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Study on the amplitude modulation of wind turbine noise: Part 1 – Physical investigation

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ABSTRACT

Amplitude modulation (AM) sound, so called swish sound, is generally contained in wind turbine noise (WTN) and it causes serious 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 former problem, a practical method to evaluate the magnitude of the AM using common acoustic measurement instrumentation is proposed in this paper. That is, the sound pressure level difference between the levels measured by using FAST and SLOW dynamic characteristics of a sound level meter is calculated for the measurement time interval under investigation and then the cumulative distribution function of the level difference is calculated. From the result, the value of 90% range is obtained as an indicator for assessing the AM. Statistical data evaluated by using this indicator for AM sounds contained in actual WTNs were obtained through the field measurements performed nationwide across Japan.

1. INTRODUCTION

When the blades of a wind turbine rotate, they generate periodic AM sound, so called "swish sound", and such AM sound increases psychological annoyance. The AM sound is related to the

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directivity of aerodynamic trailing edge noise and Doppler amplification, and its main audible frequency components are in mid-frequency range (400 to 1000 Hz) according to reference 1. It is also known that appearance of AM sound is highly dependent on the positional relationship between the rotation plane of the blades and the observer's position [1]. On the other hand, WTN changes every moment due to wind condition and is affected by the fluctuation of the atmosphere during propagation. In addition, background noise is also included. Therefore, the mean strength of the WTN observed in residential areas around wind farms varies temporally as well as the AM components. AM is a serious factor of WTN from a psycho-acoustical viewpoint and it is necessary to find a proper method for assessing the strength of AM quantitatively. Therefore, a method for estimating the extent of AM by using sound levels obtained by FAST and SLOW dynamic characteristics is proposed and the actual situation of AM sounds observed in residential (immission) areas around 18 wind farms in Japan is shown in this paper.

2. PHYSICAL PROPATIES OF AM SOUNDS

2.1 Field Measurement

In Japan, to investigate the WTN problem, the study program titled "Research on the Evaluation of Human Impact of Low Frequency Noise from Wind Turbine Generators" has been carried out over the three years from the 2010 to 2012 fiscal years sponsored of the Ministry of the Environment [2]. In this study program, WTN measurements were conducted in residential areas around 34 wind farms across Japan. The measurement for each area was performed for continuous five days by using the wide-range sound level meters equipped with double windscreen sets [3].

As an example of the measurement result, a set of data obtained around a wind turbine shown below was used for the analyses mentioned below.

- Type of wind turbine — Horizontal axis Upwind turbine
- No. of rotor blades — 3
- Rated power output — 1,950 kW
- Hub height — 65 m
- Radius of rotor — 35 m

The measurement points were set at a reference point in the vicinity of the wind turbine and seven points in the residential area around the turbine. The measurement microphone covered by a double windscreen set was set at a height of 20 cm above the ground at each point and the sound pressure signal was recorded on the SD card installed in the wide-range sound level meter.

2.2 Sound Pressure Levels

The A-weighted sound pressure levels $L_{A,F}$ simultaneously measured at the reference point (M0) and three points (M1, M5, M7) in the residential area through FAST dynamic characteristics of a sound level meter are shown in Figure 1. The average wind speed for 10 minutes at the nacelle was

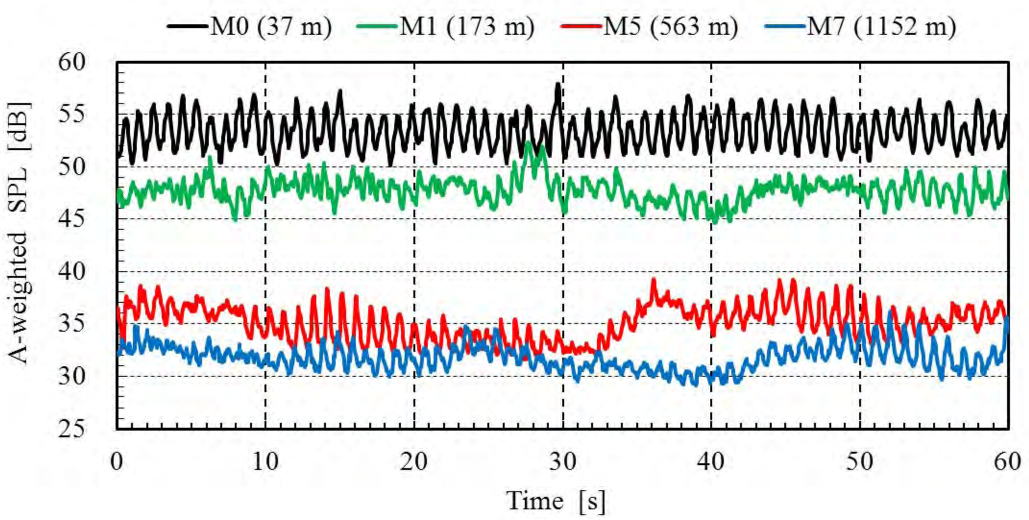


Figure 1 – Recordings of the A-weighted sound pressure levels of WTN.

11.0 m/s and the rotation speed was 20.5 rpm. The $L_{A,F}$ varied regularly with a period of 0.97 s. This period corresponds to the inverse of the blade-passing frequency (three times rotation frequency).

Figure 2 shows the 1/3 octave band sound pressure levels $L_{peq,10min}$ at the four measurement points, in which the component of 1 Hz and its harmonics are clearly seen at M0, M1 and M5 but the levels of these components can be considered to be much lower than human hearing threshold. In the figure, the criterion curve proposed by Moorhouse *et al*. [4] is plotted for a reference. In the result for M7, these frequency components are not seen; it might be due to the influenced by the wind noise occurred at the microphone.

