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Subjective experiments on the auditory impression of the amplitude modulation sound contained in wind turbine noise

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Summary

Amplitude modulation sound, so called swish sound, is generally contained in wind turbine noise and it can increase psycho-acoustical annoyance in the areas around wind farms. Therefore, the methods to assess the characteristics of this kind of sound should be investigated in both viewpoints, physically and psycho-acoustically. Regarding the latter problem, the authors performed auditory experiments by using a test facility capable of reproducing low frequency sounds including infrasound. As the first experiment, the fluctuation sensation caused by amplitude modulation sounds was examined by using actual wind turbine noises recorded on sites, in which the frequency components were limited in steps by low-pass filtering processing. As a result, it has been found that the fluctuation sensation is apt to be caused by the fluctuation of the frequency components higher than about 100 Hz. As the second experiment, the noisiness sensation due to amplitude modulation sounds were examined by using artificially synthesized sounds by changing their modulation depth in eight steps. As a result, a tendency has been seen that noisiness increases with the increase of AM depth even if the time-averaged sound pressure level is the same.

1. Introduction

Regarding wind turbine noise (WTN) problem, a research project entitled “Research on the evaluation of human impact of low frequency noise from wind turbine generators” has been conducted over the three years from fiscal year 2010, funded by a grant from the Ministry of the Environment, Japan. In this research project, nationwide field measurement [1,2], social survey [3], and auditory experiments [4-7] were performed. As an experiment regarding the third topic, the authors have investigated the effect of amplitude modulation (AM) sound and reported the experimental results at inter-noise 2013 [5]. This experiment has been continued by increasing the number of the test subjects to improve the experimental reliability and the results are shown in this paper.

The experiment consisted of two subjects: one was to examine the frequency components in WTN causing fluctuation sensation including the audibility of low frequency components (Experiment-1), and the other was to investigate the effect of AM sounds on noisiness sensation (Experiment-2). In Experiment-1, actual WTNs recorded in the field measurements was used and in Experiment-2 an artificially synthesized noise modelling general WTNs with/without AM components were used.

2. Experimental system

In this study, the same experimental facility as used in the former auditory experiments on low frequency noise [4-7] was used again (see Fig. 1 and Picture 1). The facility was constructed in the Institute of Industrial Science, The University of Tokyo. To produce low frequency sounds, sixteen woofers with a diameter of 40 cm (FOSTEX, FW405N, lowest resonance frequency: 27 Hz) were installed on the partition wall between a reverberation room and an anechoic room. For the production of mid/high frequency components up to 8 kHz, a wide-range loudspeaker was set at the centre point of the 16 woofers. The cross-over frequency between the two systems was set at 224 Hz. The listening position was set at a point of 3.5 m from the centre position of the loudspeakers. To correct the frequency characteristic of the total system, the digital inverse-filtering technique was applied.

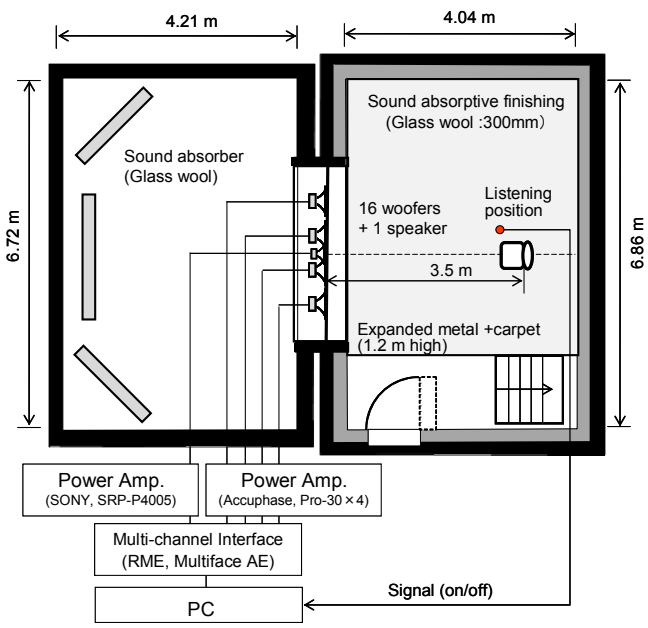


Figure 1 Experimental system.

Picture 1 Loudspeaker system and the listener's position in the receiving room.

3.EXPERIMENT-1

To examine the fluctuation sensation caused by AM sounds contained in WTNs, auditory experiment was performed by using actual WTNs recorded on sites.

