the difference in the distance between the wind tunnel test and the full-scale rotor.

$$\widehat{L}_{\mathrm{P}}^{\mathrm{fs}}(\mathrm{R}_2) = \widehat{L}_{\mathrm{P}}^{\mathrm{fs}}(\mathrm{R}_1) - 20\log\left(\frac{R_2}{R_1}\right) \tag{9}$$

Using Eq. (9), which weights the noise of the measuring position, we calculated the weighting sound pressure $\widehat{L}_{\mathrm{P}}^{\mathrm{fs}}(\mathrm{R}_2)$ at the noise measuring position (R_1) and the noise weighting position (R_2) at the measuring the sound pressure $\widehat{L}_{\mathrm{P}}^{\mathrm{fs}}(R_2)$ and applied the results to the post-treatment program.

2.4. Other considerations to consider at the post-process for a wind tunnel test

It was necessary to consider the effect on the Noy value, which refers to the irregular spectrum weighting and sound intensity at the stage of weighting the sound pressure level arising during the wind tunnel test. Its effect during the actual test result is slight, but we should consider reducing the effect of the wind tunnel test environment while weighting the wind tunnel test result to the noise result of the actual wind turbine rotor. For the Noy value, we obtained the weighting value by applying the Eq. (10) with a frequency range between 50 Hz and 10 Hz after changing the measured noise value to the sound pressure level of the 1/3-octave spectrum.

$$N\left(\theta_{\mathrm{f}}'\right) = n\left(f_{\mathrm{fs}}^{\mathrm{D}}\right)_{\max} + 0.15\left[\sum_{i=1}^{24} n_i\left(f_{\mathrm{fs}}^{\mathrm{D}}\right)\right] \tag{10}$$

Here, "$n(f_{\mathrm{fs}}^{\mathrm{D}})_{\max}$ " denotes the maximum value from among the "$n_i(f_{\mathrm{fs}}^{\mathrm{D}})$ " values of each frequency band, and "$N(\theta_{\mathrm{f}}')$ " refer to the total sound pressure level which is sensed at the measuring position of "θ_{f}' ". To weight noise that has an irregular spectrum, we should calculate the C(k) value, which is the weighting coefficient of the tone. C(k) is a weighting coefficient which is added to the sound pressure level (k) to calculate an irregular spectrum such as the tone upon the kth time increase. To calculate these weighting coefficients, ten-steps of weighting and calculating sound pressure level (from now SPL) value are necessary. Fig. 10 shows an example of a tone correction calculation result. This is only a general method which is suggested in the reference [6,7]. A fuller explanation is outside the scope of this paper.

3. Experimental apparatus and procedures

The noise test which is conducted in this paper can be divided into three parts. First, we performed the noise test on the 2D airfoil section by means of a wind tunnel test. Next, we performed the wind tunnel test with a 1/5.71 small-scale rotor test device. Lastly, we performed the noise test on an actually developed wind rotor according to the IEC 61400-11 regulation.

3.1. 2-Dimensions airfoil noise test

The aerodynamic test and the noise test on the 2D airfoil were performed in the middle size semi-anechoic wind tunnel of Chungnam National University in the condition of open-jet test section. The size of the test section for this wind tunnel was 1.25 m by 1.25 m and the cutoff frequency for the noise test was 150 Hz. The 2D airfoil is shown in Fig. 5. It is 75% of the full-scale rotor diameter. Regarding the dimensions of the blade used, the chord length was 0.35 m and the span was 1.244 m. To minimize the structural vibration and noise of the model, it was made of 60 series aluminum. The wind tunnel test model was installed in a dual-end supporting structure, fixing the blade at both sides of the top and bottom on a turn table that turns 360°. Also, the wind tunnel speed and the angle of attack of the airfoil could be adjusted according to the test condition. To measure the aerodynamics of the test 2D airfoil model, we used to three-component balances for aerodynamic performance. We installed and fixed a balance to both the top and the bottom side of the test section and performed the aerodynamic test and noise test together. The wind speed condition was about 30 m/s (Re = 700,000), and we considered a Reynolds number area of the 75% position of the full-scale rotor radius. We acquired the noise using a total of six-microphones and located them at 1750 mm and 1830 mm from the back side of the airfoil blade.

