Annoyance caused by amplitude modulation of wind turbine noise

Seunghoon Lee[a], Kyutae Kim[a], Wooyoung Choi[b] and Soogab Lee[c]

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A listening test has been performed to investigate the relationship between human annoyance and the amplitude modulation of wind turbine noise. To obtain sound samples for the listening test, sound from a 1.5 MW wind turbine in Korea was recorded. The strength of the amplitude modulation of the sound samples was defined in terms of the modulation depth spectrum, which was approximated by assuming that the sound samples are sinusoidally amplitude-modulated. The stimuli for the listening tests were created by reducing the modulation depth spectrum of the sound samples. A total of 30 participants were involved in the listening tests. The results of the listening tests indicate that the equivalent sound level and the amplitude modulation of wind turbine noise both significantly contribute to noise annoyance. *© 2011 Institute of Noise Control Engineering.*

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1 INTRODUCTION

Wind turbines produce sound with levels that fluctuate periodically at the blade passing frequency. This amplitude modulated sound is clearly perceptible at locations near the wind turbines, whereas the perception of this sound becomes difficult at large distances from the wind turbines. However, some residents living near a wind farm have claimed that in some circumstances this sound is perceived at a distance of more than 1 km from wind turbines[1]. Recent studies[2,3] have also shown that the amplitude modulation can be heard even at large distances if the background noise level is quite low.

Several previous studies[4,5] have argued that the amplitude modulation of wind turbine noise may increase noise annoyance. Van den Berg[4] reported that residents living at 500 m and up to 1900 m from a wind farm expressed annoyance due to wind turbine noise. The residents could hear a low pitched thumping sound especially at night, which is periodic at a blade passing frequency. The author maintained that this amplitude modulation may increase annoyance. Moreover, Pedersen and Persson Waye[5] performed a field study to evaluate the prevalence of annoyance caused by wind turbine noise. The result of their study suggested that wind turbine noise is more annoying than other community noise sources with the same A-weighted sound level. They mentioned that one of the reasons for this result could be the presence of the amplitude modulation of wind turbine noise.

Indeed, amplitude modulated sound is generally known to be more annoying than un-modulated sound[6,7]. Kantarelis and Walker[6] examined the source of difference between the annoyance of diesel and electric train noises. They suggested that the amplitude modulation in diesel engine noise is the reason for the extra annoyance. The annoyance caused by the diesel train noise decreased as the modulation depth was reduced from 13 dB to 5 dB. Furthermore, Bradley[7] investigated the influence of amplitude modulated low-frequency sounds from heating, ventilation, and air conditioning (HVAC) systems on annoyance, finding that annoyance is correlated with both the sound pressure level and the amplitude modulation of the noise from HVAC systems. Thus, the amplitude modulation of wind turbine noise is also thought to increase the annoyance of wind turbine noise.

However, for wind turbine noise, only a few experiments have been performed on the influence of amplitude modulation on annoyance. Persson Waye and Őhrstrőm[8] performed a listening test to evaluate annoyance from five wind turbine noise sources and analyzed the relation between noise annoyance and psycho-acoustic parameters such as loudness, sharpness, tonality, fluctuation strength and modulation. The results show that the annoyance ratings were significantly different for the different noise sources, but none of the

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[a] School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-744, REPUBLIC OF KOREA.

[b] Romax Technology Korea, Yangjae-dong 75-3, Seocho-gu, Seoul 137-889, REPUBLIC OF KOREA

[c] Institute of Advanced Aerospace Technology, School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-744, REPUBLIC OF KOREA; email: solee@snu.ac.kr.

parameters, including modulation, could explain the differences in annoyance ratings. The reason may be that this experiment was not designed to evaluate additional annoyance caused by the amplitude modulation of wind turbine noise.

Thus, our study performs a listening test to examine the annoyance caused by the amplitude modulation of wind turbine noise. Two kinds of amplitude modulated sounds from a 1.5 MW wind turbine are used for the listening tests. The strength of amplitude modulation is quantified by measuring the modulation depth spectrum of the recorded wind turbine sound assuming that the wind turbine sound is sinusoidally amplitude-modulated. The stimuli for the listening test were designed by reducing the modulation depth of the recorded wind turbine sound.

2 METHODS

2.1 Sound Recording

Noise from a 1.5 MW wind turbine was recorded by five free-field microphones (Brüel & Kjær type 4190) with sound level meters (Brüel & Kjær type 2250) for three days. This wind turbine manufactured by NEG-Micon is an active-stall fixed-speed type with a rotor diameter of 72 m and a hub height of 62 m. Sound recordings were obtained around the turbine, at distances of 62, 98, 150, and 200 m from the turbine. The microphones were placed on a circular board of 1 m in diameter and connected to the sound level meter with an extension cable. The sound level meter recorded not only the equivalent noise level and frequency spectra, but also the time-domain signal with a sampling frequency of 24 kHz. In order to minimize wind induced noise, the microphone was covered with a foam windscreen. During sound recording, wind speed was also measured at the hub height. The wind speed varied from 3 m/s to 14 m/s during the measurements.