3.1 Experimental conditions

As the test sounds in this experiment, actual WTNs recorded in four immission areas around wind farms in Japan were edited to have a duration time of 15 s (No.1, 2, 3 and 4 in Table 1). In addition, a WTN recorded at a point close to a wind turbine was also included for reference (No.5 in Table 1). The A-weighted time-averaged sound pressure levels (SPLs) for the duration time ($L_{Aeq,15s}$) of the sounds were from 35.4 dB to 59.5dB. Figure 2 shows the time-traces of the A-weighted SPL by FAST dynamic characteristics ($L_{A,F}$) of the sounds. The strength of AM of these WTNs were 3.5 dB to 5.2 dB in terms of the Amplitude Modulation Depth D_{AM} [2] (see Appendix). To avoid click sounds, the signals were gradually risen/fallen with a time of 0.5 s, respectively. Figure 3 shows 1/3-octave-band spectra of the test sounds, which were measured

Table 1 Test sounds used in this study.

No.	Distance from the nearest wind turbine	$L_{Aeq,15s}$ [dB]	$D_{AM,15s}$ [dB]
1	252 m	46.4	4.0
2	416 m	41.3	4.2
3	561 m	41.9	3.5
4	908 m	35.4	5.2
5	36 m	59.5	3.5

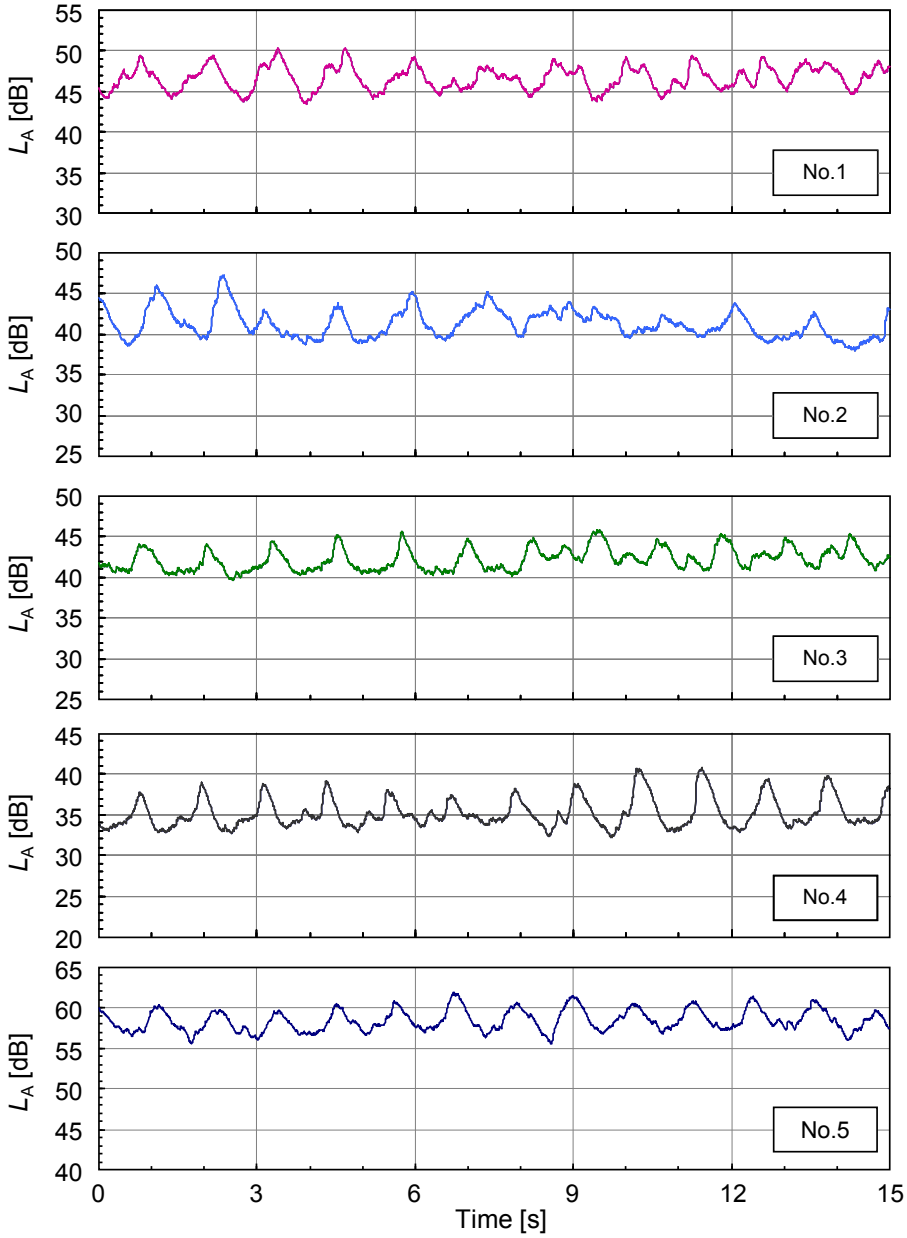


Figure 2 The time pattern of the test signals.