3.2. Small-scale rotor noise test

The baseline rotors were scaled down by a factor of 5.71 for the wind tunnel test. The small-scale wind turbine rotor has a diameter of 1.4 m and a rotating speed which ranged from 491 RPM to 1473 RPM according to tip speed ratio. By increasing the rotational speed of the small-scale rotor, the tip speed of the model blades was set such that it was equal to that of the 10 kW wind turbine blades. In addition, Fig. 6 shows the shape when a vortex generator (from now Dot) is attached considering the tripped thickness to perform the tripped condition [4].

Six microphones in total are used for the noise recording. The microphones are located at distances of 2100 mm and 2180 mm, as shown in Fig. 12. Two microphones are placed in the rotating plane, while the other four microphones are placed near the rotating plane of the rotor at an offset of 30°. The microphones was calibrated to operate at 1000 Hz, making the calibration independent of the weighting networks, all of which have zero attenuation at this frequency. The calibration level is 94 dB at 20 μPa, with an accuracy of ±0.05 dB. For the acoustic signal measurement, six piezo-electric microphones (MG M360, 1/4″, free field type) were used, and the signals were acquired simultaneously with A/D converters (NI PCI-4472) installed on a PC. In the case of a small-scale rotor, a photo sensor installed at the rotating main shaft was used as a trigger signal to synchronize the rotating speed revolutions. The data acquisition and signal processing software was coded by LabVIEW7.1™ for easy data transfer and rapid

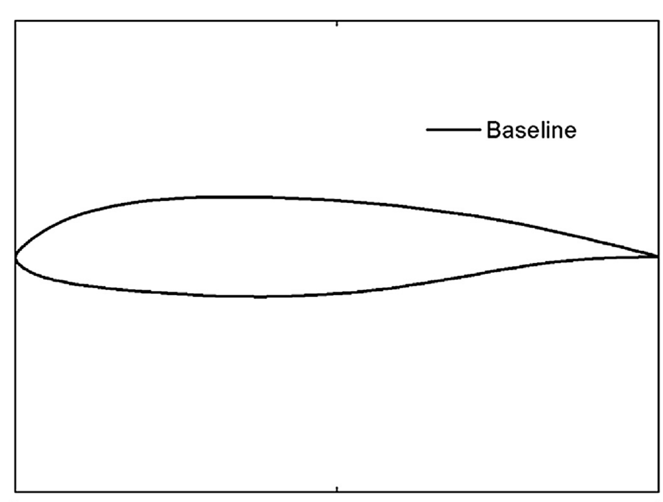

Fig. 5. The geometry of the wind turbine airfoil.

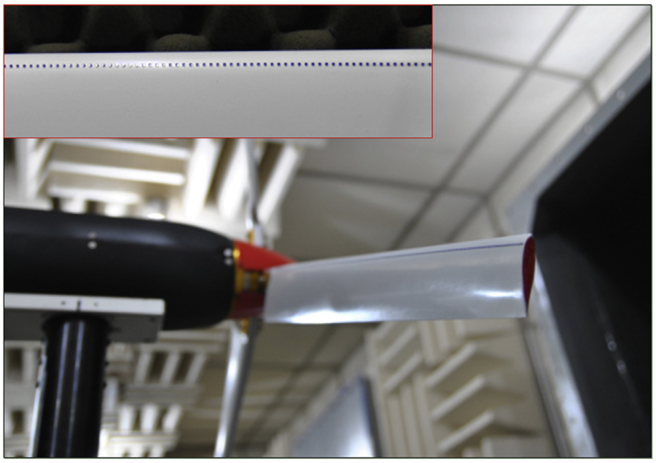

Fig. 6. Boundary layer transition dot installed in the small-scale rotor noise.

program modifications. DAQ setting parameters ware measured at a Sampling Rate of 100 kHz with a duration of 20 s.