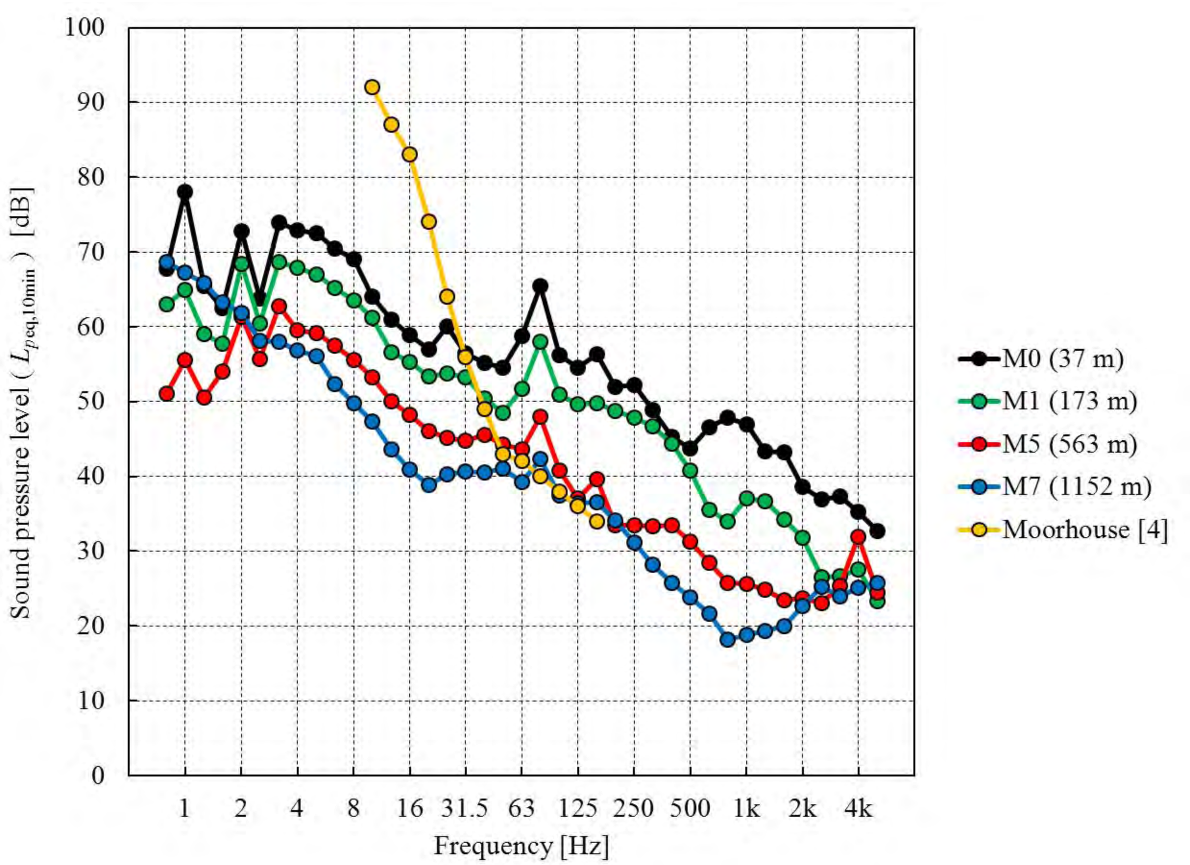


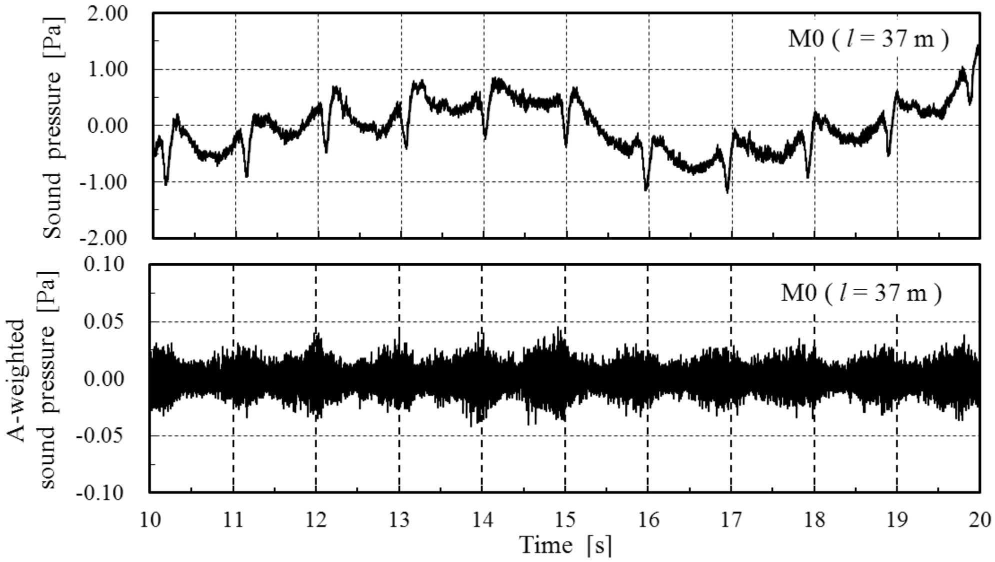
Figure 2 – An example of sound pressure levels in 1/3 octave bands of WTN

2.3 Sound Pressure and Its Auto-correlation.

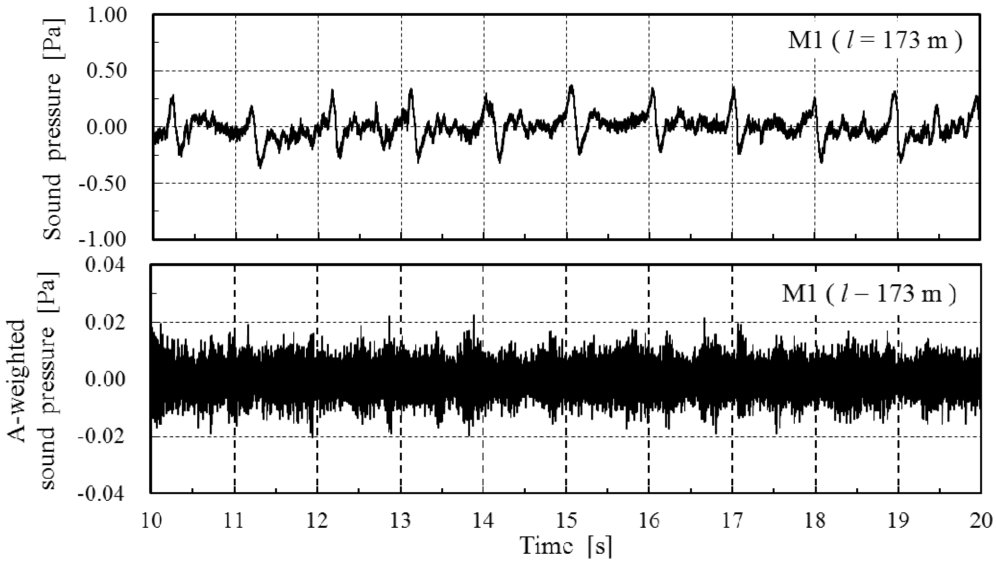
Figure 3 shows the Z-weighted and A-weighted sound pressures; in the former the components in infrasound region are dominant and pulse-like waveforms corresponding to the blade-passing interval are seen, while in the latter the components in the audible frequency range are dominant and the amplitude of the sound pressure is varying at the same time interval.

Figure 4 shows the auto-correlation of the Z-weighted and A-weighted sound pressure. In the results for the Z-weighted sound pressure, peaks with a periodicity of 0.97 s are clearly seen, while, in the results for the A-weighted sound pressure only a peak is seen at $\tau = 0$ that means the A-weighted signals are completely random.

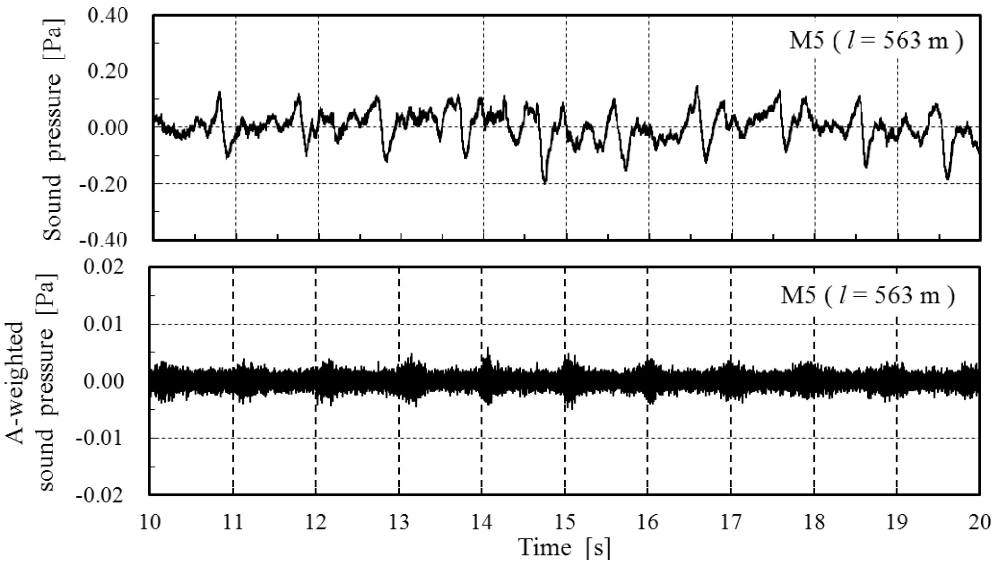
Going back to Figure 3(c), at M5, the pulses seen in the Z-weighted signal and the sound pressure maxima seen in the A-weighted signal are asynchronous. This fact might indicate the generation mechanisms of these sounds are different [1].