in the absence of the listener at the listening position where the centre of the listener's head would be. To investigate the frequency components causing "fluctuation sensation", the frequency component was limited in steps by using 8thButterworth low-pass-filter for all of the test sounds. The cut-off frequencies were set at the 1/1 octave series from 1 kHz to 250 Hz and the 1/3 octave series from 125 Hz to 20 Hz, inclusive (12 in total). As an example, Figure 4 shows the original test sound No.1 and its variations made in such a way mentioned above.

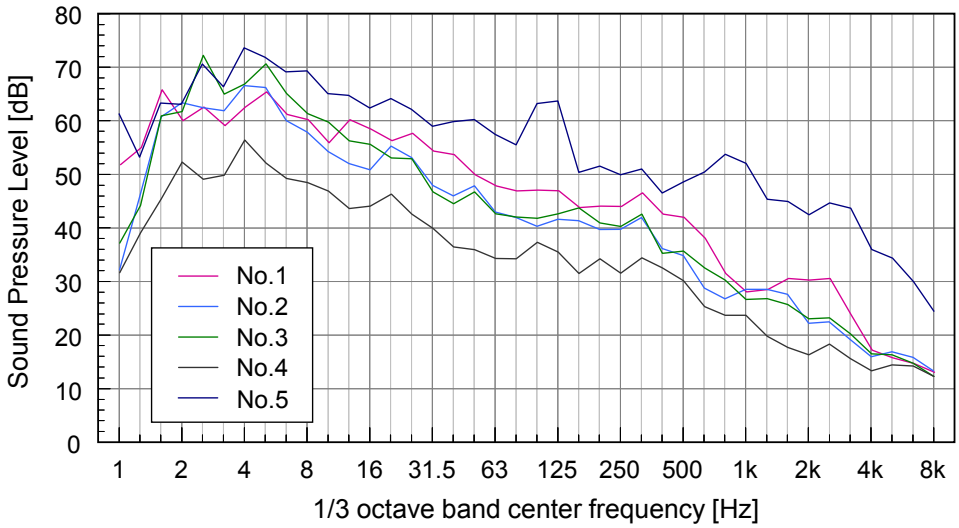


Figure 3 Sound pressure levels in 1/3 octave bands of the test

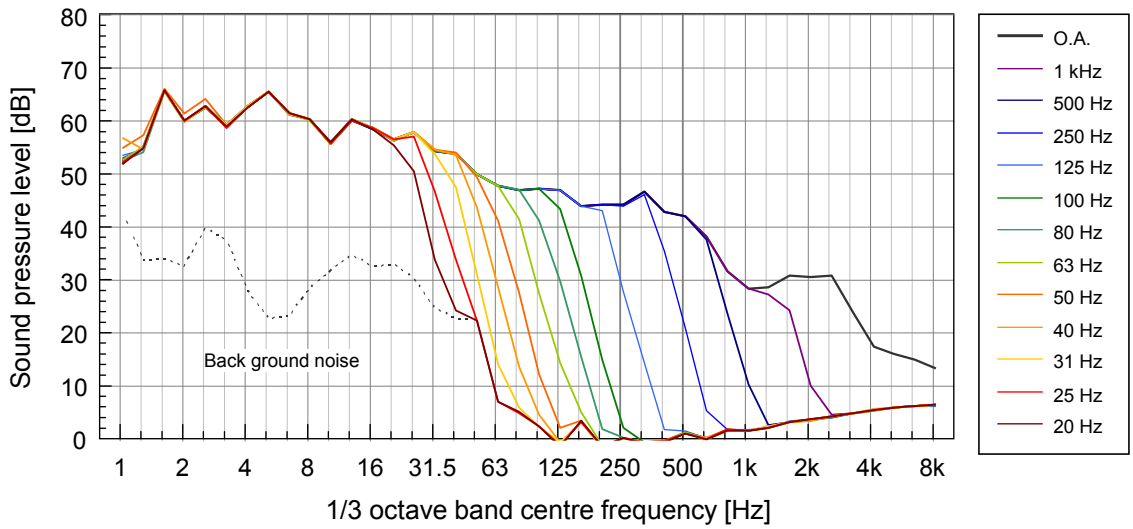


Figure 4 Sound pressure levels in 1/3 octave bands of the original test sound No.1 and its variations made by low-pass filtering.