Since two different kinds of amplitude modulated sounds were perceived in the on-axis and crosswind direction, two samples that represent the two amplitude modulation characteristics were selected from among the sound samples. The recording positions of the samples are presented in Fig. 1. One sample (Sample I) was recorded at a distance of hub height (62 m) upwind from the turbine when the wind speed was approximately 4～6 m/s. The other sample (Sample II) was taken at a distance of hub height on the right side of the turbine when the wind speed was approximately 10～12 m/s. Figure 2 shows the one-third octave band spectrum of each of the two samples. It shows that low- to mid-frequency noise is dominant in Sample I, whereas high-frequency noise is relatively dominant in Sample II. This is explained by the difference in the directivity patterns of trailing edge noise for low and high frequencies. For the low frequency noise, its directivity pattern is expressed as dipole, while the high-frequency noise has a cardioid directivity pattern. As a result, high frequency noise is present only in crosswind direction.

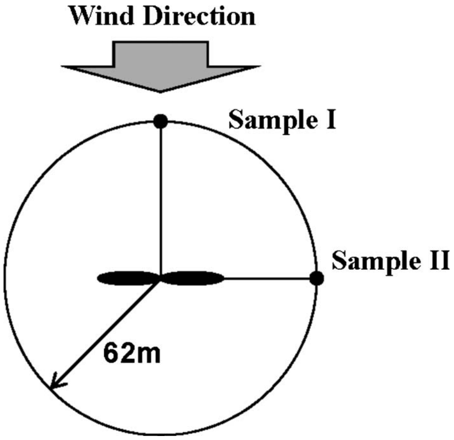

Fig. 1—Recording position of the sound samples.

2.2 Measurement of the Modulation Depth

Figure 3 presents A-weighted sound level with time weighting FAST of the two samples. It is seen that both samples are amplitude-modulated at the blade passing frequency of 0.865 Hz. The overall modulation depths of the sample I and the sample II are approximately 4 dB and 5 dB, respectively. However, the overall modulation depth should not be a parameter for quantifying the strength of amplitude modulation because it only reflects the strength of amplitude modulation in the frequency range where the sound pressure level is the highest. Thus, instead of the overall modulation depth, the modulation depth spectrum is used for quantifying the strength of the

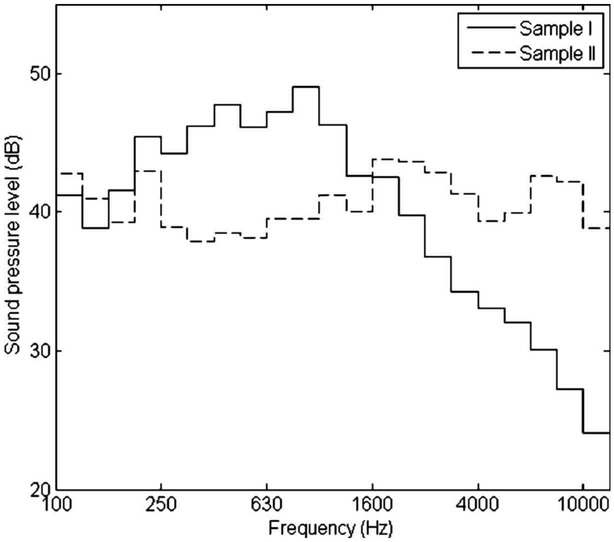

Fig. 2—One-third octave band spectrum of the two samples.