(a). Reference point M0 (horizontal distance *l* : 37 m)

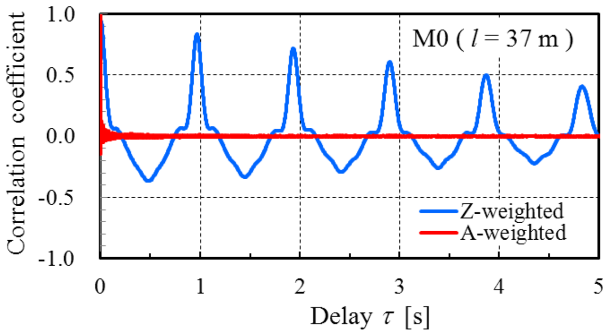


(b). Residential area M1 (horizontal distance *l* : 173 m)

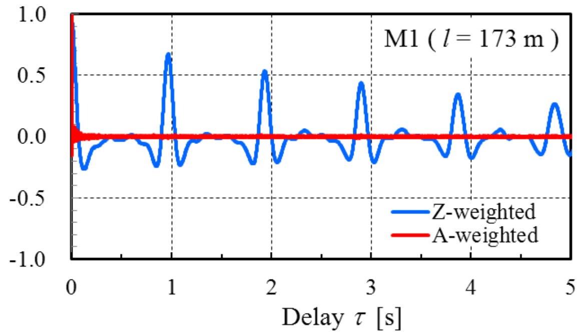


(c). Residential area M5 (horizontal distance *l* : 563 m)

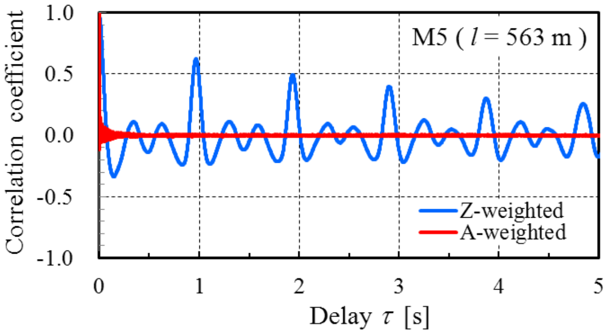
Figure 3 – Examples of sound pressure wave forms of WTN.



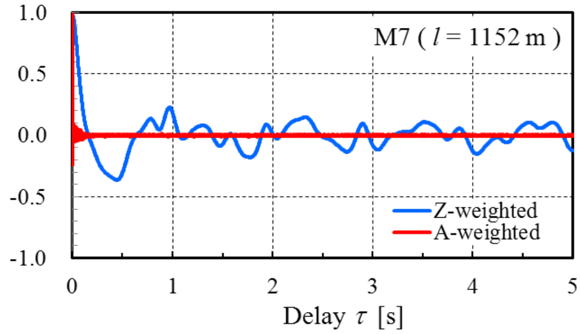
(a). Reference point M0



(b). Residential area M1



(c). Residential area M5



(d). Residential area M7

Figure 4 – Measured auto-correlation coefficients of WTN.

3. ASSESSMENT OF AM

3.1 Determination Method

For the psycho-acoustical effect of AM sound of WTN, the A-weighted sound pressure level is the most primary indicator [5,6] and in the assessment of AM sounds mentioned here the A-weighted sound pressure is focused.

When assessing the magnitude of AM in WTN, it is a problem that the mean sound pressure level varies temporally because of the atmospheric turbulence and variation of the background noise and some investigations have been made [7]. To eliminate this temporal fluctuation (drift), we have investigated a method using sound levels measured through FAST and SLOW dynamic characteristics by considering practical signal processing procedures and application.

In this method, the difference of the A-weighted sound pressure levels measured through FAST and SLOW dynamic characteristics of a sound level meter ($L_{A,F}(t)$ and $L_{A,S}(t)$, respectively) is calculated as follows:

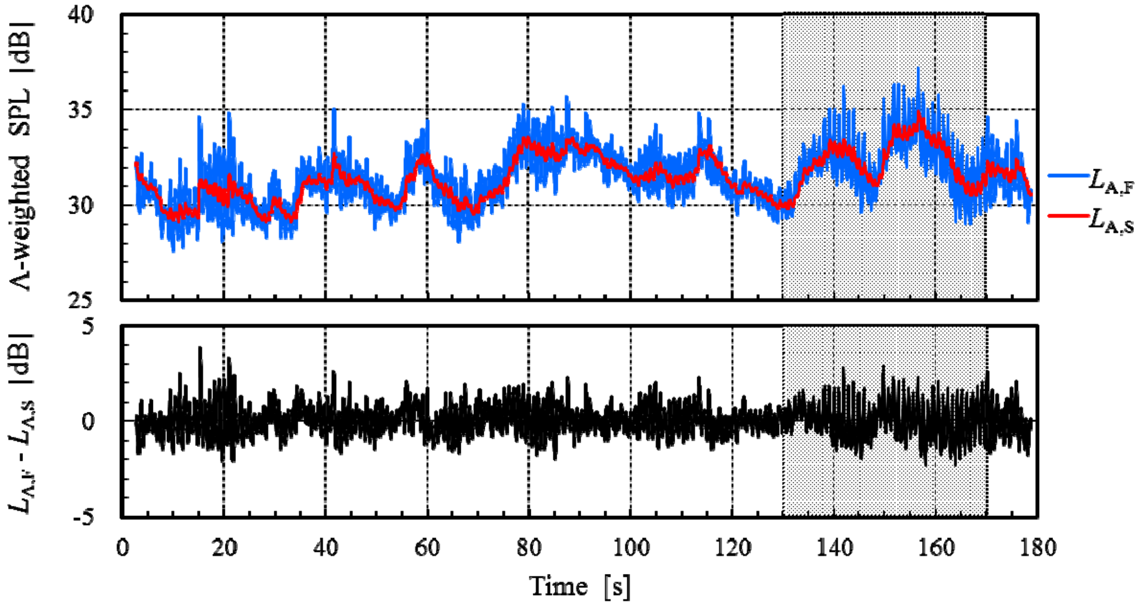
$$\Delta L_A(t) = L_{A,F}(t) - L_{A,S}(t) \tag{1}$$

As an example, Figure 5 shows $L_{A,F}(t)$, $L_{A,S}(t)$ and level difference $\Delta L_A(t)$ measured at the measurement point M7. Figure 6 shows the auto-correlation function of $\Delta L_A(t)$, in which peaks with a periodicity of 0.97 s corresponding to the rotation of the blades are clearly seen.

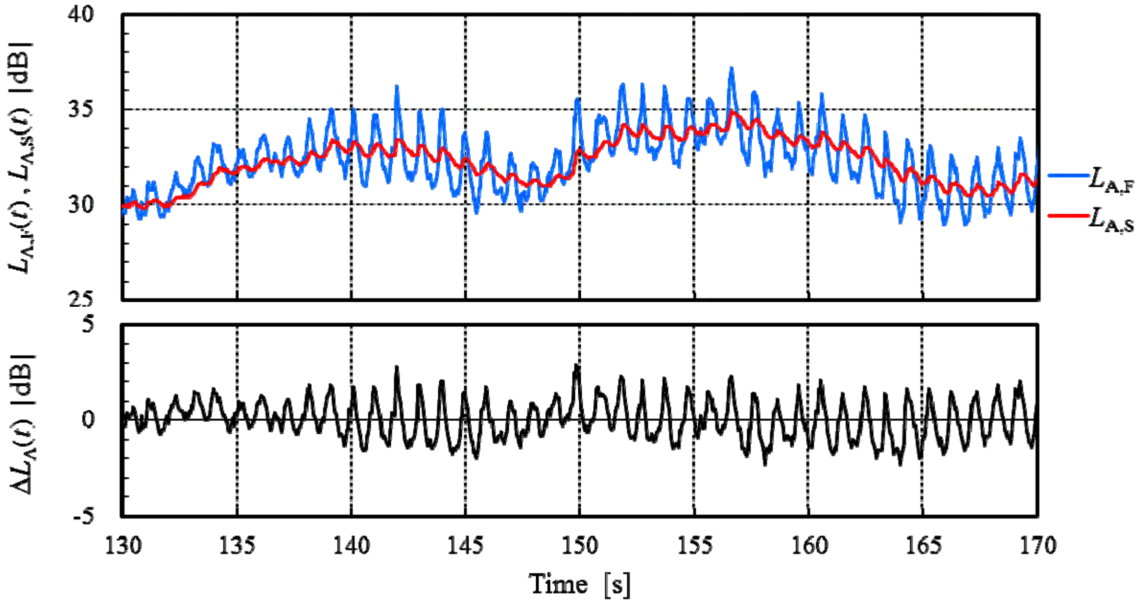
Next, in order to evaluate the magnitude of AM statistically, the AM depth is defined as the 90 % range of $\Delta L_A(t)$. That is,

$$D_{AM} = \Delta L_{A,5} - \Delta L_{A,95} \tag{2}$$

where, D_{AM} is the AM depth and $\Delta L_{A,5}$ and $\Delta L_{A,95}$ are the 5 % and 95 % levels of $\Delta L_A(t)$ [dB], respectively. Figure 7 shows the procedure to determine D_{AM}, in which the probability density function and cumulative distribution function in the case of the AM sound shown in Figure 5 are shown. In this case, the value of D_{AM} is 2.8 dB.