3.2 Experimental procedure

In advance of the auditory experiment, video recording of a rotating wind turbine was presented to each subject and he/she was informed that periodically fluctuating sounds could be heard around a wind turbine due to the rotation of the blades. In the experiment, the subject sat straight on a chair to keep his/her head near the headrest in the test room (see Picture 1). Firstly, the subject was asked to judge the “audibility/sensitivity” of the test sound. In case where the subject judged the test sound “audible/sensible”, he/she was also asked to answer the extent of the “fluctuation sensation” in three-step category as shown in Table 2. The total time needed to complete the test on 65 test sounds (the test sounds No.1 to No.5; 12 modified sounds processed by the low-pass-filtering and original sound) was about 30 minutes including rest times in between. In this experiment, 17 subjects from 21 year-old to 26 year-old (13 males and 4 females) with normal hearing abilities participated. This experiment was performed according to the ethical code of The Kobayasi Institute of Physical Research.

3.3 Experimental results

As for the “audibility/sensitivity”, the ratio of the positive response was examined for each test sound. In the result shown in Figure 5, it is seen that the sounds of which cut-off frequency was higher than 80 Hz were 100% judged to be “audible/sensible”, whereas the positive response decreased as the cut-off frequency became lower. A tendency is also seen that the positive response increases as the level of the test sound becomes higher. To see the result for test

Table 2 3-step category.

0	periodical fluctuation sensation is *not* felt *at all.*
1	periodical fluctuation sensation is felt *slightly.*
2	periodical fluctuation sensation is felt *clearly.*

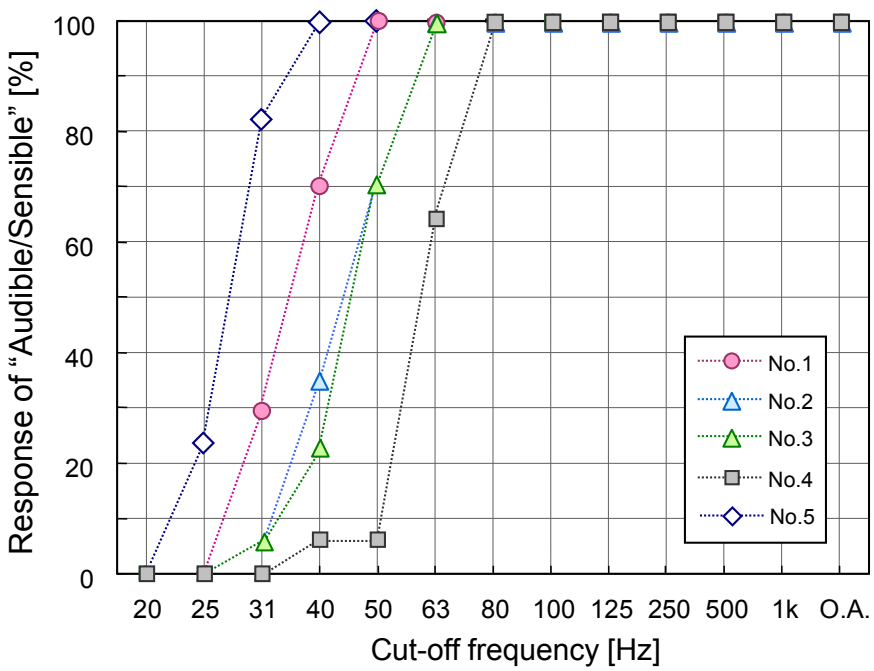


Figure 5 The ratio of the positive response of "audible/sensible" for each test sound.