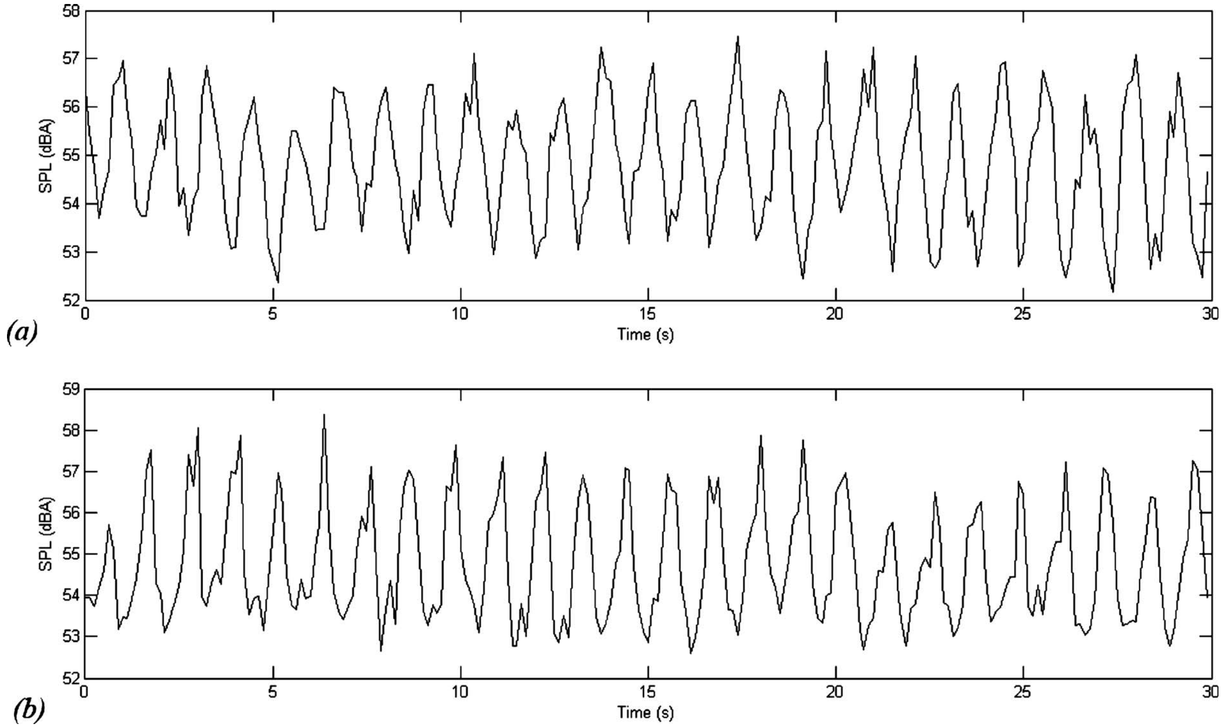

Fig. 3—A-weighted sound pressure level with time weighting FAST of (a) Sample I and (b) Sample II.

amplitude modulation in the present study. Since it is difficult to measure the modulation depth spectrum accurately, it is approximated by assuming that the sound signal is sinusoidally amplitude-modulated.

Figure 4 is a schematic of the procedure for measuring the modulation depth spectrum of the sound samples. First of all, a spectrogram is obtained by applying the Fourier transform to each time step of the signal. The time step was small enough to resolve the amplitude modulation. Next, the Fourier transform is applied again for each frequency band, but this time it is applied along the time axis. Figure 4(b), for example, shows the result of the Fourier analysis for the frequency band of 1 kHz. Since the sound signal is amplitude-modulated at the blade passing frequency, two dominant peaks are visible. One peak at 0 Hz represents the steady root-mean-square value of the signal. The other peak at the blade passing frequency represents the sinusoidal amplitude modulation of the signal. Since the sound signal is assumed as sinusoidally amplitude-modulated, all other values except the two peaks can be neglected, as shown in Fig. 4(c). In Fig. 4(c), p_0 and p_f mean the root-mean-square amplitude of the modulation at 0 Hz and the blade passing frequency, respectively. Finally, the inverse Fourier transform is applied to the result in Fig. 4(c). The modulation depth is defined as the difference between the maximum and the minimum values of the sound pressure level. Hence, the modulation depth at a frequency band can be obtained as[9]

$$\Delta L = 20 \log \frac{p_0 + p_f}{p_0 - p_f} \tag{1}$$

This procedure is applied to all frequency bands to obtain the modulation depths at a modulation frequency of 0.865 Hz for all the frequency bands. Figure 5 presents the modulation depth spectra at a modulation frequency of 0.865 Hz. The frequency resolution of the modulation spectra in Fig. 5 was set to 200 Hz.

2.3 Stimuli

If there are two amplitude modulated sounds which have different modulation depth spectra, it is difficult to identify which amplitude modulation is higher than the other, because no representative is present to determine the strength of amplitude modulation. Moreover, even though the modulation depth spectra of two sounds are the same, the strengths of the amplitude modulation can be different, if the frequency spectra of the two sounds are not the same. However, if there are two sounds which have the same frequency spectrum but the modulation depth spectrum of one sound is clearly higher than that of the other sound, it can be said that the amplitude modulation of one sound is large than that of the other sound. Hence, in order to conduct a listening test to examine the effect of amplitude modulation on annoyance, it is required that the stimuli have different modulation depth spectrum while the frequency spectrum of the stimuli remain the same.

