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Experimental study of relationship between amplitude modulation and detection threshold of wind turbine noise

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Summary

Wind turbine noise is well known to have special property, easily detectable and highly annoyed at relatively lower sound level. Many studies attributed this to its sound characteristic, amplitude modulation. Also, previous studies said that knowledge of relationship between amplitude modulation and detection threshold can be helpful for reducing the effect of wind turbine noise by using auditory masking. Thus, the objective of this study is to investigate whether the amplitude modulation is really main cause of high detectability of wind turbine noise or not. Specifically, the relationship between modulation depth and detection thresholds is analyzed. In order to test this, an experiment was conducted using four alternative force choice methods. Twelve participants determined the detection thresholds of five target sounds in the presence of background noise (masker). The results show that detection threshold is decreased as modulation depth is increased. For reliability, the empirical results are compared with predictions from partial masking models of Glasberg and Moore's. Modified method of determining detection thresholds is suggested to complement differences between empirical results and predictions. For effectiveness, the way of determining detection thresholds by using A-weighed maximum sound level is also discussed.

1. Introduction

An increased need for renewable power sources has led to an expansion of the wind power sector. Although emissions of greenhouse gases from wind turbines are lower than for other power sources, wind turbines are causing disturbances to nearby people. For instance, wind turbines are emitting noise and disrupting the view and therefore evoking annoyance. So, the needs for reducing wind turbine noise arise and many country try to reduce the wind turbine noise.

As a compliment to reduction of wind turbine noise, many studies are conducted and some of them was about masking of wind turbine noise by wanted maskers. They explain the way how to mask unwanted noise and how to estimate the efficiency of masking effect. And also explain

the way how to implement the masking theory to experiment and the empirical result of masking experiment. As a result, It was showed that wind turbine noise cause high annoyance at relatively lower levels than other noise sources.[4] But none of them exactly reveals that what factors of wind turbine noise cause high annoyance at relatively lower levels and just assumes that one factor, amplitude modulation, may one of main factor of evoking high annoyance.

So, we conduct experiment of determining detection thresholds of wind turbine noise in the presence of background noise to investigate if the amplitude modulation is truly the main cause of high detectability of wind turbine noise

2. Theory

Two partial loudness models are briefly described below.[2][3] These models incorporate the present knowledge on auditory masking of stationary and time-varing signals. At first, partial loudness model for stationary signal is described. The stationary partial loudness model estimates signal's partial loudness as well as detection thresholds. To calculate the partial loudness, the concept of Equivalent Rectangular Bandwidth (ERB) and Excitation (E) is used (see [1] for details). By using these concepts, the targets partial loudness in a specific ERB, N'_T, in sone is shown in Eq. (1).

$$N'_T = C\{[(E_T + E_M)G + A]^a - A^a\}$$
$$- C\{[(E_M(1 + K) + E_{THRQ})G + A]^a$$
$$- (E_{THRQ}G + A)^a\}(E_{THRQ}/E_T)^{0.3} \quad (1)$$

Where C = 0.047, a =0.2 A = 4.62 are constants, G is the low level gain of the cochlear amplifier at a specific frequency relative to a gain at 500Hz and above and K is a frequency dependent parameter, E_{THRQ} = 2.31 is the peak excitation produced by a sinusoidal signal at absolute thresholds, E_T and E_M are the excitations from the target and the masker. The total loudness N_T is computed by summation of N'_T over ERBs. This model defines the masked threshold as N_T = 0.003 sone.[2]

Second, partial loudness model for time-varing signal is described. The time-varing partial loudness model also estimates signal's partial loudness and detection thresholds. The procedure which estimates the targets partial loudness in specific ERB in sone is identical with the stationary partial loudness model. But, additional procedure which include the concepts Instantaneous partial loudness(IPL) and short time partial loudness (STPL) is applied to the model (see [3] for details). This procedure uses different weighing functions which depends on the value of loudness.[3]