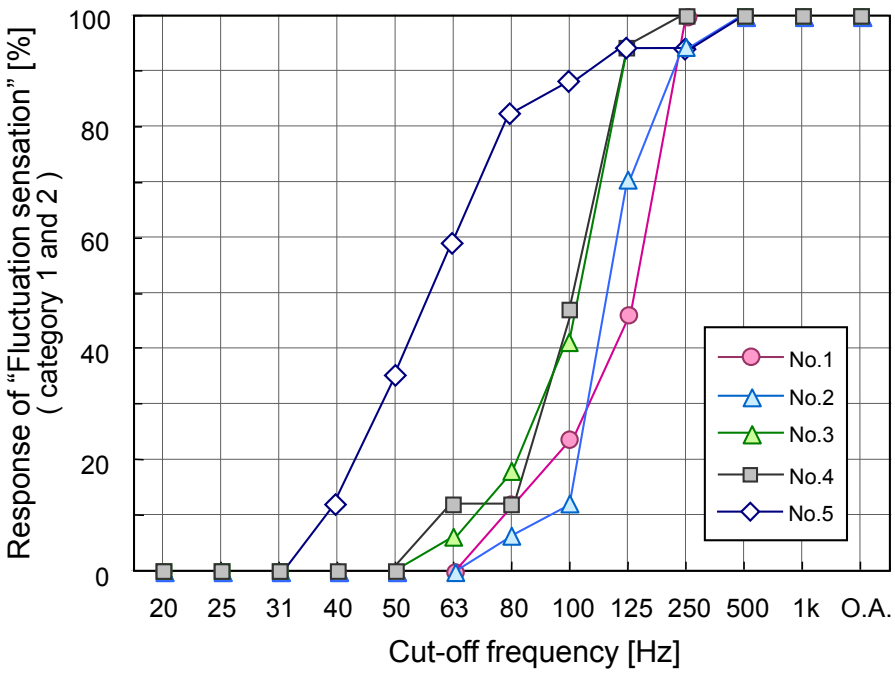


Figure 6 The ratio of the positive response for "fluctuation sensation" for each test sound.

sound No.1 which was the highest level among the test sounds recorded in immission area, the positive response was 0 % under the condition of cut-off frequency of 25 Hz or lower. As for the test sound No.5 recorded at a point close to a wind turbine, the positive response was 0 % under the condition of cut-off frequency of 20 Hz.

To investigate the extent of the “periodical fluctuation sensation”, the ratio of the experimental results of “periodically fluctuating” (categories 1 and 2 in the 3-step category shown in Table 2) was examined for each test sound. In the result shown in Fig. 6, it is seen that the sounds with cut-off frequency higher than 500 Hz were 100% judged to be “periodically fluctuating”, whereas the ratio of the sensation decreased as the cut-off frequency became lower. For the test sounds recorded in immission areas, the ratio of judgment of “periodically fluctuating” was 0% under the conditions of cut-off frequency of 50 Hz or lower and the fluctuation sensation is apt to cause at frequencies higher than about 100 Hz. Even in the case of the test sound No.5 recorded close to a wind turbine, the ratio of judgment was 0% under the conditions of cut-off frequency of 31.5 Hz or lower and the fluctuation sensation is apt to cause at frequencies higher than about 63 Hz.

4. EXPERIMENT-2

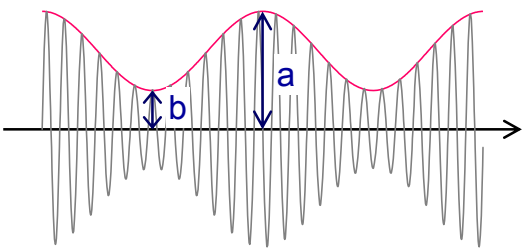
To examine the effect of AM sound in WTN on “noisiness” sensation, another experiment was performed using an artificially synthesized sound by changing its modulation depth.

4.1 Experimental conditions

To investigate the relationship between noisiness and the strength of AM, noisiness matching test was performed. As the test sounds, an artificially synthesized sound modelling the frequency characteristics of general WTNs (-4 dB/octave in band spectrum) was edited to have a duration time of 10 s. As for the standard stimulus (Ss), the model noise was set at 2-step; 35 and 45 dB in A-weighted time-averaged SPL ($L_{\mathrm{Aeq,10s}}$). As for the comparison stimulus (Sc), the model noise was modified so that its AM index (ΔL:See Fig. 7) varied in 8-step as shown in Table 3, in which the AM depth (D_{AM}) of the reproduced sounds are also shown. Figure 8 shows the variations of the test signals with 8-step different AM index. To avoid click sounds, the each sound was gradually risen/fallen with a time of 0.5 s.