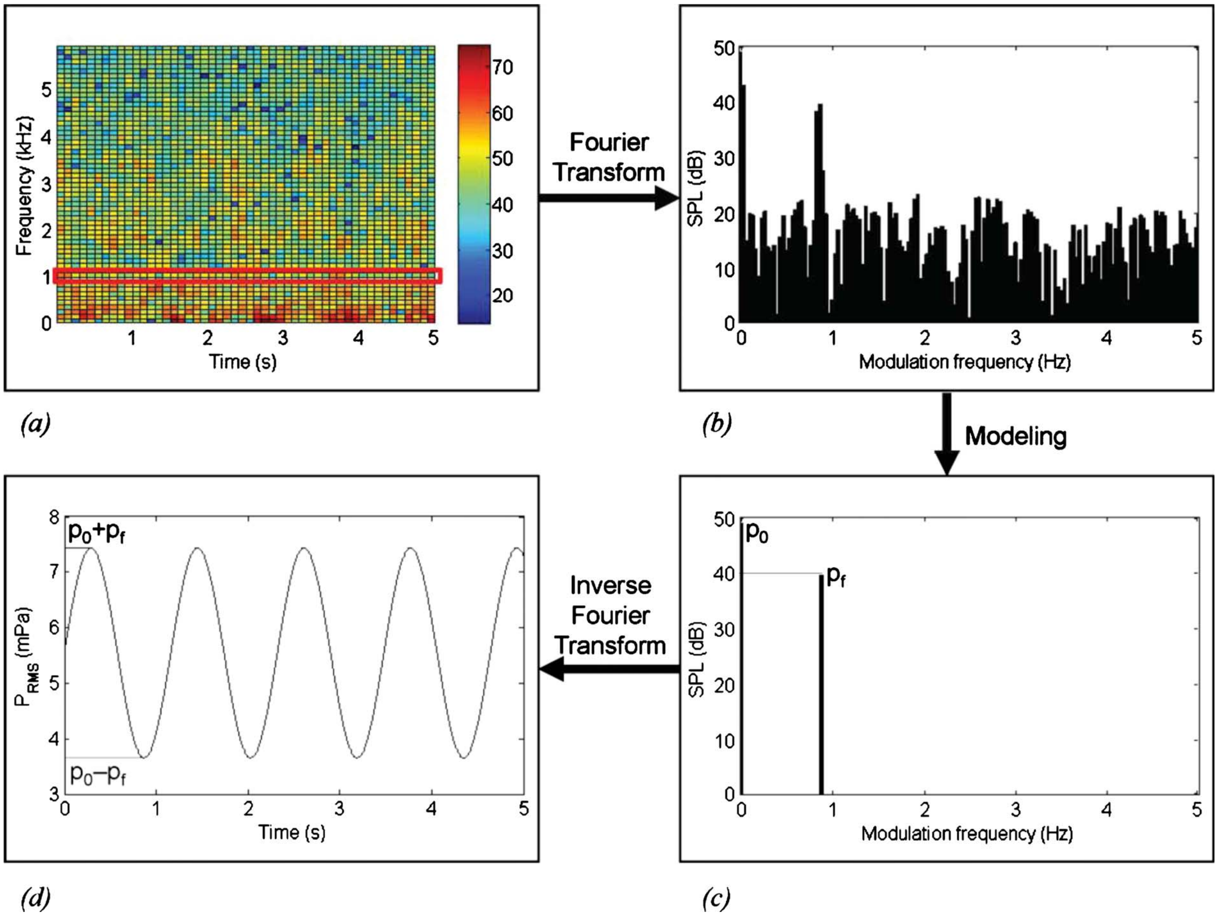

Fig. 4—Schematic of the procedure for measuring the modulation depth spectrum.

Since it is impossible to obtain these sounds by sound recording, the stimuli were created by reducing the modulation depth of the recorded samples.

Figure 6 is a schematic of the procedure for modifying the amplitude modulation of each of the sound samples. First of all, the frequency spectrum of each sample is obtained by applying the Fourier transform. This frequency spectrum is used to create a filter whose magnitude is the same as that of the original signal. The application of this filter to white noise creates a model of un-modulated wind turbine noise. This model is reasonable because the aerodynamic noise, which is the dominant noise source of modern wind turbines, is broadband in nature[10]. Finally, by adding the original sample with the un-modulated wind turbine noise, a new signal whose modulation depth is reduced from that of the original signal is obtained. The modulation depth of the new signal can be adjusted by the sound level of the white noise.

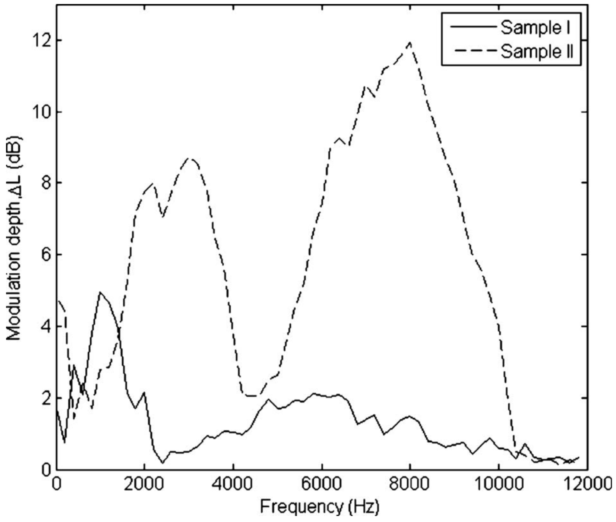

Fig. 5—Modulation depth spectra of the two samples.