3. Method

3.1 Experimental sounds

The experimental sounds consisted of five target sounds (three wind turbine aerodynamic noises and two random-phased wind turbine noise) and one background sound. The background sound was natural ambient sound which was from the trees (not specific species). Background sound was recorded from rural area where located away from the place which included other complex noise sources (ex. Traffic noises, etc). The sound was recorded on a digital analyzer B&K 2250 using omni-directional 1/2 inch free-field microphone type 4189. The microphone was placed 1.5 above the ground level. In order to decrease the pseudo-noise generated by the wind into the microphone, a 10cm diameter foam windscreen was used. To record sufficiently high level of sound sample, the recordings were conducted when wind speed

exceeded 5m/s. The background noise recorded was 95.8 dB in equivalent sound level and 60.1 dB in A-weighed equivalent sound level.
Five target sounds were used in the experiment. Three sounds were wind turbine aerodynamic noises and two sounds were random-phased wind turbine noises. Three wind turbine noises were the signals which were estimated from one type of wind turbine at various locations.[5] As opposed to the background sound's case, three sounds were generated by house codes. The reasons why three sound were generated by artificial ways were the followings. First, it was difficult to record real wind turbine noise at several locations at once. Second, it was also difficult to record real wind turbine noise except for other unwanted signals. When real wind turbine sounds were recorded, other kinds of signals were always existed. Only filtering the unwanted parts couldn't make the sound naturally.
A general 2.5 MW wind turbine was modeled numerically to generate three wind turbine noises. An inflow wind speed was assumed to be uniform with 10m/s, the relative humidity was set at 60%, the air temperature was 15℃ was and the air pressure was 1standard 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.[5]
Selection criteria for the number of target sound were based on directions from the wind turbine. The target sounds were measured at three azimuth angle locations (0 degree, 30 degree, 60 degree) and at 500m. From measurement, It was known that sound from 0 degree had the smallest modulation depth and sound from 60 degree had the biggest modulation depth. The playback time of the target sounds set at 5s.[4]
The other two random-phased wind turbine noises were also artificial sounds which the random-phased filter was applied. After the random-phased filter was applied, another signal was made which didn't have AM but had equal spectral property. These two random-phased signal was made to compare the experiment's results of the sound which had AM and the sound which didn't have. So, three generated wind turbine noises and two artificially filtered noises were used in the experiment.

3.2 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. Twelve well trained listeners participated in the study. Most of them were the member of Aero-Acoustic and Noise Control laboratory, Seoul, South Korea. Their ages varied between 25~39 years old with an average of 29.8. One was female and eleven were men.

3.3. Procedure

A forced choice method was used to minimize effects of response bias. Auditory detection experiments suggest that more than two alternatives are to be preferred over two-alternative forced choice. So the experiment was conducted by using four alternative force choice methods with 1-up 1-down stepping rule.
The participants had to determine which of four signals contained wind turbine noise (target sound). In one random signal the target was mixed with the masker and other three signals contained background sound (masker) only. The threshold gain value of signal which contained target sound and masker changed from trial to trial depending on the participant's previous response. Each signal consisted of four intervals. The participants could listen to the target sound separately before and after all four signals had played. Also participants could listen to all four signals again if they want. The participants were guided to detect which of four signals contained target sound by using 1-up 1-down stepping rule. The experiment always started with a series of descending trials and changed to an ascending trial if the participants chose a signal which contained target sound and changed from an ascending to a descending trial if the participants chose a signal which didn't contain target sound. The experiment was ended after three alterations. It was started with threshold gain of -15dB and the step size of 5dB in the first step of descending trials. And the step size changed to 3dB on first step of ascending trials. Then the step size changed to 1dB on second step of descending trials. The experiment

continued in a similar way until the participants correctly chose the signal which contained target sound on ascending trials of step size 1dB. Introductions how to perform the experiment was displayed on the screen during the test. The experiment conducted for all target sounds.[1]

4. Results and Discussion

4.1 Partial loudness comparision

The empirical results are presented as A-weighed sound levels (dB) and compared with the results of computed results by stationary partial loudness model and time-varing partial loudness model. The results of each partial loudness model were determined in the following way.

The results of stationary partial loudness model were determined by the LAeq of the target sound which satisfied the total partial loudness N=0.003 in sone as mentioned above. However, the results of time-varing partial loudness model were determined by the LAeq of the target sound which satisfied the detectability index d'=0.84.

