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An experimental study on rating scale for annoyance due to wind turbine noise

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ABSTRACT

Wind turbine noise referred to as “swishing sound” causes annoyance due to the amplitude modulation of the aerodynamic noise from the blades. For that reason, many studies for rating scale realizing annoyance from the noise have been examined, but show little coherence with change of noise level. In the present study, an appropriate index for describing the annoyance tendency is suggested with jury test and correlation analysis. Twenty-eight stimuli created by numerical simulation for the test were provided and thirty-two subjects assessed noise-induced annoyance based on 7 point numerical scale. Additionally, a correlation analysis between sound descriptors and subjective annoyance was performed by using regression analysis with statistics 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.

Keywords: Wind turbine noise, Amplitude modulation, Jury test, Annoyance index

1. INTRODUCTION

Wind turbine noise is a combination of mechanical noise and aerodynamic noise. The aerodynamic noise which causes several sources of noise is generated by fluid-structure interactions on the blades, among which the trailing-edge causes amplitude modulation called the whooshing or beating sound [1]. Several studies show that the amplitude-modulated sounds are easy to perceive than constant sounds, even at greater distances, and have been found to be more annoying [2-3]. Although transportation and industrial noises are certainly louder than wind turbine 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]. The noise from a wind turbine, especially in the night, could cause sleep disturbance and as the size of wind turbine becomes bigger, the people disturbed by noise are expected to increase significantly [1].

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Several nations in Europe regarded wind turbine noise as environmental noise and have imposed regulations to control it. Most guidelines call for regulating the sound- pressure 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, since, as the noise level increases, an error between the annoyance due to wind turbine noise and the rating index is significantly seen, L_{den} has the difficulty to be defined as regulation. For this reason, the fundamental researches associating noise-induced annoyance relating to the attributes of wind turbine noise should be conducted and then exposure-response relationship studies for wind turbine noise have to be derived.

In the present study, jury tests were conducted in an anechoic room taking advantage of 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 following sections, 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.

2. METHOD

2.1 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℃ 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 [6].

Selection criteria for the number of stimuli were based on distances and directions from the wind turbine. The azimuth angles were divided 7 parts spaced at 15° apart (0°, 15°, 30°, 45°, 60°, 75° and 90°) and distances were separated into 4 parts from 128m to 1000m (128m, 250m, 500m and 1000m).According to previous studies, when the residents dwelling around the wind turbine were exposed to the wind turbine noise, 85% of them could recognize the noise, even at a level of about 35 dB(A) [7]. Since the sound level at 1,000m was about 35 dB(A), the distance for stimuli was limited to 1,000 m. Background noise level was set to 40 dB and the playback time of the stimuli were set at 15s.

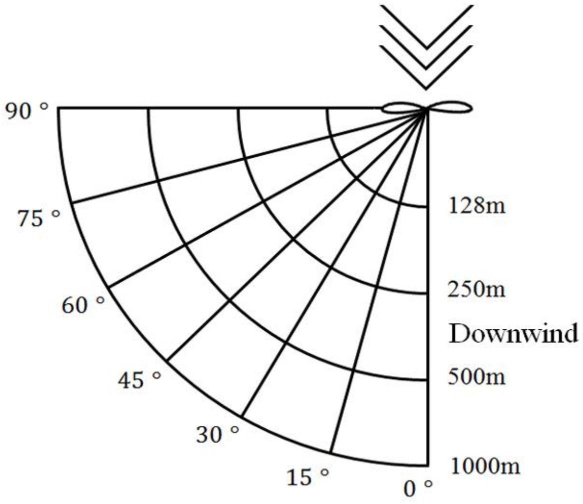

Figure 1 - Distances and azimuth angles for stimuli

2.2 Jury test condition

The jury tests were conducted in an anechoic room. The anechoic room was a 3.2 × 3.2 × 2.1 m^3 large and insulated. The background noise level was about 20 dB(A) and the cut-off frequency was 200Hz. For the study, thirty two subjects participated in the test(male: 17, female: 15) and they were 20 to 34 years old, with an average of 25.7 years. The sound pressure levels of the stimuli were calibrated every day by checking the output signal of B&K head and torso simulator and the stimuli were presented to the subjects by headphones.