Using the procedure illustrated in Fig. 6, a total of 50 stimuli (2 base samples × 5 equivalent sound levels × 5 degrees of modulation) were produced. The equivalent sound level was varied in steps of 5 dB from 35 to 55 dBA. The degree of amplitude modulation is also varied in five steps, as shown in Fig. 7, which shows the modulation depth spectra of the stimuli at an L_{Aeq} of 35 dBA. Figure 8 presents the narrowband spectra of the stimuli at an L_{Aeq} of 35 dBA. Although the stimuli were

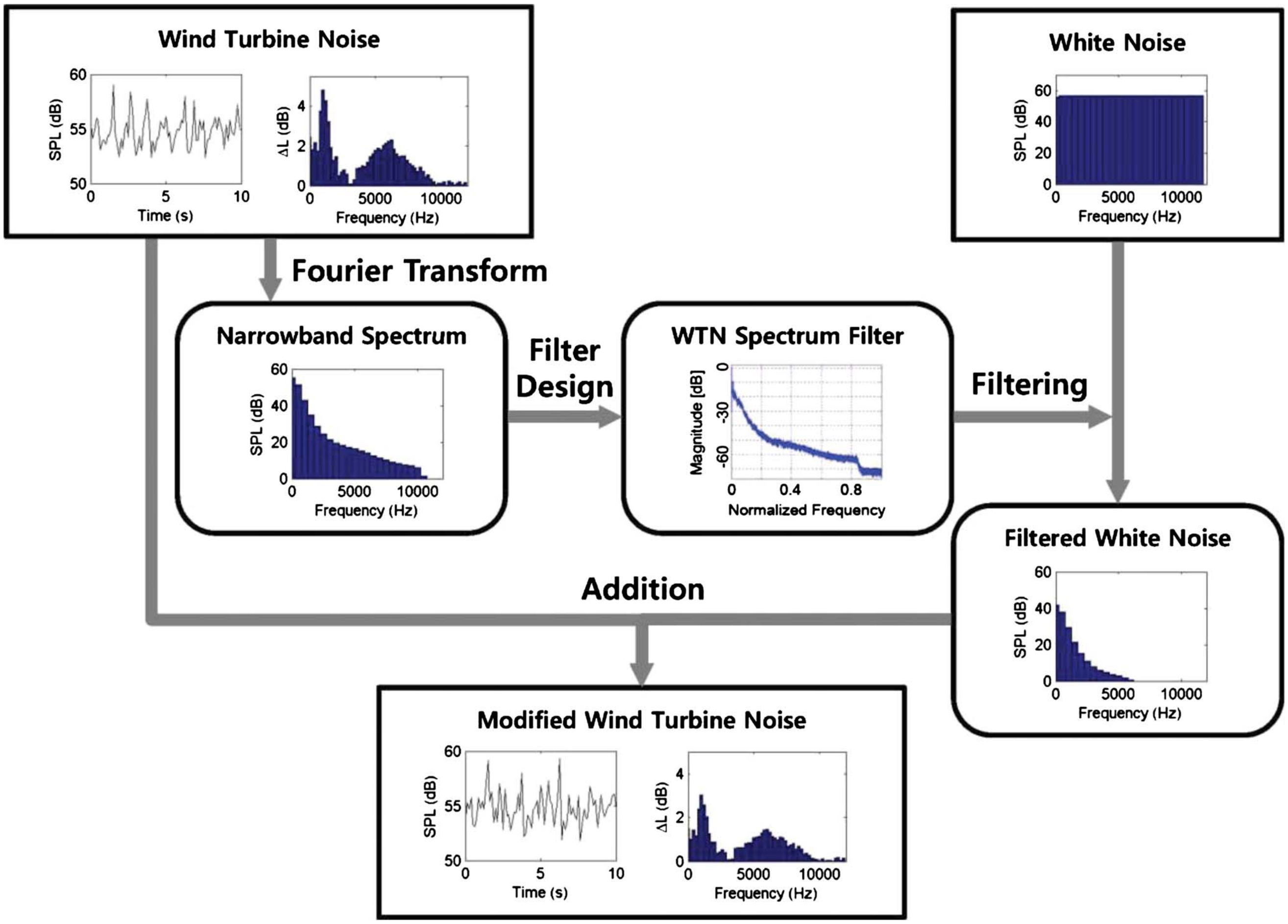

Fig. 6—Schematic of the procedure for modifying the amplitude modulation.

modified from the base samples, it is seen that the frequency spectra of the stimuli were similar to those of the base samples.

The duration of subject exposures in this study was set to 30 s. In a related laboratory test, wind turbine noise exposures were 3 and 10 minutes[8], which is longer than the exposure time in this study. However, Poulsen[11] found that exposure time did not have a significant effect on the annoyance rating for impulse noise and traffic noise. Although no related study was performed for wind turbine noise, it was assumed that the shorter exposure times can be applied for wind turbine noise. Thus, the short exposure time of 30 s was chosen for this study.