(a). Variation of SPLs and its difference in three minutes



(b). Zoom up of horizontal axis (130-170 s)

Figure 5 – A-weighted sound pressure levels $L_{A,F}$, $L_{A,S}$ and their difference $\Delta L_A(t)$ at M7.

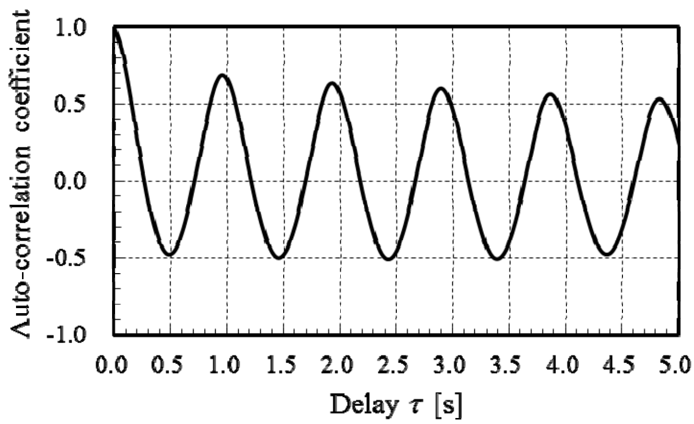


Figure 6 – Auto-correlation coefficients of $\Delta L_A(t)$

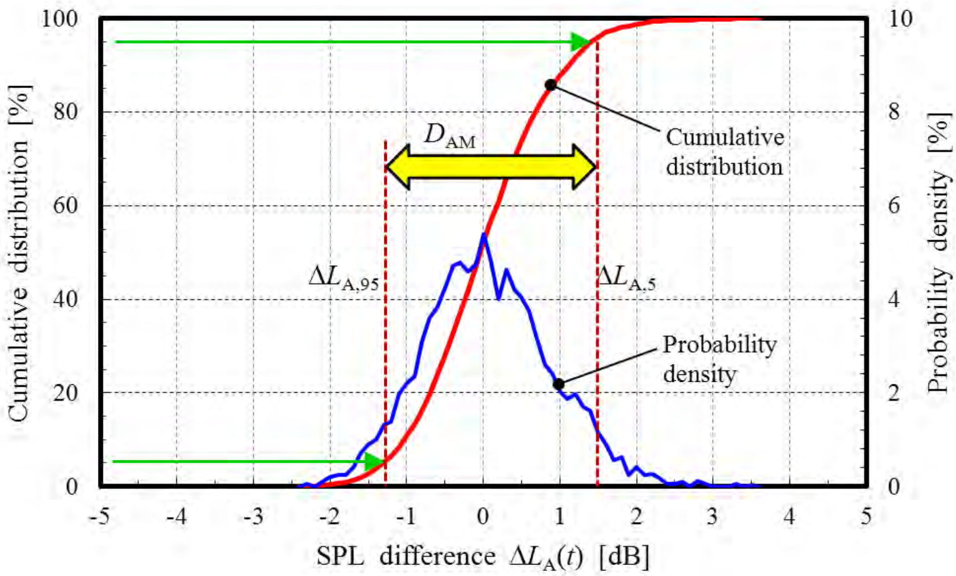
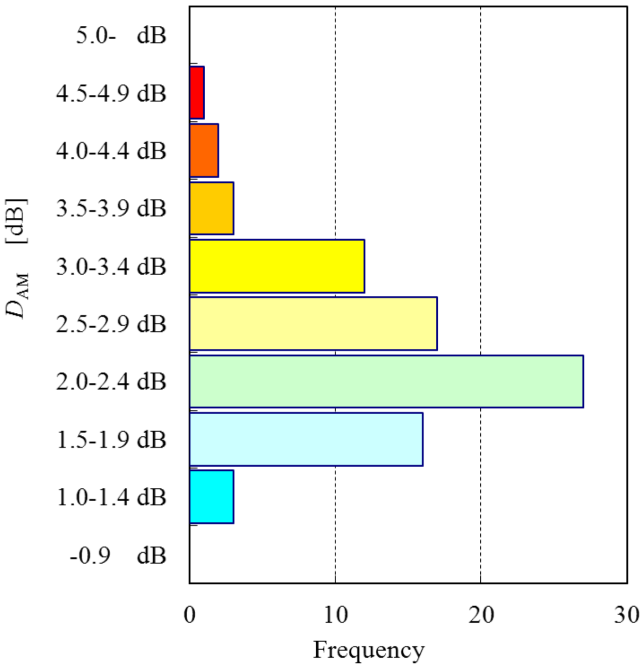


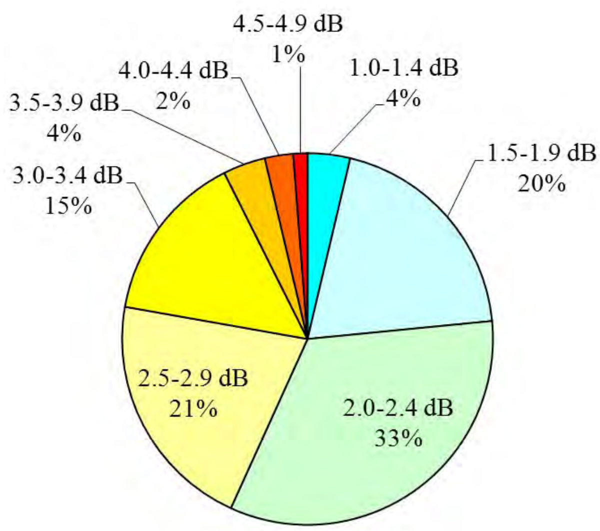
Figure 7 – Cumulative distribution of $\Delta L_A(t)$ and determination of D_{AM} of AM sound.

3.2 Actual Situation of AM Depth

To examine the actual situation of AM depth, the procedure mentioned above was applied to the sound pressure recordings made at 81 points in 18 wind farm sites. In this study, the recordings of sound pressure for 3 minutes were taken and the values of D_{AM} were obtained. As a result, the frequency distribution is shown in Figure 8(a) in the form of histogram and the component distribution ratio is shown in Figure 8(b) in the form of circle chart. It is seen that the range of D_{AM} was 1 to 5 dB and the mode appeared in 2.0 – 2.4 dB category. According to previous studies [1], the fluctuation sensation begins at the AM of around 2 dB. This point has been confirmed in the recent subjective experiment performed by our colleagues in Japan [5]. According to these findings, fluctuation by AM is sensible in about three-quarters of the measurement points examined in this study.



(a). Frequency distribution



(b). Component distribution ratio

Figure 8 – Frequency distribution of the AM depth D_{AM} of WTN in the residential areas around 18 wind farms in Japan.

3.3 Directivity of AM sound

To investigate the directivity of the AM sound, a measurement was performed at 7 points located on a circle of 90 m radius centered on a wind turbine of 1,500 kW rated power, 35.25 m rotor blade radius and 65 m hub height. The measurement was performed for continuous four days and the two samples in different wind direction were selected among the obtained data. The average wind speed for 10 minutes at the nacelle height was approximately 10 to 11 m/s. Figure 9 and Figure 10 show the angular dependence of $L_{Aeq,10min}$ and $D_{AM,3min}$ of the AM sound, respectively. In these results, it is seen that L_{Aeq} tends to become higher in the direction of rotation axis. On the other hand, the values of D_{AM} tend to become higher in the perpendicular direction to the axis. These findings are in good agreement with references 1 and 8.