A wind tunnel experiment was performed in this study. The performances of a small-scale wind-turbine rotor were measured in the low-speed semi-anechoic wind tunnel at Chungnam National University. The volume of the anechoic chamber was 211.9 m^3 and the tapered anechoic chambers had a cut-off frequency of 150 Hz. Test section of the wind tunnel had a 1.8 by 1.8 m cross-section and the maximum operational speed was 35 m/s. PC Base DAQ equipment was used to measure the aerodynamic performance of the small-scale rotor and an analog joystick was used to control the output power in a hydraulic system for the operation of the main shaft of the rotor. The data was collected and measured using a self-authored LabVIEW7.1™ program. Regarding the configuration of the test system, the small-scale wind turbine rotor was secured and a rotating balance capable of measuring the thrust and monitoring the hub moment was installed. The rotor test stand was covered with a wind-shield in the direction of the slipstream to prevent the fluid from interfering with the supporting area and the wind turbine rotor. The RPM of a small-scale rotor was measured using a torque meter, and a pitot-tube was installed to read the velocity of the wind tunnel. The temperature, air pressure, and humidity were recorded during the test to measure the environmental conditions.

3.3. Full-scale rotor noise test

The diameter of the full-scale rotor was 8 m, and we used a 10 kW class wind turbine. It rotates at 180 RPM at 10 m/s, which is the standard operation condition of this type of wind turbine. It can operate up to 225 RPM.

To measure the noise signal, we used a pre-polarized free-field 1/2″ microphone (type 4189 by Brüel & Kjær). To record the measured signal, we used a hand-held analyzer (type 2250 with a sound level meter from the same company). Fig. 8 shows the microphones and hand-held noise analyzer for the noise measurements as used in this paper.

Considering the possibility of a sudden change in the wind direction in the case of the small wind turbine, we installed at least two pairs of microphones and measured the noise at the same time based on the incoming wind direction, measuring the noise consecutively without moving the microphones. Also, to raise the reliability of the noise measurement, we used a hand-held LAN-XI Type 3050 device to assist with the measurement when the change of the wind direction was extreme. We measured the noise at a place at a distance of the length of the added hub height and the radius of the disk to the wind direction going by the wind turbine based on the IEC 61400-11 regulation, as shown in Fig. 7. To do this, the measurements took place 22 m away at the back side of the wind turbine, which became the noise source.

In principle, we had to measure the noise at the back of the turbine, in accord with the axis of rotation of the wind turbine, as shown in Fig. 8. However, the wind direction changes over time and the azimuth that the wind turbine rotor faces also changes slightly. Thus, it is very difficult always to measure the noise at the exact position, as in the picture above.

Regarding this problem, the IEC 61400-11 regulation permits a -15 to $+15°$ margin of error between the azimuth of the measuring position and the full-scale rotor. Therefore, we performed the test with a -15 to $+15°$ margin of error in this paper. If the error exceeded this, we measured the results using nearby microphones or moved the microphones.

We installed the microphones and amplifier on a wooden board 1 m in diameter and installed a hemisphere windscreen on top of it. The wind speed was not very high when we measured the noise; therefore, we omitted the secondary windscreen during these measurements. The microphones and amplifier were connected to the hand-held noise analyzer with an extension cable, and the hand-held noise analyzer acquired the SPL according to the time with a frequency of 48 kHz.

When the noise data was acquired, the wind speed and direction of the atmosphere were measured and recorded at the same time. The anemometrical device and anemoscope installed at the tower of the wind turbine acquired the average value of the wind speed and the direction, respectively, for 1 min. Also, before the test, we synchronized the information of the measuring time of all of the equipment and equalized the measuring times of all of the data.

For the aerodynamic data of the full-scale rotor as well, we acquired the average value of power for 1 min (kW) as generated by the wind turbine and the rotating speed (RPM) of the rotor together with the wind speed and direction. These were also sent to the same computer that recorded the wind data. The photo below shows the test device used to control the wind turbine and record the turbine and waiting situation.