2.4 Listening Test

A total of 30 participants, 15 males and 15 females, between 20 and 30 years of age, were involved in the listening tests. Prior to the listening tests, a screening test was performed with pure tones, which consisted of the six octave band center frequencies from 250 Hz to 8000 Hz. Since none of the participants had a hearing loss greater than 20 dB from the reference equivalent threshold sound pressure level (RETSPL)[12], all the participants were regarded as having normal hearing.

The experiment was conducted in an anechoic chamber (3 m × 3 m × 2 m) where the background noise level was between 20 and 25 dBA. The stimuli were reproduced using a PC (Pentium IV) with a sound card (RME DIGI 96/8 PAD), and delivered to the listeners through a supra-aural headphone (Sennheiser HD25-1) via a power amplifier (NAD C320BEE), as shown in Fig. 9. In order to obtain a flat frequency response at the eardrums of the listener, the sound field was calibrated using a head and torso simulator (Brüel & Kjær Head and Torso Simulator Type 4128) and an audio analyzer (Brüel & Kjær PULSE Type 3560C). Before each test session, the headphone was placed over the ears of the dummy head, which was connected to the audio analyzer; then the frequency response obtained by the audio analyzer was corrected to have a flat frequency response using a software equalizer.

The participants were told that they were going to be presented with two kinds of wind turbine sound. They were instructed to record the degree of annoyance after each stimulus. The responses were recorded on an 11-point numerical scale because it was assumed that respondents were more familiar with this scale rather than a shorter 7, 9 or 10-point numerical scale[13]. The

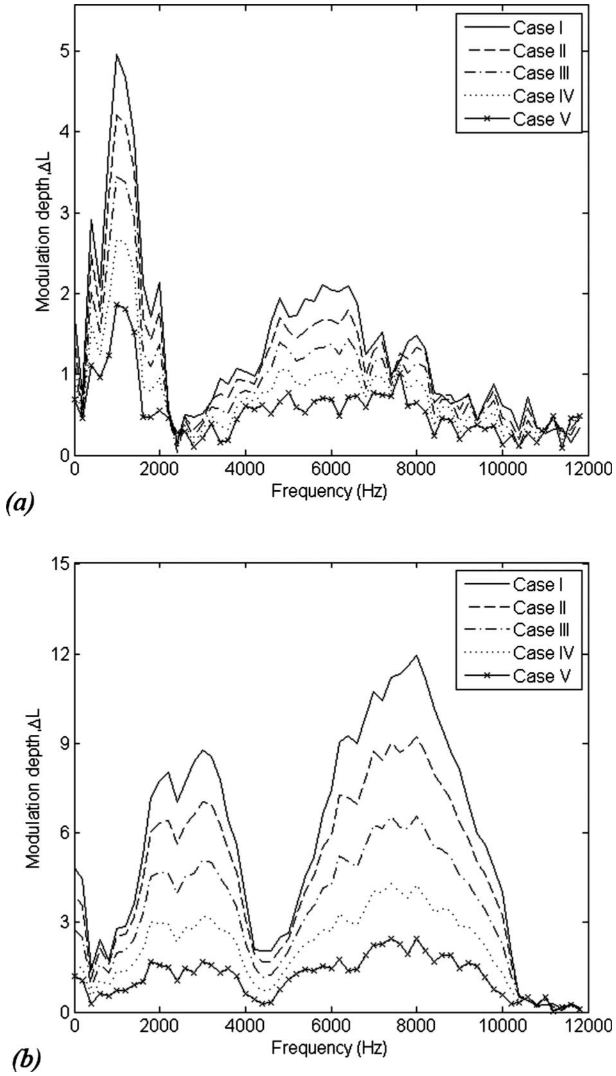

Fig. 7—Modulation depth spectra of the stimuli from (a) Sample I and (b) Sample II at 35 dB L_{Aeq}.