4.2 Experimental procedures

As the test procedure, the method of adjustment was applied using the experimental system shown in Figure 9. In each condition, the standard stimulus (Ss) was firstly presented and secondly the comparison stimulus (Sc) was presented. After that, the subject was asked to adjust the “noisiness” of Sc so as to be equal to that of Ss by using a volume controller (see Picture 2). For the ascending/descending series in the case of Ss was set at 45 dBA, Sc was firstly set at 30/60 dB, respectively. The pair of Ss and Sc was repeated until the subject completed the adjustment. For each experimental condition, four trials (ascending/descending/ ascending/descending) were performed. For each test sound, the subject was also asked to express orally his/her impression on Sc using arbitrary onomatopoeic words. The total time needed to complete the test of 16 test sounds was about 2 hours including rest times in between. In this experiment, the test subjects were the same participated in the former experiment.



$$\begin{cases} a = 1 + m \\ b = 1 - m \end{cases}$$

$$\therefore m = \frac{a - b}{a + b}$$

$$\Delta L = 10 \log_{10} \frac{a^2}{b^2} = 10 \log_{10} \left(\frac{1 + m}{1 - m} \right)^2$$

$$\therefore m = \frac{10^{\Delta L / 20} - 1}{10^{\Delta L / 20} + 1}$$

* m : amplitude modulation degree

Figure 7 Definition of the AM index; ΔL.

Table 3 Strength of AM of the comparison stimuli (Sc).

AM index (ΔL) [dB]	D_{AM} [dB] (Ss: 35 dB)	D_{AM} [dB] (Ss: 45 dB)
0	0.8	0.8
1	1.2	1.1
2	1.7	1.7
3	2.3	2.3
4	3.0	3.0
6	4.3	4.3
8	5.5	5.6
10	6.7	6.9

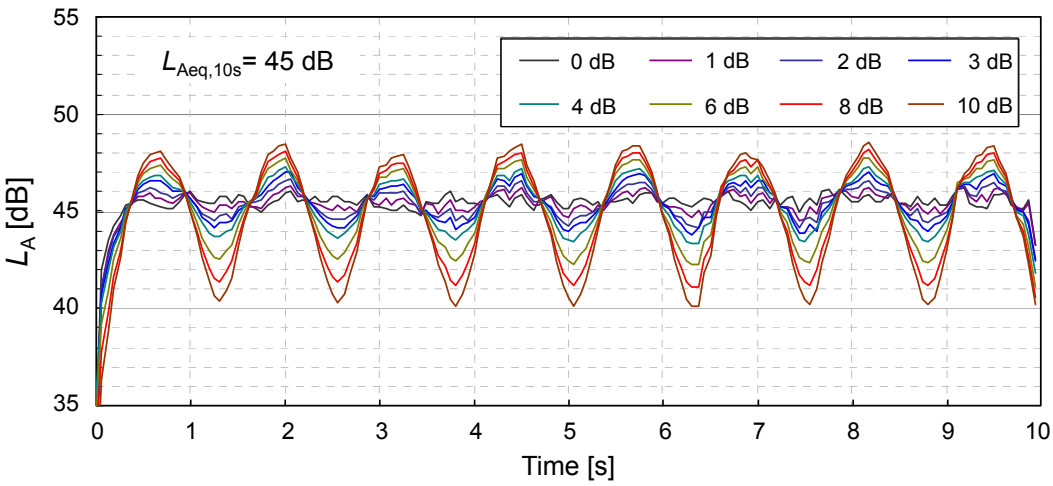


Figure 8 Variations of the test signals modulated in 8 steps (ΔL).

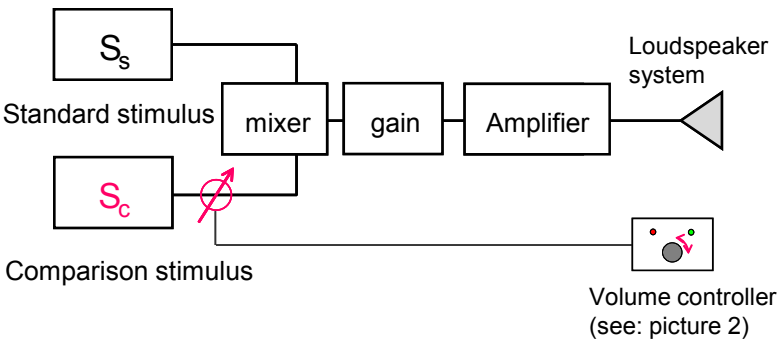
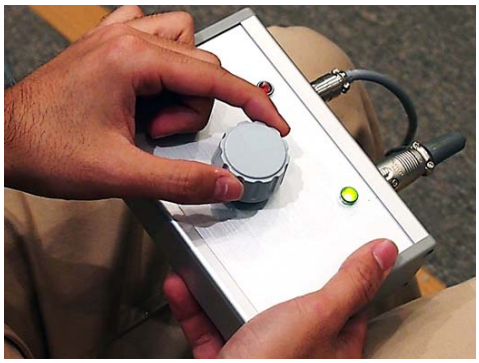


Figure 9 Experimental system for the noisiness matching test.