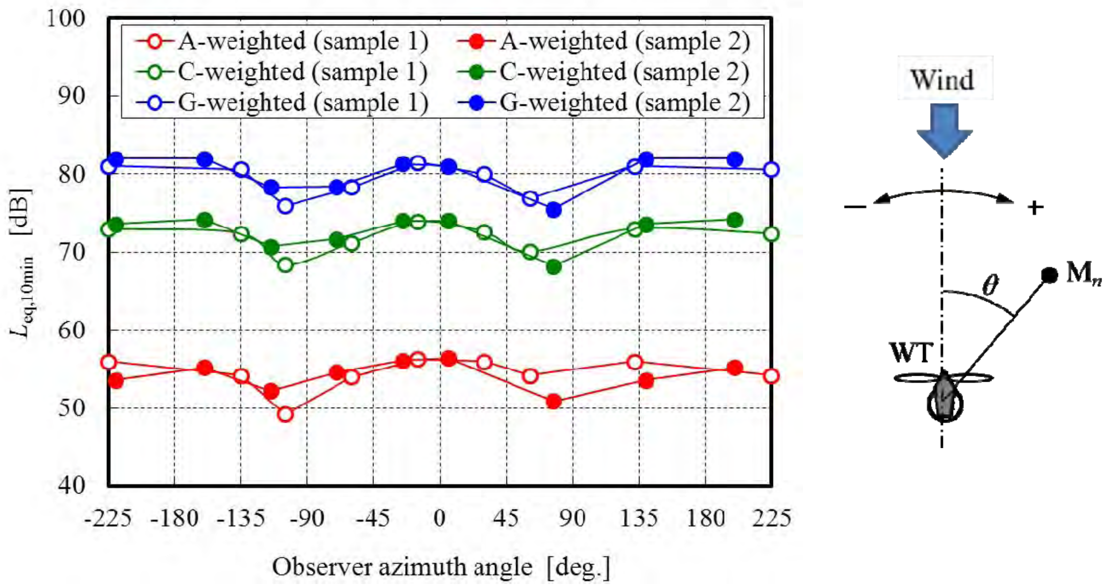


Figure 9 – Measurement results of the directivity of sound pressure levels ($L_{eq,10min}$) of the WTN.

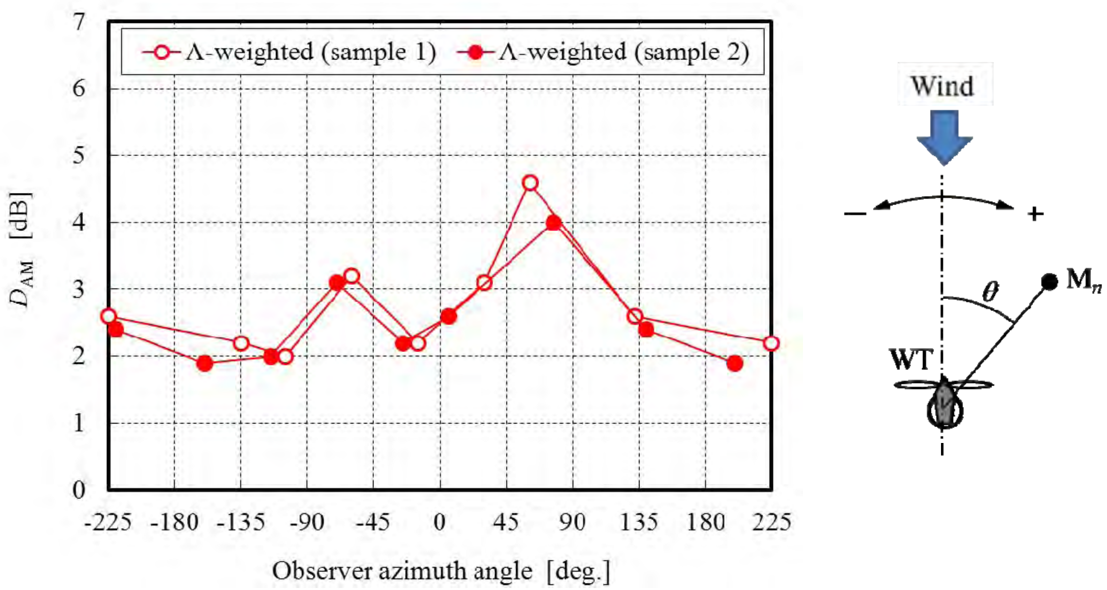


Figure 10 – Measurement results of the directivity of AM depth ($D_{AM,3min}$) of the WTN.

4. CONCLUSIONS

In the assessment of WTN, the magnitude of AM is an important factor as well as the time-averaged sound pressure level. Thus, a method for the assessment of the extent of AM in WTN was contrived and an indicator has been proposed in this paper. As a result of investigation using 81 measurement results obtained at 18 wind farm sites in Japan according to this assessment method, sensible AM sounds were found in about three-quarters of the WTNs.

ACKNOWLEDGEMENTS

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Study on the amplitude modulation of wind turbine noise: part 2- Auditory experiments

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ABSTRACT

Amplitude modulation (AM) sound, so called swish sound, is generally contained in wind turbine noise (WTN) and it causes serious annoyance in the areas surrounding 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, auditory experiments were performed by using a test facility capable of reproducing low frequency sounds including infrasound. As the first experiment, the fluctuation sensation caused by AM sounds was examined by using actual WTNs 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 cause at frequencies higher than about 125 Hz. As the second experiment, the noisiness sensation to AM 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.

Key words: Low frequency noise, Wind turbine noise, Swish sound, Amplitude modulation, Noisiness impression, Fluctuation sensation, Auditory experiment

1. INTRODUCTION

The authors have been carrying out a synthetic research program on wind turbine noise titled “Research on the Evaluation of Human Impact of Low Frequency Noise from Wind Turbine Generators” from the 2010 fiscal year [1]. This research program consists of field measurement [2-5], social survey on the response of nearby residents [6-7], and laboratory experiments [8-11]. Regarding the third topic, we have been making a series of subjective experiments regarding human audibility of low frequency sounds. In these experiments, the thresholds of hearing in low frequency range [8,11] and the human hearing sensation to WTN [9-11] have been examined.

In this study, to investigate the method of assessing AM sounds, two kinds of auditory experiments were performed. As the first experiment, the fluctuation sensation caused by AM sounds was examined by using actual WTNs. Following the study, the noisiness sensation was investigated by using artificially synthesized sounds.

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2. EXPERIMENTAL SYSTEM

In this study, the same experimental facility as used in the former auditory experiments on low frequency noise [9, 11] was also used. The facility is constructed in the Institute of Industrial Science, The University of Tokyo as shown in Figure 1 and Picture 1. 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 center position of the loudspeakers. To correct the frequency characteristic of the total system, the digital inverse-filtering technique was applied.

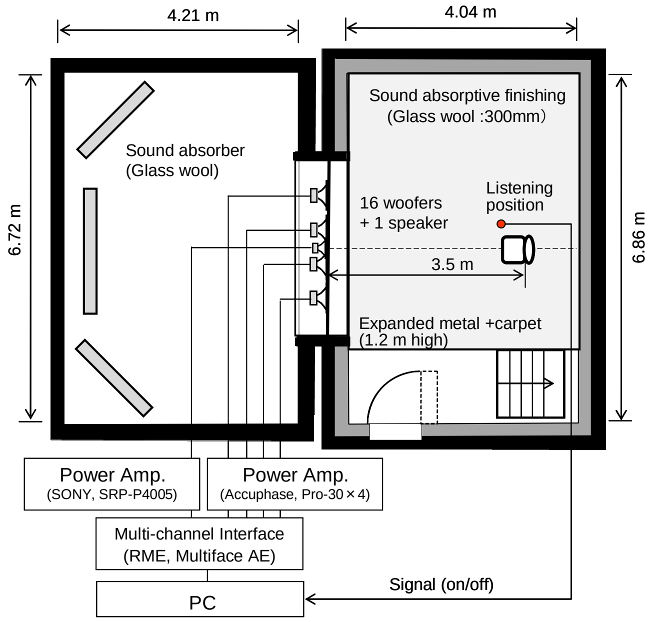


Figure 1 – Experimental system.