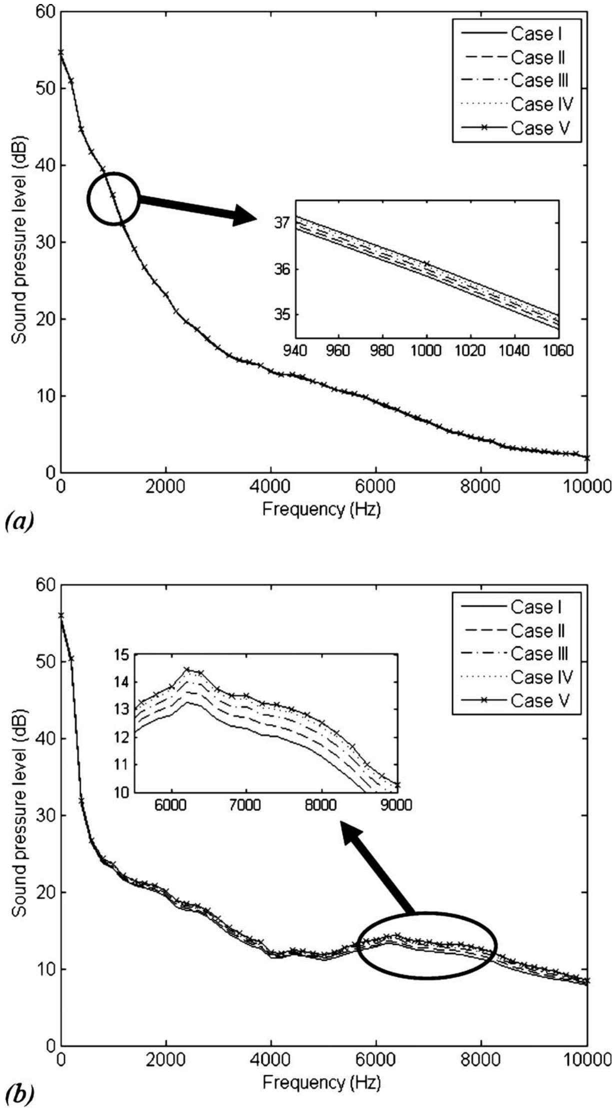

Fig. 8—Narrowband spectra of the stimuli from (a) Sample I and (b) Sample II at 35 dB L_{Aeq}.

listening test was carried out in two steps. First, the 25 stimuli originated from Sample I were randomly delivered to the participants (Test I). After a rest for three minutes, the 25 stimuli originated from Sample II were presented in the same manner (Test II). Each stimulus lasted for 30 s and the interval between consecutive stimuli was 10 s. The listening test took approximately 40 min for each participant.

3 ANALYSIS AND RESULTS

The annoyance ratings for each modulation depth spectrum in Test I and Test II are plotted in Fig. 10. These values represent average values for all of the participants.

In order to test whether the A-weighted equivalent sound level and the modulation depth are significant factors in determining the annoyance, statistical analysis was performed by a two-way analysis of variance (ANOVA). A p-value of less than 0.05 was regarded as statistically significant. The results of the ANOVA are presented in Table 1. The annoyance rating increased significantly with A-weighted equivalent sound level for both tests [Test I: $F(4,725)=114.7$, $p<0.00001$; Test II: $F(4,725)=126.2$, $p<0.00001$]. The effect of the modulation depth on the annoyance rating was also significant [Test I: $F(4,725)=2.93$, $p=0.02$; Test II: $F(4,725)=4.03$, $p=0.003$]. Thus, it can be concluded that both the A-weighted equivalent sound level and the modulation depth are significant parameters in the present study.

Moreover, post hoc pair-wise comparison was performed using Tukey's HSD. Table 2 shows the results of the pair-wise comparison. The mean annoyance difference in Table 2 represents the difference between the mean annoyance rating for the stimuli

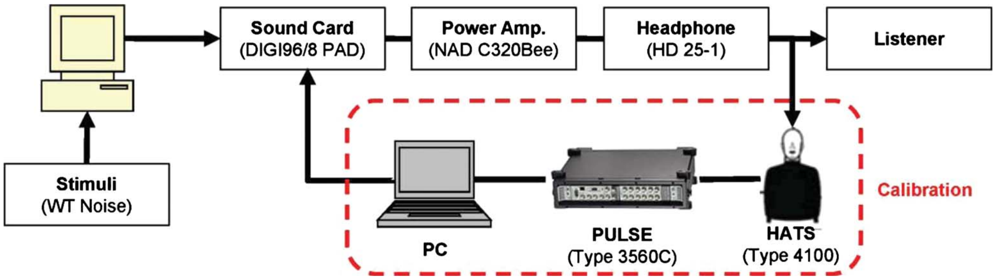

Fig. 9—The listening test setup.

having the modulation depth of (B) and the stimuli having the modulation depth of (A). It is seen that the mean annoyance difference gradually increases as the modulation depth of the stimuli increases for both tests. However, pair-wise comparison showed that not all the mean annoyance differences are statistically significant. For Test I, the annoyance rating for the stimuli having the highest modulation depth was only significantly higher than the annoyance rating for the stimuli for Case V [p=0.02], while for Test II, the stimuli of Case I and Case II were significantly more annoying than that of Case V [p=0.002; p=0.029].