2.3 Test procedure

All subjects underwent an audiometry-screening test that progressed as pure tones which were 15~20 dB over than RETSPL (reference equivalent threshold sound pressure level) at central frequency in octave band (125 Hz~8 kHz). They were considered to have normal hearing when they perceived those signals [8]. After the screening test, the subjects took a 5-minute break and then went on to the main test. The subjects then listened to a number of wind turbine noise samples and assessed the annoyance of each sample on a questionnaire using a 7-point numerical scale: “highly annoyed” = 7, “do not notice” = 1. The subjects rated the relative annoyance through a subjective point of view with hearing the stimuli.

3. RESULTS AND DISCUSSION

3.1 Annoyance response due to wind turbine noise

Annoyance response from the test differed depending on the stimuli as shown in Figure 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 few pairs, p-values were less than 0.05 indicating a confidence level higher than 95% at most of pairs.

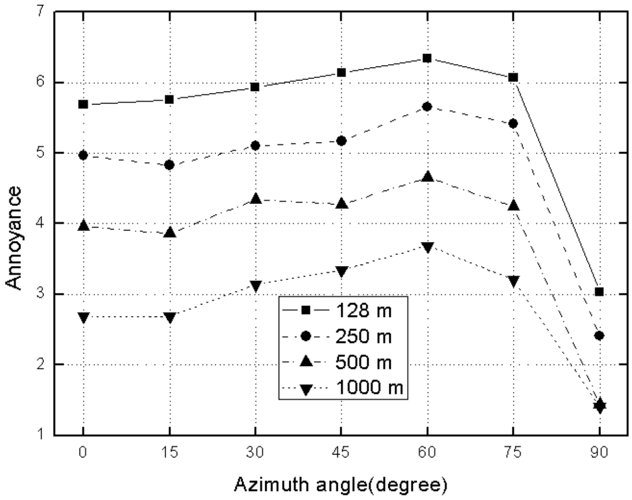

Figure 2 - Results of the annoyance response due to wind turbine noise

3.2 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 degrees of 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 less convinced 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 regards the response of the human ear used to how the index was correlated with annoyance results. The R^2 value was calculated using regression analysis in Figure 3(a) to promptly understand the correlation. The R^2 value was calculated 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 compared to annoyance response was calculated using commercial software (B&K PULSE LapShop) and plotted in Figure 3(b). The R^2 value was less than the result in energy equivalent metric.

Thirdly, 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 degree of annoyance. The values of fluctuation strength against annoyance level were evaluated by commercial software (B&K PULSE LapShop). In Figure 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 1Hz, a fast time constant (125ms) was chosen. The results are plotted below in Figure 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.