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

For the experiment, four actual WTNs including AM sounds recorded around wind farms in Japan were edited to have a duration time of 15 s (see Table 1). The A-weighted time-averaged sound pressure levels for the duration time ($L_{\mathrm{Aeq,15s}}$) of the sounds were distributed from 35.4 to 46.4 dB. They are typical WTNs observed outside in residential areas around wind farms. Figure 2 shows the A-weighted sound pressure levels by FAST dynamic characteristics ($L_{\mathrm{A,F}}$) of the sounds. The AM depth ($D_{\mathrm{AM,\,15s}}$) [3] (See appendix) of the sounds are distributed from 3.5 to 5.2 dB. To avoid click sounds, the signals were gradually risen/fallen with a time of 0.5 s, respectively. Figure 3 shows the sound pressure levels in 1/3 octave bands of these test sounds which were measured in the absence of the listener at the listening position where the centre of the listener's head would be. In order to investigate the "fluctuation sensation" of the low frequency components contained in WTNs, test sounds were made by limiting the frequency components of respective test sounds using low-pass-filtering processing (shown in Figure 4; the center frequency (f_{center}) of 1/3 octave band is used as the nominal cut-off frequency in this study). 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 5 shows the original test sound No.1 and its variations made in such a way mentioned above.

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

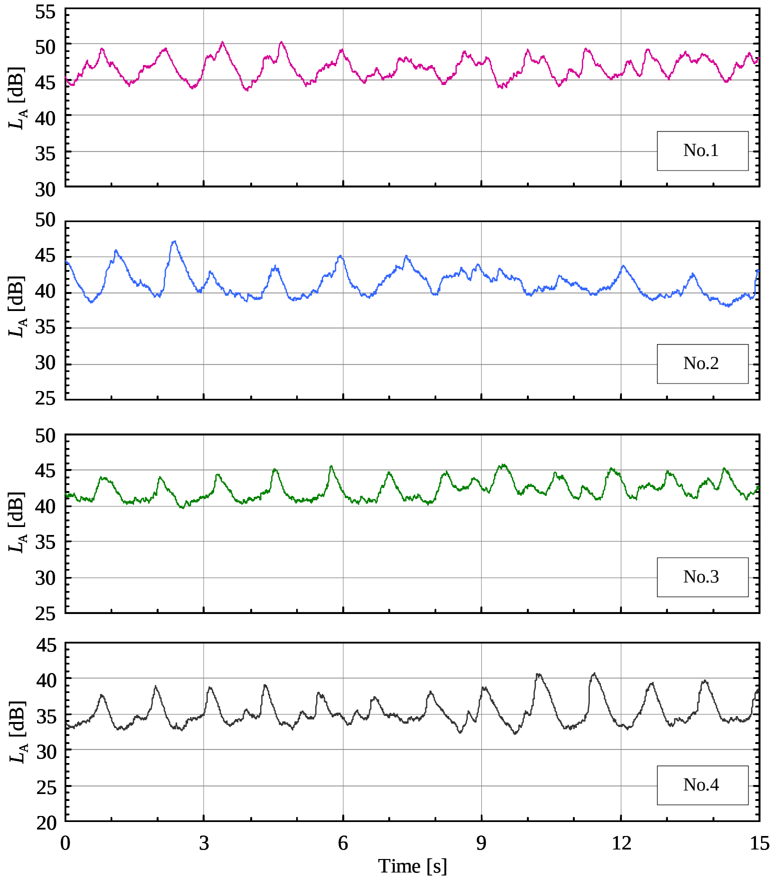


Figure 2 – The time pattern of the test signals.

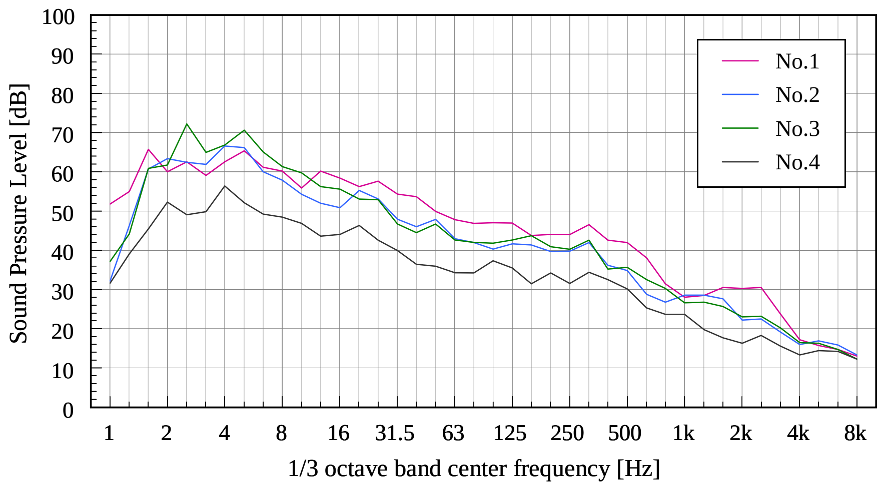


Figure 3 – Sound pressure levels in 1/3 octave bands of the test sounds.

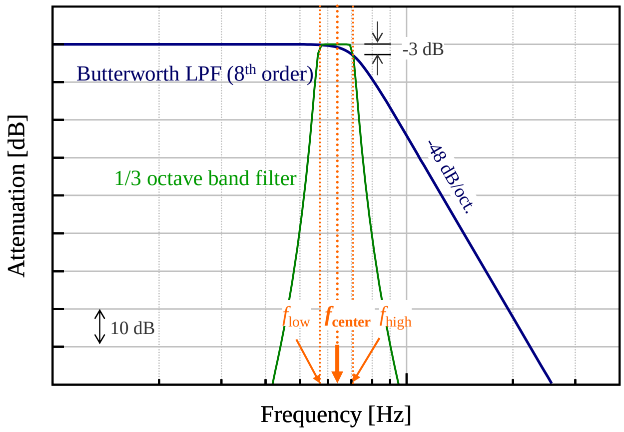


Figure 4 – Frequency characteristics of the low-pass filter.

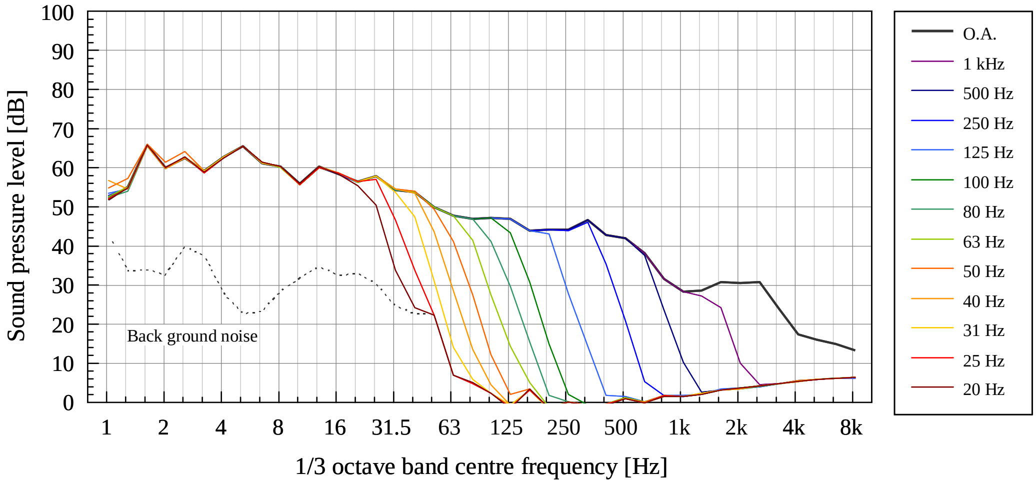


Figure 5 – Sound pressure levels in 1/3 octave bands of the original test sound No.1 and its variations made by low-pass filtering.

