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An experimental study on annoyance scale for assessment of wind turbine noise

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Wind turbine noise referred to as "swishing sound" causes annoyance due to the amplitude modulation of the noise aerodynamically generated from blades. For the propagation characteristic of sound emitted from blade, the noise can be heard differently from place to place. For that reason, many studies on numerical index evaluating annoyance caused by wind turbine noise have been examined. The results, however, showed little correlation with change of equivalent continuous sound pressure level. In the present study, twenty-eight stimuli created by numerical simulation for the test were provided and thirty-two subjects assessed noise-induced annoyance. Additionally, a correlation analysis between sound descriptors and subjective annoyance was performed by using regression analysis with SAS software. This study shows that the maximum sound pressure level with fast time A-weighting (L_{AFmax}) explains well the annoyance characteristics compared to the other descriptors considered. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4821811]

I. INTRODUCTION

Wind turbine noise is a combination of mechanical noise and aerodynamic noise, the larger portion of the total noise being caused by the latter. Aerodynamic noise is generated by fluid-structure interactions along the blades of the turbines, with trailing-edge interactions being the specific source of the amplitude modulation called the whooshing or beating sound.[1] Several studies indicate that the noises with amplitude modulation are easier to perceive than constant noises at greater distances, and have been found to be more annoying.[2,3] In addition, as the noise level is varied with propagation pattern of sound emitted from blades, a strength of amplitude modulation can be different depending on listener's position and consequently a difference in annoyance at every point can arise.[1]

The number of people disturbed with sleep disorder especially at night is expected to increase significantly as wind turbine size becomes larger.[1] Although wind turbine noise is certainly quieter than transportation and industrial noise, the percentage of people annoyed by wind turbine noise at low exposure levels has been found to be higher than the percentage of people annoyed by transportation and other industrial noise at much higher levels.[4] Several nations in Europe regarded wind turbine noise as environmental noise and have imposed regulations to control it. Most guidelines call for regulating the soundpressure level of the noise using an equivalent measure of about 40–50 dB,[5] while others have employed calculations regarding the dose-response relationship between annoyance and sound parameters such as Annual day-evening-night A-weighted equivalent noise level (L_{den}). However, the proportion of subjects annoyed by wind turbine noise changed very little or decreased as the noise level increased.[6] In other words, L_{den}

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has difficulty in being adopted as rational regulation. Therefore, fundamental research relating noise-induced annoyance to the attributes of wind turbine noise should be conducted.

In the present study, jury tests were conducted in an anechoic room using prepared stimuli to assess the degree of annoyance due to wind turbine noise. The results were then used to create an appropriate index to explain the correlation between wind turbine noise and annoyance response. In Secs. II A–II C, a composition procedure of stimuli and a jury test process are detailed. Comparison studies demonstrating trends calculated by sound parameters considering acoustic characteristics of wind turbine noise are described and then the results are discussed using a regression analysis and residual analysis.

II. METHOD

A. Stimuli

In order to collect enough data to analyze general trends in annoyance response, the effects of the stimuli at various locations needed to be measured. While it is difficult to record real wind turbine noise at several locations at once, simulated stimuli can easily be produced in accordance with any conditions necessary. In this study, a general 2.5 MW wind turbine was modeled to simulate stimuli, which were generated by numerical models. An inflow wind speed was assumed to be uniform with 10 m/s, the relative humidity was set at 60%, the air temperature was 15 °C and the air pressure was 1 standard atmospheric pressure. The sound level was attenuated at each frequency to account for sound absorption. Validation for similarity across the frequency spectrum can be confirmed from the previous study.[7]

Selection criteria for the number of stimuli were based on distances and directions from the wind turbine. The stimuli were measured at seven azimuth angle locations (0°, 15°, 30°, 45°, 60°, 75°, and 90°) and at four distances (128 m, 250 m, 500 m, and 1000 m) as Fig. 1. According to previous studies, when persons residing near the wind turbine were exposed to wind turbine noise, 85% of them could recognize the noise at a level of about 35 dB(A).[8] Since the sound level at 1000 m was about 35 dB(A), the distance was limited to 1000 m. Background noise level was set to 40 dB and the playback time of the stimuli set at 15 s.