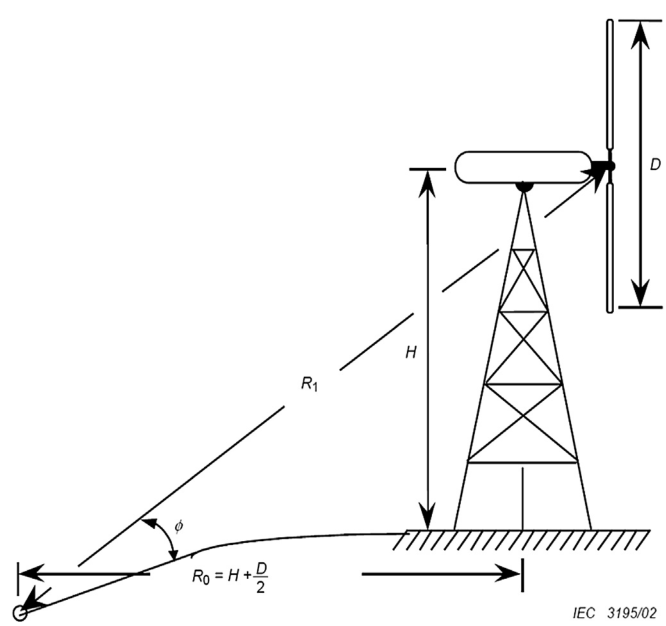

Fig. 7. The noise measurement position according to IEC 61400-11 [1].

Fig. 8. Configuration of the 10 kW class noise measurement test.

As shown in the chart in Fig. 9, we performed the post-process using software composed with MATLAB™ after recording a wave-format file through the microphone. In the post-process, we analyzed the changes in the noise level according to the rotation speed of the rotor while synchronizing the wind speed and the rotating speed of the rotor with the noise signal.

Through the post-process, we acquired the 1/3-octave band spectrum and narrowband spectrum according to the wind speed or rotating speed of the rotor in 1-min units. Also, the calculated 1/3-octave band spectrum and narrowband spectrum were reclassified according to the rotating speed of the rotor at the measuring time and were used to calculate the average spectrum according to the rotating speed of the rotor. The process of measuring the wind turbine noise was performed outside; therefore, it is inevitably exposed to background noise. When I measured the wind turbine's noise at the site, the level of the wind turbine noise was much higher than the background noise when operating in general the wind turbine in excess of 80 RPM. Thus, we confirmed that the background noise would not cause any problem when measuring the noise. However, if any strong noise source such as a car passes the measuring device, the noise signal is degraded. Therefore, we checked the 1-min average noise level. If we found an outlier, we weighted the background noise such that we eliminated the signal in this paper.

3.4. Other considerations during the wind tunnel test

At the open-jet test section during the noise test process using the wind tunnel, we needed a weighting process according to the wind speed condition, as the relative angle of attack differs along with the angle of attack during the actual test device when performing the 2D blade test [3]. Also, we needed to consider the cutoff frequency in the undirected wind tunnel, the background noise, and the turbulence intensity of the wind tunnel during the post-treatment process of the noise test. In the case of the small-scale rotor test, the aerodynamic characteristics of the small-scale rotor, which is reduced to 1/5.71 as regards the full-scale rotor, are different from the full-scale wind rotor. Therefore, to weight it, we performed the test considering the effect using a tripped condition [4].

4. Experiment results and discussion

For the noise measuring result, we compared the data based on the 1/3-octave band spectrum and primarily compared the SPL and dB(A) results, of which the A-weighting was applied according to the test condition. We confirmed the differences in the noise values due to the frequency area for several performance conditions.

The noise measurement of the full-scale rotor was conducted according to the wind speed condition for which the wind turbine was installed. Therefore, the operating condition of the wind turbine is not fixed but is scattered in a certain range based on the same wind speed and rotating condition. In this paper, this condition was that closest to the design operation condition area among the full-scale rotor. It was compared with the result of the full-scale rotor wind rotor noise measurement using the wind tunnel test noise measuring value.

The wind speed should satisfy the condition of 7–9.5 m/s while the rotating speed ranges from 170 RPM to 215 RPM. We selected the result that satisfied a tip speed ratio ranging from 9 to less than 10 and compared it to the wind tunnel test result.