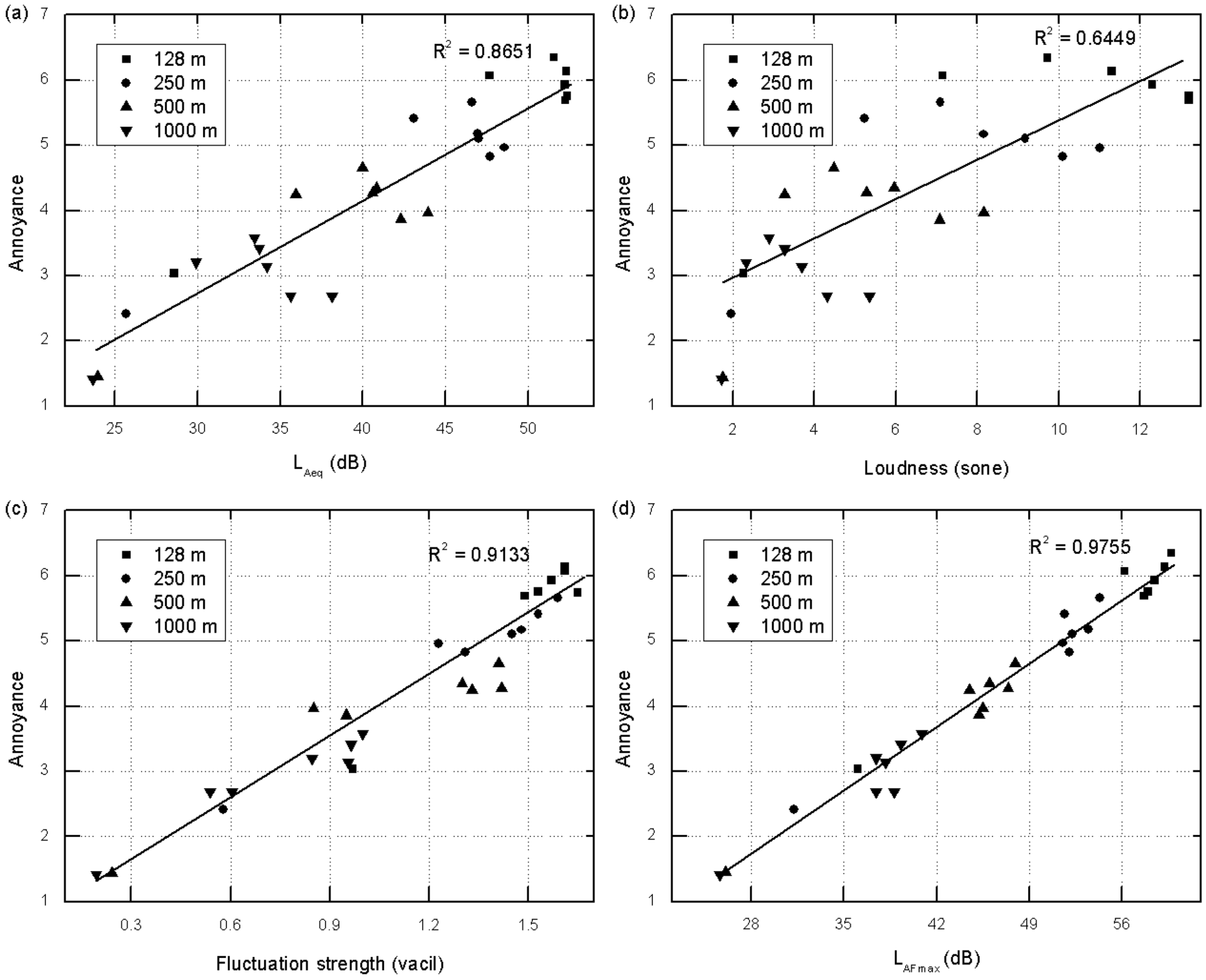

Figure 3 - The results of correlation using linear regression analysis between annoyance with 4 sound metrics (a) L_{Aeq} (b) Loudness (c) Fluctuation strength (d) L_{AFmax}

The L_{Aeq} is still used as a regulation standard for measuring wind turbine noise and other acoustic fields in practice [9].[11] 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 used widely for assessment of annoyance and the evaluation of sound quality and it is only compatible with sound which has little variation of level. Since wind turbine noise causes amplitude modulation, the loudness could not precisely describe the annoyance due to the maximum noise level. In detail at the same distance, 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.

The stimuli compared with actual wind turbine noise were produced in condition of constant angular variation and steady swishing without acoustic reflection and acoustic refraction. Although the angular velocity of rotors and the swishing are arbitrary, the wind turbine noise retains the characteristics of amplitude modulation even at large distance [1]. In other words, the trend of annoyance response could be changed with direction, but the annoyance is certainly induced by the maximum noise level of wind turbine noise. Besides, the strong wind shear is known to enhance the amplitude modulation, that is to say, the wind turbine noise-induced annoyance occurs more severe when the wind shear is presented [10].[12]

The wind turbine noise has not only the characteristics of amplitude modulation, 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. The According to previous studies, both the maximum level and the duration of the sound can result in psychological stress and weighted equivalent continuous perceived noise level(WECPNL) using the maximum noise level has been, in fact, used to assess the annoyance caused by aircraft noise [11].[13] Therefore, L_{AFmax} is also able to be the descriptor for explaining the annoyance due to wind turbine noise with its amplitude modulation.

4. CONCLUSIONS

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

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