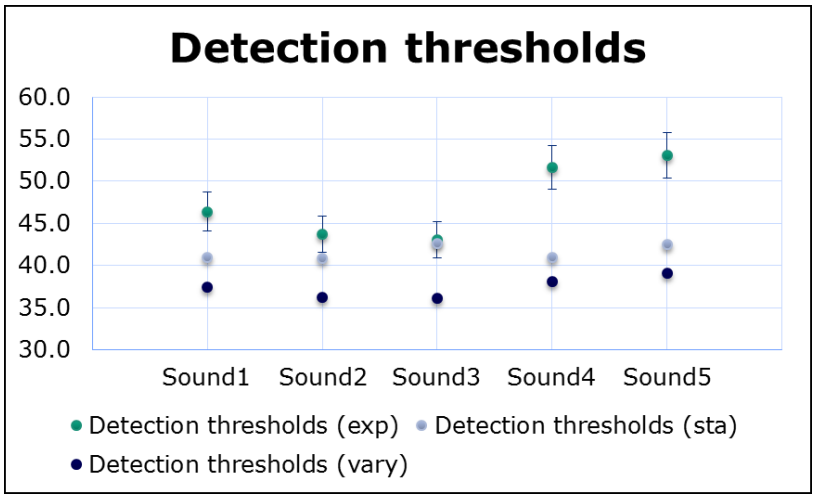

Figure 1. Detection thresholds of target sounds

In Fig 1, average A-weighed equivalent sound levels of target sound for detection threshold are presented. The error bars indicate the 95% confidence interval around the median. The empirical results for thresholds are compared with the prediction results of stationary partial loudness model and time-varing partial loudness model.

For sound 1, the detection threshold from empirical results existed on 46.4 dB(A). Prediction of stationary partial loudness model was 5.4 dB lower than the average empirical threshold. The prediction of the time-varing partial loudness model was 9 dB lower than the average empirical thresholds. For other sounds, the detection thresholds from empirical results and from predictions summarized as Table 1.

Table 1. Detection thresholds of target sounds in LAeq

	Sound 1	Sound 2	Sound 3	Sound4	Sound5
Experiment	46.4	43.7	43.1	51.6	53.1
Stationary model	41.0	40.8	42.6	40.9	42.5
Time-varing	37.4	36.2	36.1	38.1	39.1

One of five predictions by the stationary partial loudness model was within the 95% confidence interval of empirical thresholds and none of five predictions by time-varing loudness model was within the 95% confidence interval of empirical thresholds. This meant that the detection thresholds of empirical data were not well matched to that of predictions. The reason why there existed large difference between them was explained through followings.

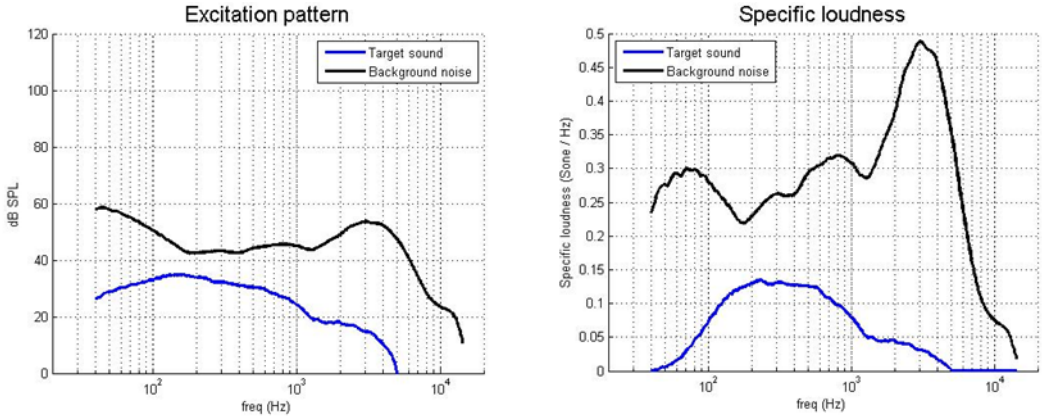

Figure 2. Excitation parttern and specific loudness of sound 4 and background noise.