3.2 Experimental procedure

In advance of the auditory experiment, video recording of an actual rotating wind turbine was presented to each subject and he/she was informed that regular fluctuation sounds could be heard in the residential area around the wind farm generated by 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 "regular fluctuation sensation" in three-step category (see Table 2). The total time needed to complete the test on 52 test sounds (the test sounds No.1 to No.4; 12 modified sounds processed by the low-pass-filtering and original sound) was about 30 minutes including rest times in between. In this experiment, 10 subjects from 21 year-old to 25 year-old (7 males and 3 females) with otologically normal hearing abilities participated. This experiment was performed according to the ethical code of The University of Tokyo.

Table 2 – 3-step category.

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

3.3 Experimental results

As for the “audibility/sensitivity”, the ratio of the experimental results of “audible/sensible” was analyzed for each test sound. In the result shown in Figure 6, 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 response of “audible/sensible” decreased as the cut-off frequency became lower. The tendency that the “audible/sensible” judgment increases as the level of the test sound becomes higher is seen. To see the result for test sound No.1 which was the highest among the test sounds, the response of the “audible/sensible” sensation was 0 % under the condition of cut-off frequency of 25 Hz or lower.

To investigate the extent of the “regular fluctuation sensation” on AM sounds, the ratio of the experimental results of “regularly fluctuating (category 1 and 2; in the 3-step category)” (see Table 2) was analyzed for each test sound. In the result shown in Figure 7, it is seen that the sounds with cut-off frequency higher than 500 Hz were 100% judged to be “regularly fluctuating”, whereas the ratio of the sensation decreased as the cut-off frequency became lower. Under the conditions of cut-off frequency of 50 Hz or lower, the ratio of judgment of “regularly fluctuating” was 0%.

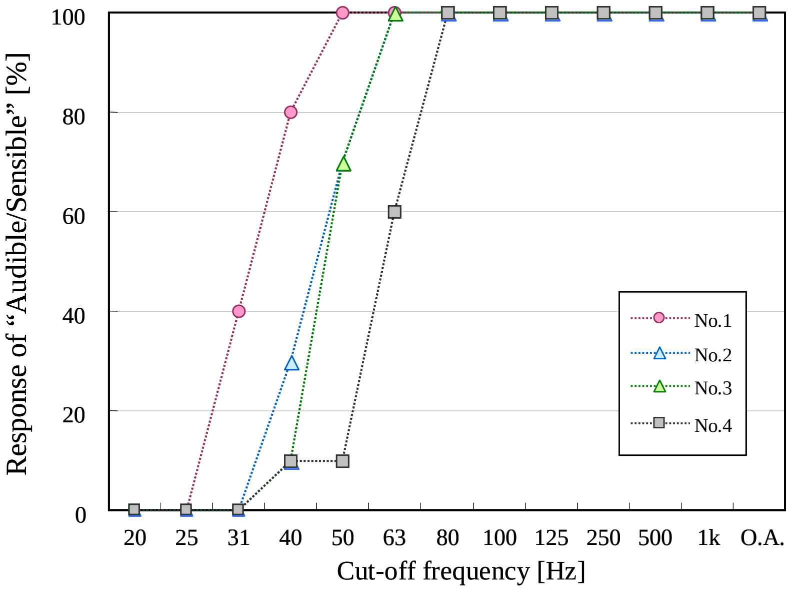


Figure 6 – The ratio of the experimental results “audible/sensible” for each test sound.

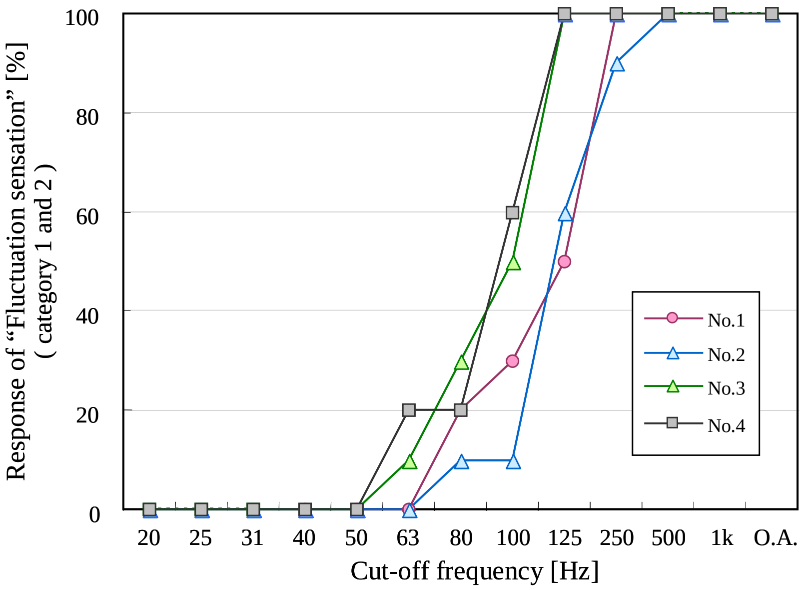


Figure 7 – The ratio of the experimental results “fluctuation sensation” for each test sound.

4. EXPERIMENT-2

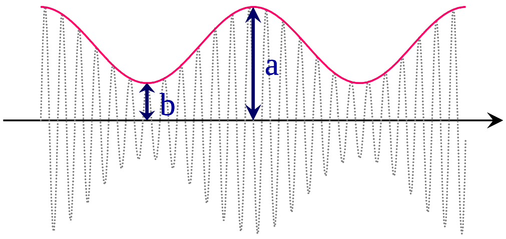
To examine the noisiness sensation to AM sounds contained in WTNs, auditory experiment was performed by using an artificially synthesized sound by changing its modulation depth.

4.1 Experimental conditions

To investigate the relationship between noisiness sensation and the strength of AM, noisiness matching test was performed. In this experiment, an artificially synthesized sound modeling the frequency characteristics of the 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 synthesized sound was set at 2-step; 35 and 45 dB in A-weighted time averaged S.P.L. ($L_{\mathrm{Aeq,10s}}$) at the listening position. As for the comparison stimulus (Sc), the synthesized sound was modified so that its AM index (ΔL) varied in 8-step (see Table 3). In this study, the AM index (ΔL) was defined as shown in figure 8. In Table 3, the AM depth ($D_{\mathrm{AM,\ 15s}}$) [3] (See appendix) of the reproduced sounds are also shown. Figure 9 shows the variations of the test signals changed their AM index. To avoid click sounds, the each sound was gradually risen/fallen with a time of 0.5 s.

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



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

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

$$\Delta L = 10\log_{10}\frac{a^2}{b^2}$$

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

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

Figure 8 – Definition of the AM index; ΔL.

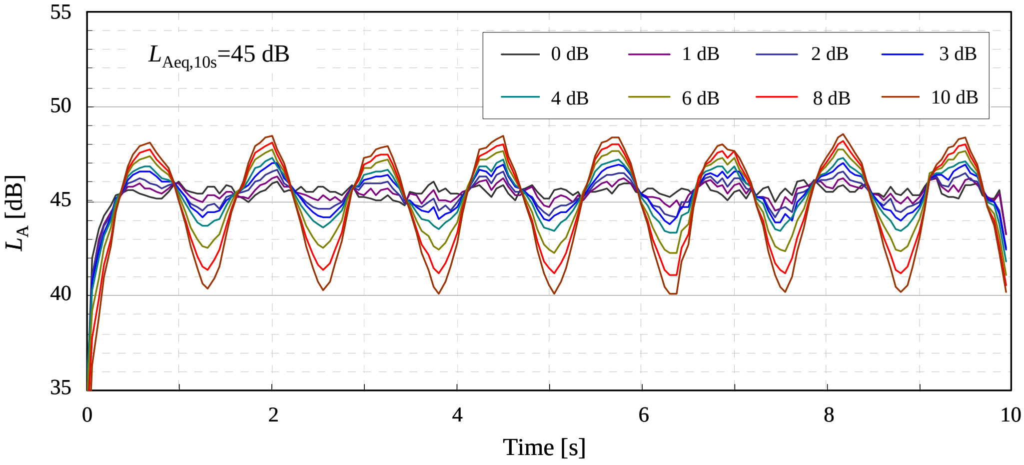


Figure 9 – Variations of the test signals modulated in 8 steps (ΔL).