B. Jury test condition

The jury tests were conducted in an anechoic room. The anechoic room was large, measuring $3.2 \times 3.2 \times 2.1\,m^3$. The background noise level was about 20 dB(A) and the cut-off

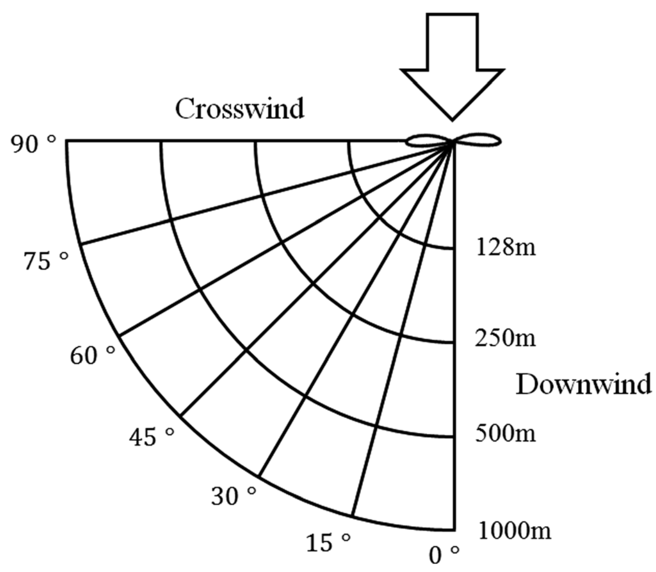

FIG. 1. Distances and azimuth angles for stimuli.

frequency was 200 Hz. Since the wind turbine noise had a center frequency between 500 and 1000 Hz, participants were able to hear only the wind turbine noise. For the study, thirty two subjects participated in the test (male: 17, female: 15). Their ages ranged from 20 to 34 years, with an average age of 25.7 years. The sound pressure levels of the stimuli were calibrated everyday by checking the output signal of B&K HATs (head and torso simulator) and the stimuli were presented to the subjects by headphones. Using the anechoic room and headphone for the test, it is possible to prevent the interference from reflected noise, background noise in anechoic room.

C. Test procedure

All subjects underwent an audiometry-screening test that progressed as pure tones 15–20 dB higher than the RETSPL (reference equivalent threshold sound pressure level) at central frequency in octave band (125 Hz–8 kHz). The subjects were considered to have normal hearing if they perceived these signals.[9] After the screening, the subjects took a 5 min break and then went on to the main test. The subjects then listened to several wind turbine noise samples and assessed the annoyance of each sample on a questionnaire using a 7-point numerical scale, where 7 equaled "highly annoyed" and 1 equaled "did not notice." In earlier studies, the 5-point scale was used for social survey on wind turbine noise problem. However, since a 7-point likert scale is known to be more prone to reflect a respondent's subjective evaluation and a 5-point scale has limited range of values to evaluate an annoyance, the assessment using a 7-point likert scale was performed.[10,11]

III. RESULTS

A. Annoyance response to wind turbine noise

Annoyance response from the experiment differed depending on the stimuli as shown in Fig. 2. Interestingly, the subject's level of annoyance due to noise depended on the location relative to the wind turbine even at the same distance from the wind turbine. Since the experiment was a subjective evaluation of wind turbine noise and the results of annoyance response were represented as average values, within-subject design in analysis of variance was conducted to find out whether there were any significant differences among values. As a result, except for