Picture 2 Volume controller used in the matching test.

4.3 Experimental results

Figure 10 show the experimental results of the noisiness matching test. In each figure, X-axis indicates AM index (ΔL) of Sc and Y-axis indicates the adjusted level in $L_{Aeq,10s}$. In both the figures, 0 dB on Y-axis means the $L_{Aeq,10s}$ of S_S and values of $L_{Aeq,10s}$ of S_C adjusted by the subjects were plotted in relatively level. The gray plots are the levels of adjusted Sc by each subject, the red ones are the arithmetic average of the levels of adjusted Sc by all subjects and the vertical bars indicate the standard deviations. In these results, it is seen that the averaged level of the adjusted Sc decreased as the AM index became higher. However, it is also seen that the standard deviation increased as the index became higher. This might mean that there are differences among individuals in noisiness sensation for noises with strong amplitude fluctuation.

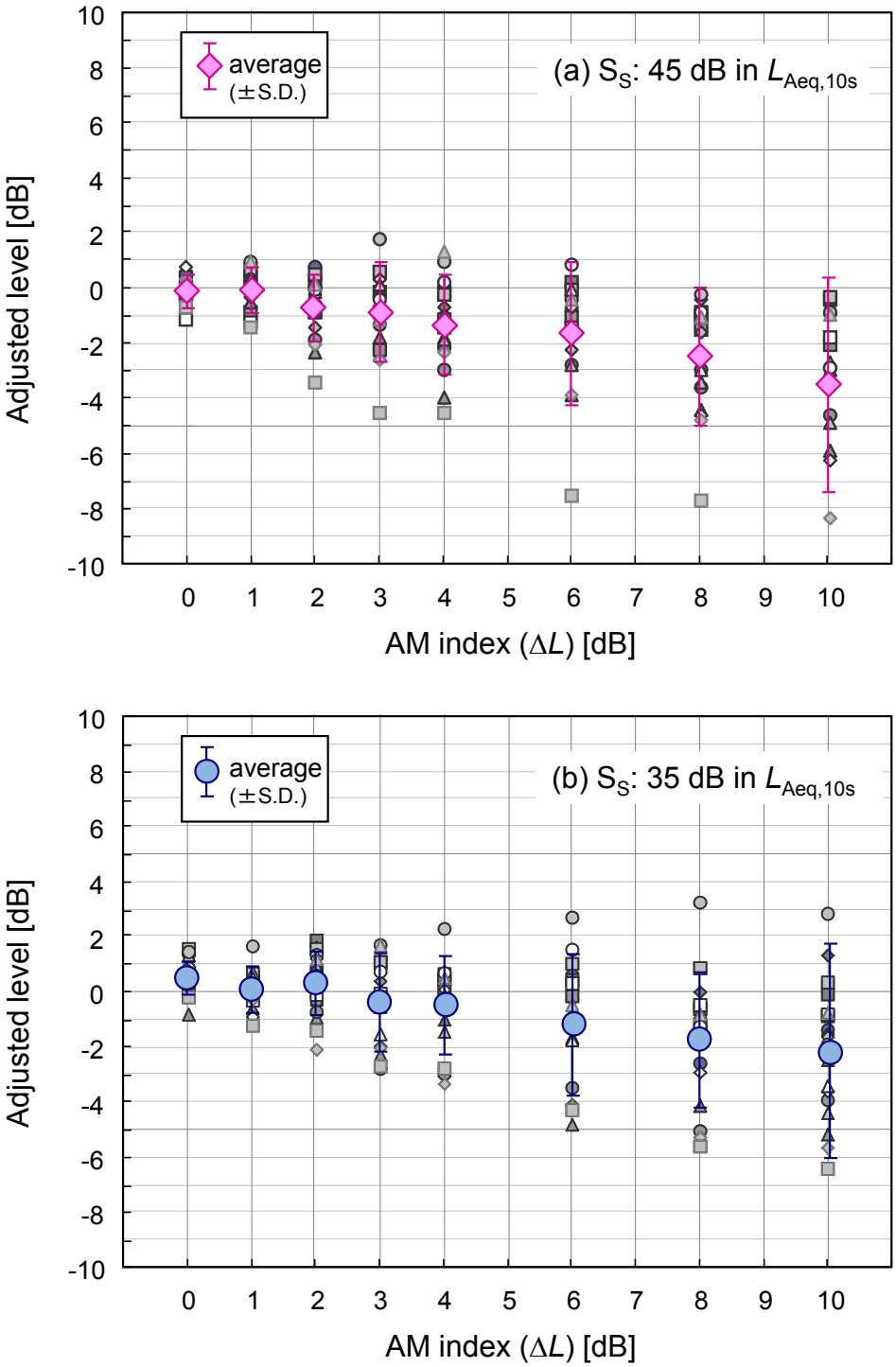


Figure 10 Experimental results of noisiness matching test.