4.1. Comparison of the overall sound pressure level

The result acquired from the wind tunnel test was initially compared based on the overall SPL, dB(A), to which the A-weighting was applied. We compared the noise result before applying the scaling and estimation technique to the wind tunnel test result and after the weighting. The result is shown in Table 1. For the noise value of the 2D airfoil, the result after the weighting was approximately 15.1 dB(A) and the change of the total noise was relatively small. For the noise result of the small-scale rotor, we performed the test in an un-tripped test condition and a tripped test condition and noted a major difference of more than 5.4 dB(A) in both conditions. For the total noise value of the small-scale rotor test, we confirmed that there were no differences between the un-tripped and tripped conditions. When we compared the wind tunnel test result in which the scaling and weighting technique were applied with the total noise result of a full scale rotor, there was a large difference of more than 10.1 dB(A) for the 2D airfoil test but it was less than 5 dB(A) for the small-scale rotor.

4.2. Comparison of the 1/3-octave band spectrum

We compared the test result with the above-mentioned noise value to which the scaling and estimation techniques were applied based on the 1/3-octave band spectrum condition. Fig. 11 shows the results of the comparison of the noise value before weighting the measured test data from the wind tunnel test and the full-scale rotor. We confirmed that the result of the wind tunnel had numerous errors and that the result was not in agreement with the SPL, dB(A) and the frequency domain. Fig. 12 shows the result of the comparison of the wind tunnel test for which the weighting technique was applied and the noise measurement result of the full-scale rotor based on the 1/3-octave band spectrum. Unlike the result before the weighting, we confirmed that every value was in accord in the frequency domain. In the cases of the SPL of the