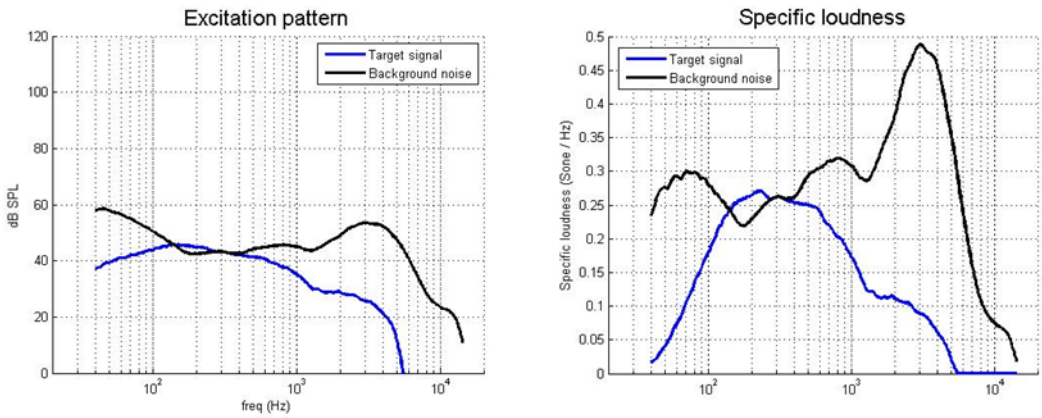

Figure 3. Excitation pattern and specific loudness of sound 4 which had equal detection threshold of empirical data and background noise.

To compute the detection thresholds, determining excitation patterns and specific partial loudness were needed as mentioned above. From both partial loudness models, sound 4's excitation pattern and specific partial loudness were presented as Fig 2. And the excitation pattern and specific partial loudness which were modified to have equal detection threshold of empirical data of sound 4 were presented as Fig 3. In Fig 2, graph lines of target sound and background noise were not crossed at any interval. However, graph lines of target sound and background noise were crossed at the interval of 150~250Hz in Fig 3. Besides of sound 4, all other target sounds had equal spectral property. We thought that the target sounds could be heard only when there existed interval where graph lines of target sound and background noise were crossed because actual neural activity in response to a sound as a function of frequency was referred to as an excitation pattern. That is, if there didn't exist any interval where graph lines of target sound and background noise were crossed, the target sound couldn't be heard. So, we thought that the partial loudness models should be modified by considering the empirical results which was conducted in this paper.

4.2 Detection experiment

The results of jury test are showed in Table 2. The results are represented as averaged value of Leq (equivalent sound level) and LAeq (A-weighed equivalent sound level).

From comparison of sound 1 (0 degree) & sound 4 (0 degree & random phased) pair and sound 3 (60 degree) & sound 5 (60 degree & random phased) pair, the wind turbine noises with AM have 5~10 dB lower hearing thresholds and also seem to be well detected by participants in comparison with the wind turbine noises without AM. Furthermore, from comparison of sound 1 (0 degree) & 2 (30 degree) & 3 (60 degree), it is showed that sound 3 with biggest modulation depth have the lowest hearing threshold value.

Table 2. Empirical result of detection experiments in dB

	Sound 1	Sound 2	Sound 3	Sound4	Sound5

Thresholds gain	-25.5	-28.0	-27.5	-20.0	-17.5
Leq	59.0	55.6	52.3	64.6	62.4
LAeq	46.4	43.7	43.1	51.6	53.1

In terms of wind turbine noise detection, to investigate if the amplitude modulation was truly the main cause of high detectability of wind turbine noise, other noise measurement unit had to be applied to empirical results. Because of the fact that sound pressure level of target sounds were changed considerably as a function of time and the general assumption that the largest part of target sound was the most audible part of that sound, noise measurement unit , LAmax, was applied to the results. LAmax was defined differently according to the value of time constant. Officially, three kinds of time constant existed such as 1 (s) for LASmax, 0.125 (s) for LAFmax, 0.035 (s) for LAImax.