4.2 Experimental procedure

As the test procedure, the method of adjustment by subject was applied. The experimental system was shown in Figure 10. 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 to that of Ss by using a volume controller (see Picture 2). For the ascending/ descending series in the case of Ss equal to 45 dBA, as the initial condition, Sc was set at 30/60 dB, respectively. The couple of Ss and Sc was repeated until each subject finished 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 by using arbitrary onomatopoeic word. The total time needed to complete the test of 16 test sounds was about 1.5 hours including rest times in between. In this experiment, the test subjects were the same participated in the former experiment.

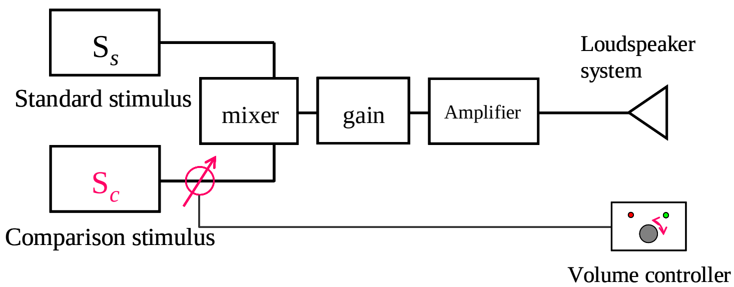


Figure 10 – Experimental system for the noisiness matching test.

Picture 2 – Volume controller used in the matching test.

4.3 Experimental results

Figure 11 show the experimental results of the noisiness test performed by changing the AM depth of the model noise in steps. In these figures, X-axis indicates AM index (ΔL) of Sc and Y-axis indicates the adjusted level in $L_{Aeq,10s}$. In the both of the figures, 0 dB (Y-axis; adjusted level) means the level of Ss, 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 lines are the standard deviations. In these results, it is seen that the averaged level of adjusted Sc decreased as the AM index became higher, whereas its averaged value held around 0 in the case where the index was less than 1 dB. It is also seen that the standard deviation increased as the index became lower. These results show that "noisiness" increased with the increase of AM index.

From the result of expression by using an onomatopoeic word for each test sound, the ratio of "fluctuation sensation" was calculated by applying the logistic regression analysis. In this study, such onomatopoeic words as "Zah, Zah", "Zahn, Zahn", "Guon, Guon" were regard as "fluctuating". Figure 12 shows the relationship between AM index (ΔL) of Sc and the ratio of "fluctuating". In the result, it is seen that the "fluctuating" was caused when AM index was higher than 2.0 dB (corresponding to D_{AM} equal to 1.7 dBA). This tendency is consistent with the reference [12].

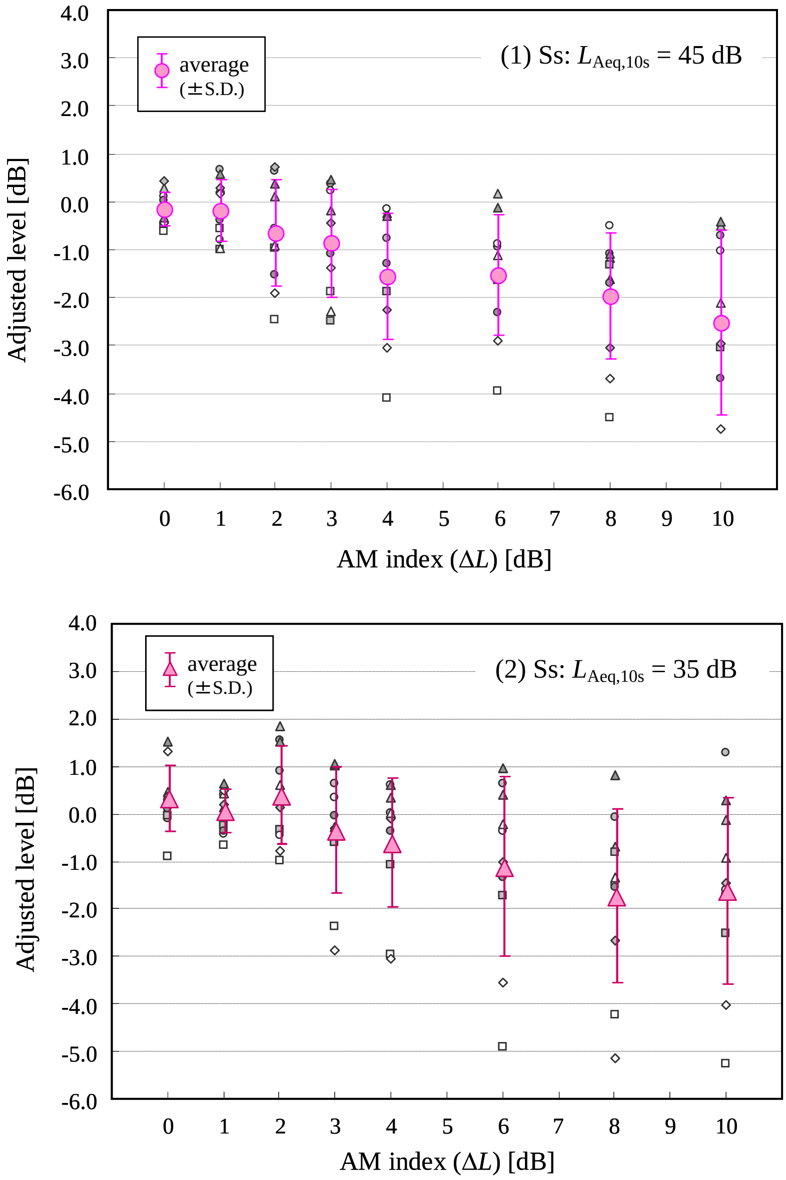


Figure 11 – Experimental results of noisiness matching.

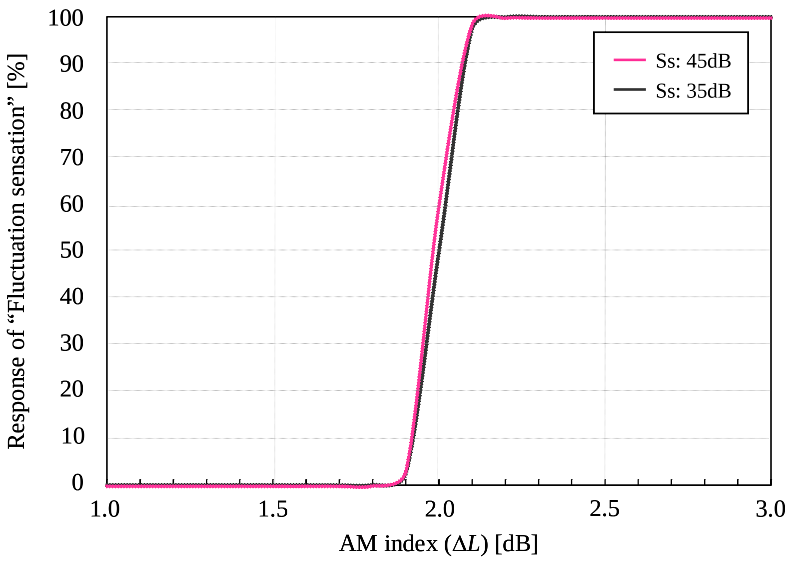


Figure 12 – Fluctuation sensation vs. AM index (ΔL) .

5. CONCLUSIONS

In this study, the effect of amplitude modulation sounds generally contained in wind turbine noises has been investigated by using the actual noises recorded on sites and a model sound representing general wind turbine noises. From the result of the experiment for the sensation of fluctuation, it has been found that the sensation is apt to cause at frequencies higher than around 100 Hz. From the result of second experiment, the fluctuation sensation has been confirmed under the condition where AM index ΔL is higher than 2.0 dB (corresponding to D_{AM} higher than 1.7 dBA).

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APPENDIX

In this study, the difference of the A-weighted sound pressure levels measured through FAST and SLOW dynamic characteristics of a sound level meter ($L_{A,F}(t)$ and $L_{A,S}(t)$, respectively) is calculated as follows:

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

In order to evaluate the magnitude of AM statistically, the AM depth is defined as the 90 % range of $\Delta L_A(t)$. That is,

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

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