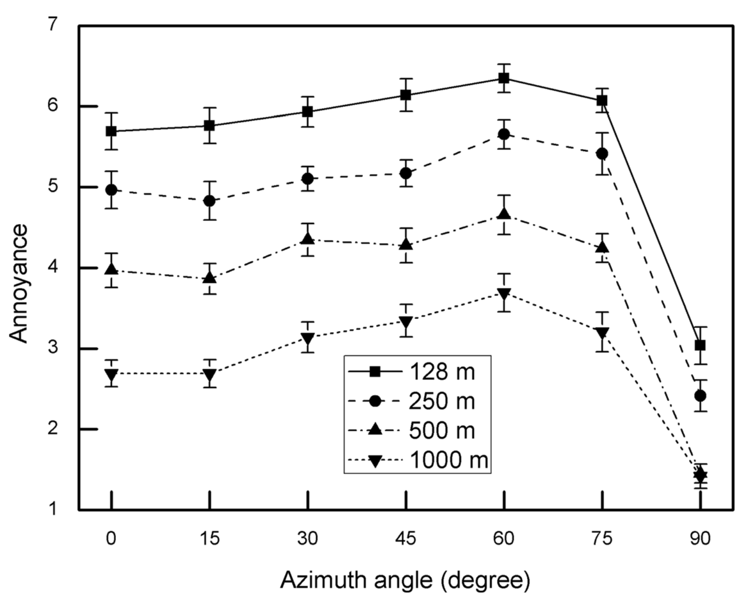

FIG. 2. Results of the annoyance response due to wind turbine noise.

few pairs, p-values were less than 0.05 indicating a confidence level higher than 95% at most of pairs.

B. Comparison of annoyance response with acoustic parameters

Annoyance is generally derived from the emission level of the sound. Several studies in Europe have been conducted on the relationship between annoyance ratings and noise level. The findings suggested that the L_{den} converted by the A-weighted sound pressure level (L_{Aeq}) was appropriate for assessment of annoyance due to wind turbine noise, but the proportion of annoyed person is smaller at higher L_{den}. Thus the parameter in use and the descriptor considering the acoustic characteristic of wind turbine noise such as L_{Aeq}, loudness, fluctuation strength, and L_{AFmax} were used to analyze the correlation between them.

In the first step of analysis, the L_{Aeq} which reflects the response of the human ear was used to figure out how the index was correlated with annoyance results. The R^2 value was calculated using regression analysis in Fig. 3(a) to directly understand the correlation. The R^2 value was quite high and there was a generally linear proportional relationship between annoyance and the L_{Aeq}.

The following procedure was used to examine loudness, a psychological indicator used to consider physical strength and human auditory sensation.[4] Since the psycho-acoustic experiment also included the participants' subjective evaluation, the loudness of stimuli was calculated using a commercial tool (B&K PULSE LapShop) and plotted in Fig. 3(b). The R^2 value was less than that found in energy equivalent metric.

Third, the correlation between fluctuation strength and annoyance was examined. One of the unique characteristics of the wind turbine noise is amplitude modulation, the fact that the sound level of a signal varies periodically over time. Additionally, amplitude modulation is known to affect how easily a noise is perceived and could thus have a significant effect on the annoyance. The values of fluctuation strength against annoyance level were evaluated by a