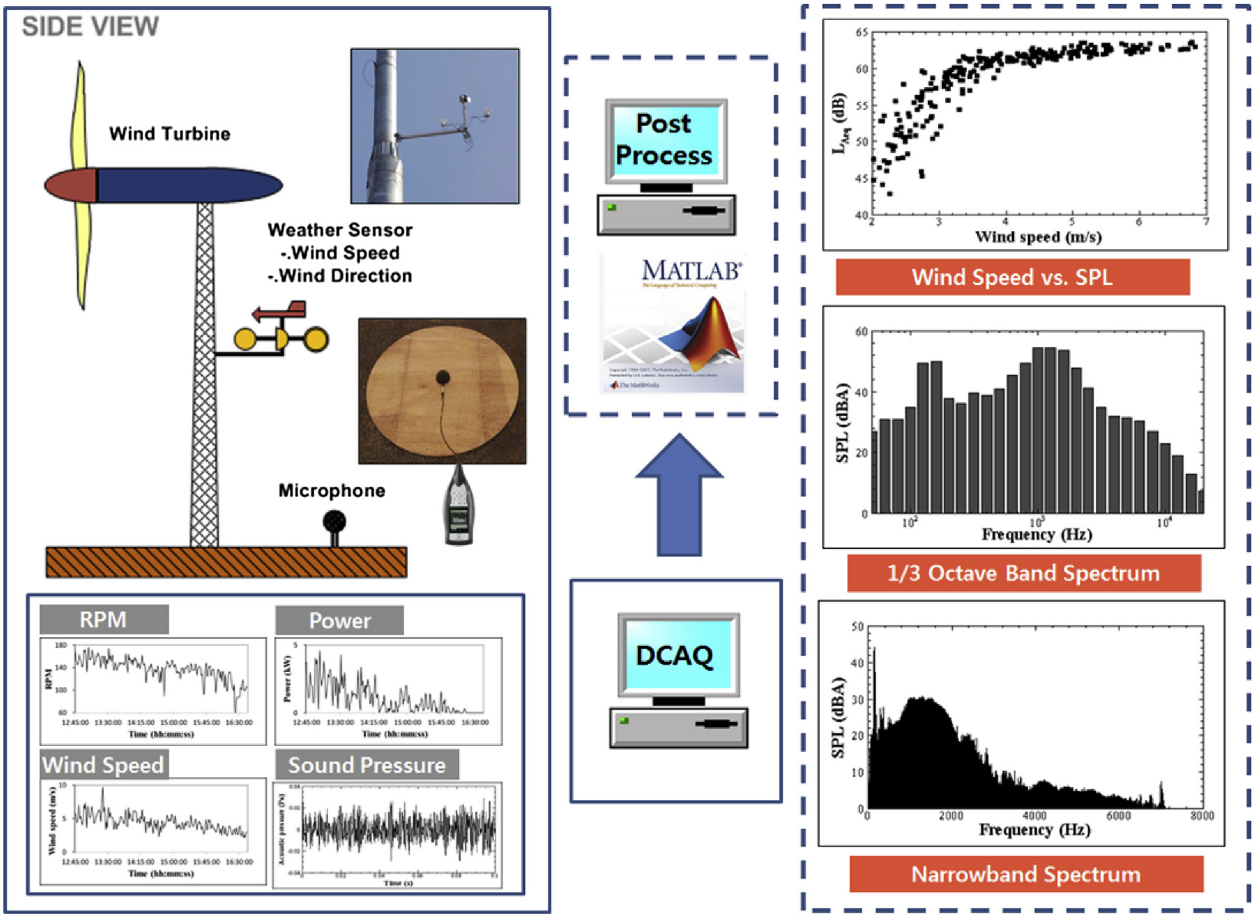

Fig. 9. Layout of the control and data post-process for the 10 kW class wind turbine.

frequency, we confirmed that the test result of the small-scale rotor showed much clearer noise characteristics for the rotating condition. However, the weighting result for the noise value of the 2D airfoil was in accord with the other frequency domain in the 50 Hz–500 Hz range, which was mainly affected by the change in the noise due to the design parameters of the airfoil [4].

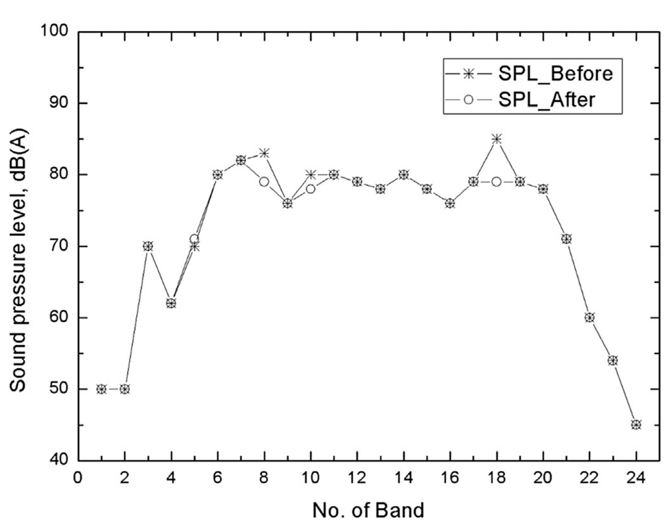

Fig. 10. Example of the tone correction calculation result for 1/3-octave band spectrum.

5. Conclusion

This paper introduced a noise estimation method for a full-scale rotor using noise test results acquired from a wind tunnel test of a 2D airfoil section and a small-scale rotor test during the process of developing a 10 kW level wind turbine rotor. We analyzed the noise capacity according the operation conditions through the noise test results and conducted a comparison with a full-scale rotor based on the IEC 61400-11 regulation. First, for the wind tunnel test conditions of the 2D blade section, we confirmed that the noise effect did not affect the rotating component of the BPF (blade passing frequency). When we compared this with the noise measurement result of the full-scale rotor, we confirmed that it showed a 10.1 dB(A) difference based on the overall sound pressure level. In

Table 1
Comparison between the wind tunnel scaling result and the full-scale rotor noise: The scaling method and estimation technique were applied in the wind tunnel test.

Test condition	OASPL scaling		Scaling difference [c]	Noise level difference [d]
	Before [a]	After [b]		
2D airfoil	66.4 dB(A)	51.3 dB(A)	15.1 dB(A)	−10.1 dB(A)
Model rotor (un-tripped)	69.2 dB(A)	66.7 dB(A)	2.5 dB(A)	5.4 dB(A)
Model rotor (tripped)	68.8 dB(A)	66.3 dB(A)	2.5 dB(A)	4.9 dB(A)
Full-scale rotor	61.4 dB(A)			

[c] = [a]−[b].
[d] = [b]−[Full-scale rotor noise level].