From the results of expression using onomatopoeic words for each test sound, the ratio of "fluctuation sensation" was calculated by applying the logistic regression analysis. In the analysis, such onomatopoeic words as "Zah, Zah", "Zahn, Zahn", "Guon, Guon" were regarded as "fluctuating". Figure 11 shows the relationship between AM index (ΔL) of Sc and the ratio of the results judged as "fluctuating", in which it is seen that the "fluctuating" was caused when AM index was higher than 1.7 dB in the case of Ss was set at 45 dBA (1.5 dB in terms of D_{AM}) and 1.9 dB in the case of Ss was set at 35 dBA (1.6 dB in terms of D_{AM}), respectively. This tendency is consistent with reference [8].

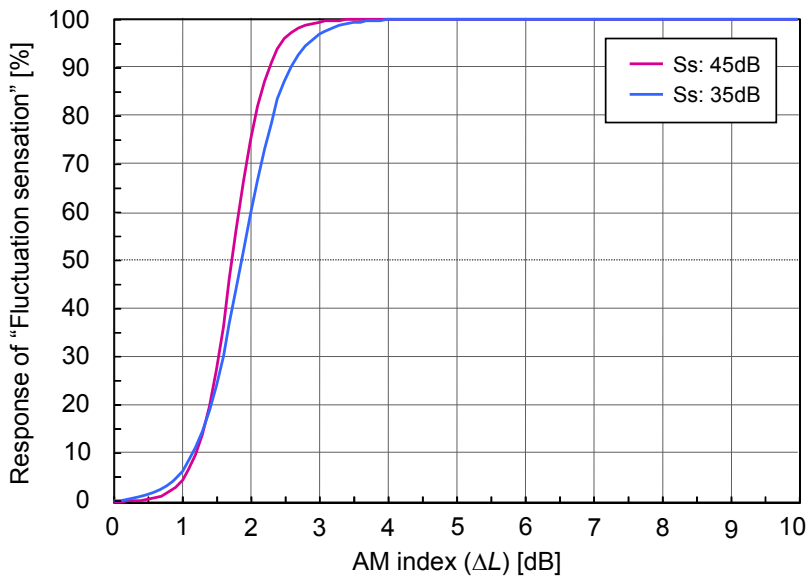


Figure 11 Fluctuation sensation vs. AM index (ΔL) .

4. CONCLUSIONS

In this study, the effects of amplitude modulation sounds generally contained in wind turbine noise have been investigated in two kinds of auditory experiments. From the results of the first experiment performed using actual WTNs recorded at wind farm sites, it has been suggested that the frequency components lower than 25 Hz are not "audible/sensible" and "periodical fluctuation sensation" causes due to the frequency components higher than about 100 Hz for WTNs observed in the immission areas.

From the results of the second experiment performed using artificially synthesized test noises with varying strength of AM, the tendency has been found that the noisiness increases as the increase of the strength of AM, whereas there aredifferences among individuals in noisiness sensation for noises with strong amplitude fluctuation. From the results of examination using onomatopoeic words,it has been observed that "fluctuation sensation" causes the AM index was higher than 1.7 dB (1.5 dB in terms of D_{AM}) for WTNs of 45 dB in L_{Aeq}.

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APPENDIX

The procedure to calculate the AM depth, D_{AM}, is as follows.
The difference of the A-weighted sound pressure levels measured through FAST and SLOW dynamic characteristics of a sound level meter ($L_{\mathrm{A,F}}(t)$ and $L_{\mathrm{A,S}}(t)$, respectively) is calculated as follows:

$$\Delta L_{\mathrm{A}}(t) = L_{\mathrm{A,F}}(t) - L_{\mathrm{A,S}}(t)$$

To evaluate the magnitude of AM statistically, the AM depth is defined as the 90 % range of $\Delta L_{\mathrm{A}}(t)$. That is,

$$D_{\mathrm{AM}} = \Delta L_{\mathrm{A,5}} - \Delta L_{\mathrm{A,95}}$$

where, D_{AM} is the AM depth and $\Delta L_{\mathrm{A,5}}$ and $\Delta L_{\mathrm{A,95}}$ are the 5 % and 95 % A-weighted sound pressure levels [dB], respectively.