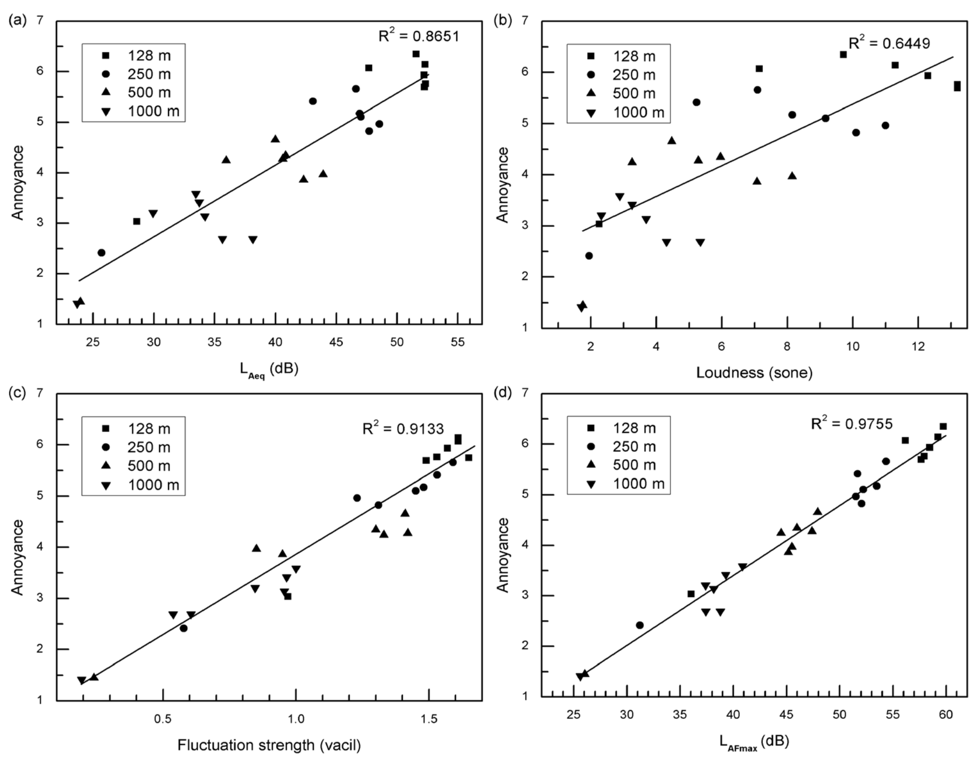

FIG. 3. The results of correlation using linear regression analysis between annoyance with 4 sound metrics, (a) L_{Aeq}, (b) Loudness, (c) Fluctuation strength, and (d) L_{AFmax}.

commercial tool (B&K PULSE LapShop). In Fig. 3(c), the fluctuation strength correlated well with annoyance compared to the former descriptors with a higher R^2 value.

The L_{AFmax} measure was used to evaluate the wind turbine noise and regression analysis conducted to examine the correlation of the L_{AFmax} and annoyance result. This parameter is widely accepted as an indicator of annoyance, disturbance to sleep and as a guideline for community noise levels. Since the modulation frequency of stimuli was about 1 Hz, a fast time constant (125 ms) was chosen. The results are plotted below in Fig. 3(d). The trend of L_{AFmax} was most similar to the results of the jury test. The R^2 value of the L_{AFmax} was also significantly higher than the other measures. The correlation coefficient between annoyance and sound metric was generally obtained in scatter plot using linear regression analysis.

However, even if the coefficient had an high level, the regression model should be verified by analysis of residual whether it is suitable for being applied, and then validation of the analysis can be assured when the studentized residuals (e_{st}) is within the boundary in ± 2.

In residual plots, the e_{st} of L_{Aeq} and fluctuation strength exceed the boundary and the e_{st} of loudness is biased to $+2$ as the loudness increases. In other words, the e_{st} distribution for the above metrics except the case of L_{AFmax} in Fig. 4 does not satisfy a condition of equal-variance and the statistical estimation using regression analysis is hardly applied to those metrics.

IV. DISCUSSION

The L_{Aeq} is still used as a regulation standard for measuring wind turbine noise and other acoustic fields in practice.[6] However, those parameters took the minimum noise level into account and calculated an average over the whole period so that the disturbance from the maximum noise level is not sufficiently reflected. Loudness is also widely used for assessment of annoyance and the evaluation of sound quality, but it is only compatible with sound which has little variation of level. Since wind turbine noise causes amplitude modulation, the loudness