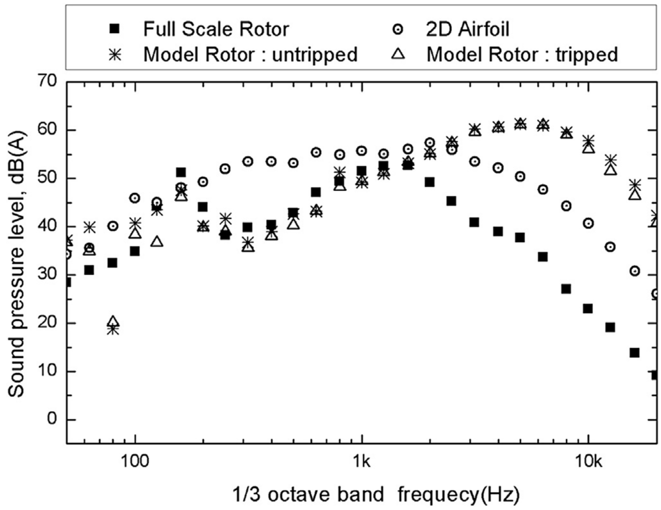

Fig. 11. Comparison of the results of the wind tunnel test and the 10 kW class wind turbine noise.

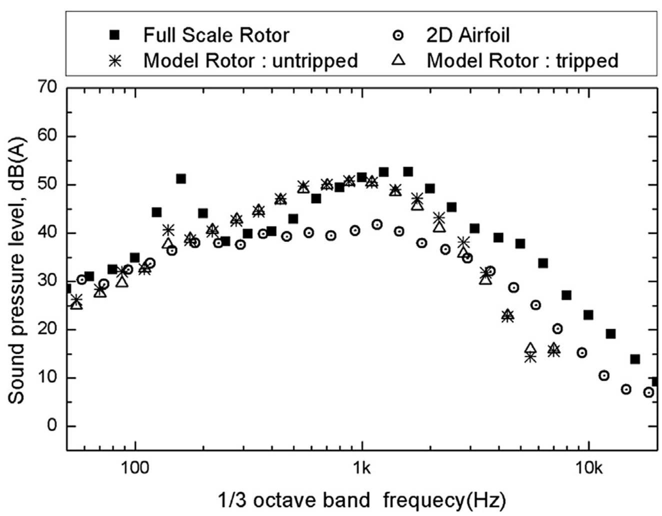

Fig. 12. Comparison between the noise estimation result using the wind tunnel test result and the noise result of the 10 kW class wind turbine and the 1/3-octave band spectrum while applying the scaling method and estimation technique.

the frequency range, it showed error of about 2–12 dB(A), except in the 50 Hz–500 Hz range, which was affected by the section shape of the airfoil. The small-scale rotor was used in two test conditions: an un-tripped condition and a tripped condition. We were able to confirm that the rotational composition in both conditions was in the 100 Hz–200 Hz range, and we also confirmed that the 1/3-octave band spectrum showed a test result similar to that of the full-scale rotor. The comparison and result for the overall SPL showed a difference of less than 5 dB(A). From these results, we confirmed that we could estimate the full-scale rotor from the small-scale rotor test. In the future, we plan to study applicable theories and weighting techniques which can increase the correctness of the full-scale rotor's noise and estimation using the wind tunnel tests results of the 2D bladed section, which showed relatively large errors. In addition, we plan to study a 1/5.71 small-scale rotor, like that used in this paper, as well as noise estimation techniques using wind tunnel test data on large rotor of more than 1/30.

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Nomenclature

Latin letters

M	Mach number
Re	Reynolds number
f_{ss}^{D}	Doppler-frequency of the small-scale model
θ'	the emitting angle of the noise source
f	frequency (Hz)
R	noise source location (m)
L_P	sound pressure level (dB)
$\widehat{L}_P$	sound pressure level, as measured in experiment, corrected for microphone effect (dB)
$n_i(f_f^D)$	Noy value

Subscripts

SPL	sound pressure level (dB(A))
Dot	vortex generator

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