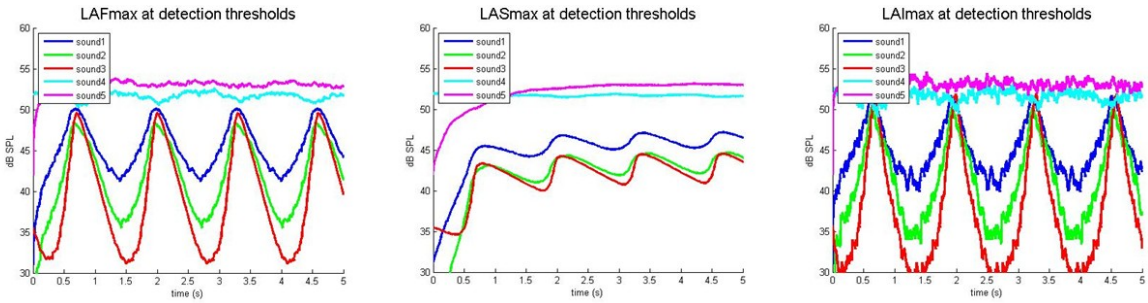

Figure 4. Plot of target sounds in LAFmax, LASmax and LAImax

In Fig 4, LAFmax (the most commonly used) values of target sounds which had exactly same LAeq value of detection thresholds from empirical results respectively as function of time were presented. From the general assumption mentioned above, detection thresholds of target sounds could be expressed respectively as the largest value of LAFmax. Like LAFmax, the values of target sounds expressed as LASmax and LAImax were presented in right side of Fig 4. From Fig 4, the detection thresholds of target sounds were determined as Table 3.

Table 3. Detection thresholds from three kinds of LAmax.

	Sound 1	Sound 2	Sound 3	Sound4	Sound5
LAFmax	50.2	48.3	49.6	52.5	53.8
LASmax	47.2	44.7	44.5	51.9	53.1
LAImax	51.7	50.3	51.9	53.2	54.6

From Table 3, difference between detection threshold of sound 1 and 4 from LAFmax was much smaller than that from LASmax and bigger than that from LAImax. Likewise, difference between detection threshold of sound 2 and 5 had similar tendency as that of sound 1 and 4. These results agreed with the excitation pattern of detection thresholds that target sound could be heard only small part of it crossed over the background noise. From the result above, it could be said that the difference between detection thresholds get much smaller when time constant for calculating LAmax became smaller. In other words, there didn't exist enough difference between detection thresholds (lower than 3dB between sound pairs (sound 1&4, sound 2&5) when time constant was applied differently.

5. Conclusion

The present results suggest that detection threshold of target sounds are affected by amplitude modulation of target sounds. For reliability of our study, the results are compared with predictions from Glasberg and Moore's partial loudness model. It is identified that results from experiment and predictions were not well matched and also was discussed for the reason why

they were not well matched in terms of excitation patterns and partial specific loudness. Afterward, we show that when the empirical results are dealt with other noise measurement unit, LAmax, the results are presented differently. The difference between detection thresholds gets smaller when time constant becomes smaller. So, we suggest that LAmax with proper time constant should be considered when the detection threshold of target sound with amplitude modulation are estimated.

Acknowledgments

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References

[1] K. Bolin, M. E. Nilsson, S. Khan, The potential of natural sounds to mask wind turbine noise, *Acta Acustica,* 2010; 96:131-137

[2] B. C. J. Moore, B. R. Glasberg, T. Bear, A model for prediction of thresholds, loudness and partial loudness, *Journal of the Audio Engineering Society*, 1997; 45:224-240

[3] B. R. Glasberg, B. C. J. Moore, Development and evaluation of a model for prediction the audibility of time-varying sounds in the presence of background sounds, *Journal of the Audio Engineering Society*, 2005; 53:906-918

[4] Y. Seong, S. Lee, D. Gwak, Y. Cho, J. Hong, S. Lee, An experimental study on annoyance scale for assessment of wind turbine noise, *Journal of renewable sustainable energy*, 2013; 5

[5] S. Lee, S. Lee, and S. Lee, Numerical modeling of wind turbine aerodynamic noise in the time domain, *J. Acoust. Soc*, 2013; 133:94-100