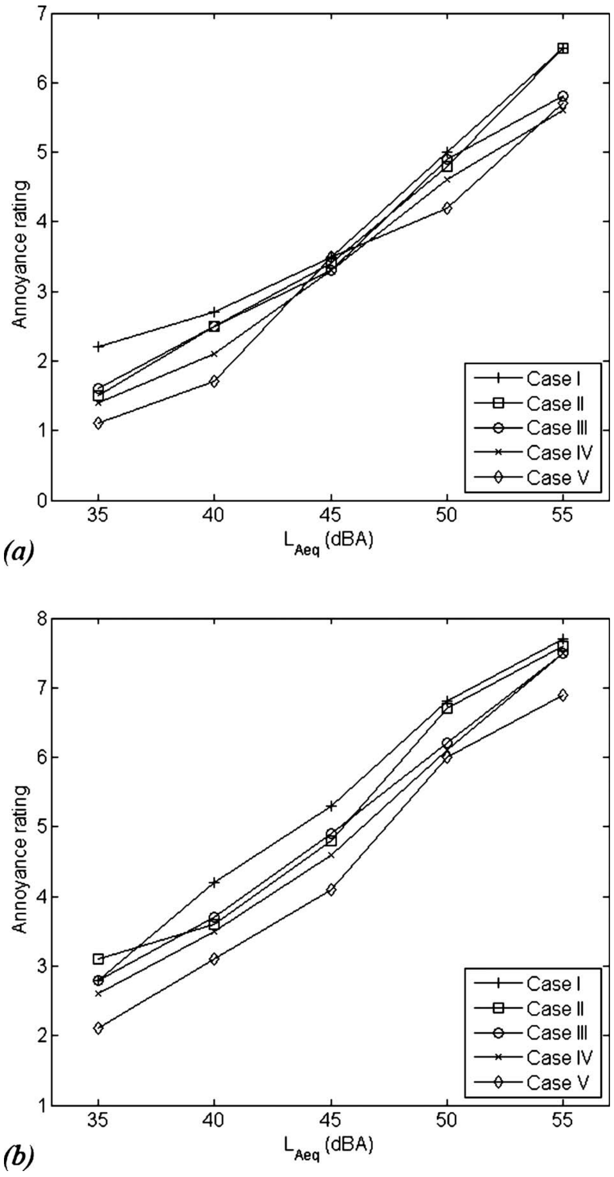

Fig. 10—The annoyance rating for (a) Test I and (b) Test II.

4 DISCUSSION

The result that the noise annoyance increases with the amplitude modulation of wind turbine noise is consistent with the result of the related previous studies cited in the introduction. However, it is not possible to make a quantitative comparison with the previous studies because not only the modulation depth spectrum but also the frequency spectrum of the stimuli used in these tests is different from those of the stimuli in the present study.

Although it has been shown that the amplitude modulation of wind turbine noise increases annoyance, it is still unclear that this amplitude modulation is present at large distances from a wind farm where residents usually live. In general, there is a buffer zone between a wind farm and residents, so if the amplitude modulation is present only near a wind turbine, or if the strength of the amplitude modulation at large distances is too weak to cause additional annoyance, the effect of the amplitude modulation on annoyance might be insignificant. However, as cited in the introduction, there is evidence that in some circumstances the amplitude modulation is high enough to causes annoyance to residents living far from wind turbines. Thus, more extensive studies are necessary to investigate the presence of the amplitude modulation at large distances from a wind turbine.

In this study, the amplitude modulation of wind turbine noise was quantified by using the modulation depth spectrum. Since the modulation depth spectrum is not a single value, but a function of frequency, the relation between additional annoyance and the amplitude modulation could not be quantified. However, if a representative value for the strength of the amplitude modulation exists, the extra annoyance caused by the

Table 1—The results of two-way ANOVA.

Listening test	Factor	Degree of freedom	F value	Significance
Test I	Equivalent sound level	4	114.7	<0.00001
	Modulation depth	4	2.93	0.020
Test II	Equivalent sound level	4	126.2	<0.00001
	Modulation depth	4	4.03	0.003

Table 2—The results of pair-wise comparison using Tukey's HSD.

Listening test	Modulation depth (A)	Modulation depth (B)	Mean annoyance difference (B-A)	Significance
Test I	Case V	Case IV	0.14	0.977
		Case III	0.37	0.535
		Case II	0.50	0.219
		Case I	0.73	0.020
Test II	Case V	Case IV	0.43	0.412
		Case III	0.55	0.162
		Case II	0.72	0.029
		Case I	0.93	0.002

amplitude modulation of wind turbine noise could be predicted. Therefore, further studies are necessary to determine the representative value for the strength of the amplitude modulation of wind turbine noise.

5 CONCLUSION

In this paper, in order to investigate the noise annoyance caused by the amplitude modulation of wind turbine noise, a listening test was performed with two sets of stimuli which were modification of recorded wind turbine noise. The results of the listening test showed that the amplitude modulation of wind turbine noise has a statistically significant effect on noise annoyance. Thus, it is concluded that when assessing community responses to wind turbine noise, not only the equivalent sound level but also the amplitude modulation of wind turbine should be considered.

However, it is still a matter of controversy whether the amplitude modulation which causes additional annoyance is also present at large distances from wind turbines. Moreover, at present no value is available to represent the extra annoyance due to the amplitude modulation. Therefore, further studies are required to investigate the characteristics of the amplitude modulation of wind turbine noise.

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