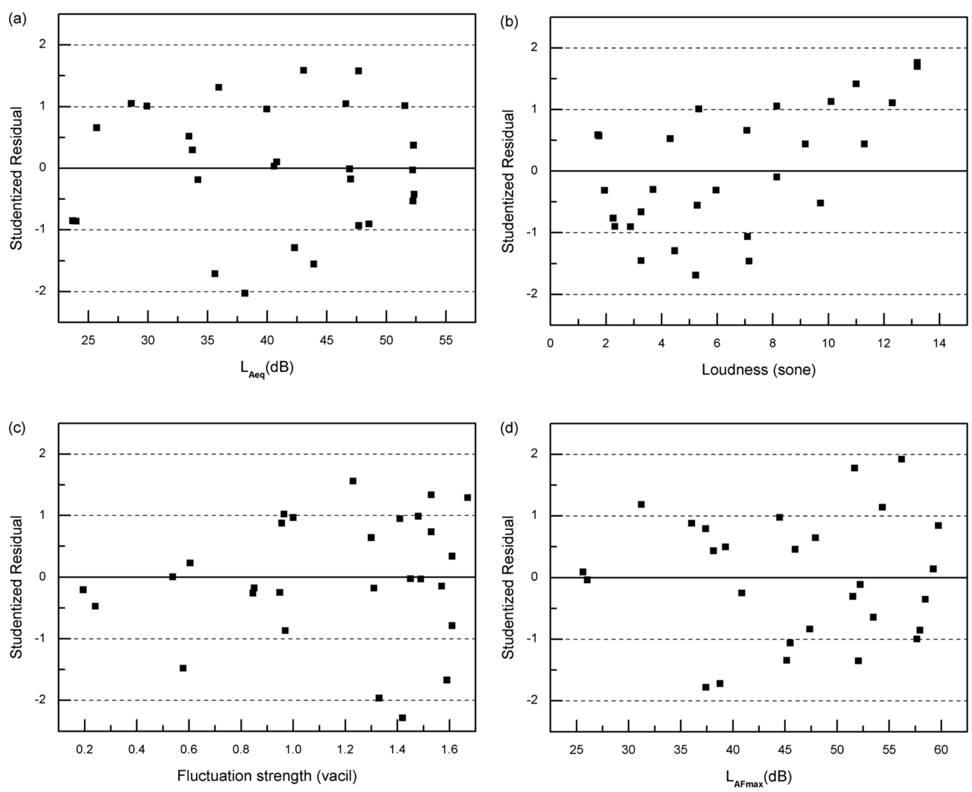

FIG. 4. The results of residual analysis for e_{st} between annoyance with 4 sound metrics: (a) L_{Aeq}, (b) loudness, (c) fluctuation strength, and (d) L_{AFmax}.

could not precisely describe the annoyance due to the maximum noise level. In this experiment, results show that as the L_{Aeq} and loudness increases, the degree of annoyance becomes lower. Therefore, energy equivalent indices demonstrated this weakness in explaining the annoyance from wind turbine noise.

As actual wind turbine noise compared with the stimuli is produced in condition of arbitrary angular variation and swishing, the trend of annoyance response, in effect, could be changed with direction in effect. Even so, because the wind turbine noise retains the characteristics of amplitude modulation even at large distance, the annoyance is certainly induced by the maximum noise level of wind turbine noise.[1] In addition, strong wind shear is known to enhance amplitude modulation and therefore the wind turbine noise-induced annoyance.[12]

As stated above, the wind turbine noise has not only the characteristics of amplitude modulation, but also low frequency modulation. In other words, the difference between the maximum and minimum noise level due to amplitude modulation is clearly perceived by frequency modulation and the disturbance could be mainly caused by the sound at its maximum level. The stimuli compared with actual wind turbine noise were produced in condition of constant angular variation and steady swishing. According to previous studies, both the maximum level and the duration of the sound can result in psychological stress and the indices based on the maximum noise level, in fact, have been used to assess the annoyance caused by aircraft and ground vehicle noise.[13] Therefore, L_{AFmax} is able to be the descriptor for explaining the annoyance due to wind turbine noise.

V. CONCLUSION

In the present study, a jury test was implemented using wind turbine noise. From the test, the annoyance response due to wind turbine noise was obtained, and analysis regarding its acoustical characteristics was performed to find out which index best fits the annoyance tendency. As a result, it was statistically confirmed that a L_{AFmax} can explain annoyance response relatively well compared to the other descriptors considered. This means that the annoyance for wind turbine noise should be assessed in terms of the maximum noise level, not daily averaged value and that further study then compared with existing research on fundamental data for environmental policy is needed. For reference, field surveys with real wind turbine noise should be performed and a quantitative method of analyzing annoyance further developed.

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