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Practical measurement method of wind turbine noise

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Summary

Wind turbine noise (WTN) is a broadband noise with a spectral characteristic approximated by -4 dB/octave and it can be primarily assessed by time-averaged A-weighted sound pressure level (L_{Aeq}). In actual measurements of L_{Aeq}, however, it is apt to be seriously influenced by background noise because WTN is generally not so strong in residential areas around wind farms. An alternative method to avoid this problem is to assess the 90 or 95 percentile level (L_{A90} or L_{A95}) which are robust against background noise. So, the relationships between L_{Aeq} and these percentile levels were investigated using a lot of data obtained in the field measurements conducted across Japan. As a result, it has been found that L_{Aeq} can be estimated from L_{A90} or L_{A95} with a considerably high accuracy.

Another important issue of WTN is amplitude modulation (AM) which causes serious annoyance. To quantitatively evaluate the magnitude of AM by eliminating its slow temporal variation (drift) of WTN, we proposed a simple and practical method (F-S method), in which the instantaneous fluctuation by AM is detected by calculating the difference between the A-weighted SPL by Fast time-weighting ($L_{A,F}$) and that by Slow time-weighting ($L_{A,S}$), and the 90% range of the level difference is calculated as an indicator of AM depth. The theoretical background of this method is considered and a comparison with the method detecting the amplitude fluctuation by applying Hilbert transform (Envelope method) is discussed.

In addition, the method of assessing the residual noise at wind farm sites by L_{A90} or L_{A95} is discussed.

1. Introduction

To investigate the actual condition of wind turbine noise (WTN) in Japan, 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, field measurements at 34 wind farm sites and 16 control sites without WTN were conducted across Japan [1]. Using the data obtained in the field measurements, the method to eliminate the influence of background noise in the assessment of time-averaged WTN, the quantitative assessment method of amplitude modulation (AM), and the method to assess the ambient acoustic condition in quiet rural districts are investigated in this paper. Regarding the effect of tonal components contained in WTN is reported in another paper [2]. The sound pressure signals used in this paper were recorded using prototype wide-frequency-range sound level meters manufactured for the

requirements of the measurement frequency range from 1 Hz to 20 kHz, with a function for recording the sound pressure signal built into its body (48 kHz sampling, 16 bits, WAVE format). Regarding the frequency weighting for the assessment of WTN, the applicability of the A-weighting has been confirmed through auditory experiments [3,4]. Therefore, the investigations in this paper are based on the use of the A-weighted sound pressure level (SPL).

2. Assessment of time-averaged level of WTN

Figure 1 shows an example of A-weighted SPL measured at a point 1.2 km apart from a wind turbine (2.4 MW). In this result, WTN with AM components is clearly observed, but the pass-by noise of a road vehicle come a long way. In such a case, the extraneous noise (background noise) has to be carefully eliminated to assess the WTN. In actual measurements, this process is very troublesome and time-consuming. An alternative method to avoid this problem is to assess the 90 or 95 percentile level (L_{A90} or L_{A95}) which are robust to extraneous noise.

In this regard, the influence of background noise in WTN measurements and the relationships between L_{Aeq} and L_{A90} or L_{A95} were investigated using the data obtained at 81 points in residential areas (200 m to 1.2 km from the nearest wind turbine) around 18 wind farms. Figure 2(a) shows the comparison between $L_{Aeq,3min}$ obtained by carefully eliminating the background noise and that obtained without such a processing, in which an extreme case of 25 dB or more difference was seen. On the other hand, in the cases of $L_{A90,3min}$ and $L_{A95,3min}$ (Figure 2(b),(c)), the level obtained by eliminating the background noise and that obtained without the eliminating process are in fairly in good agreement in both cases. This indicates the robustness of L_{A90} and L_{A95} against background noise. For this reason, L_{A90} is adopted as the noise indicator for WTN in some countries such as the UK and New Zealand [5,6].

On the other hand, L_{Aeq} is the most primary noise indicator and applied to WTN in many

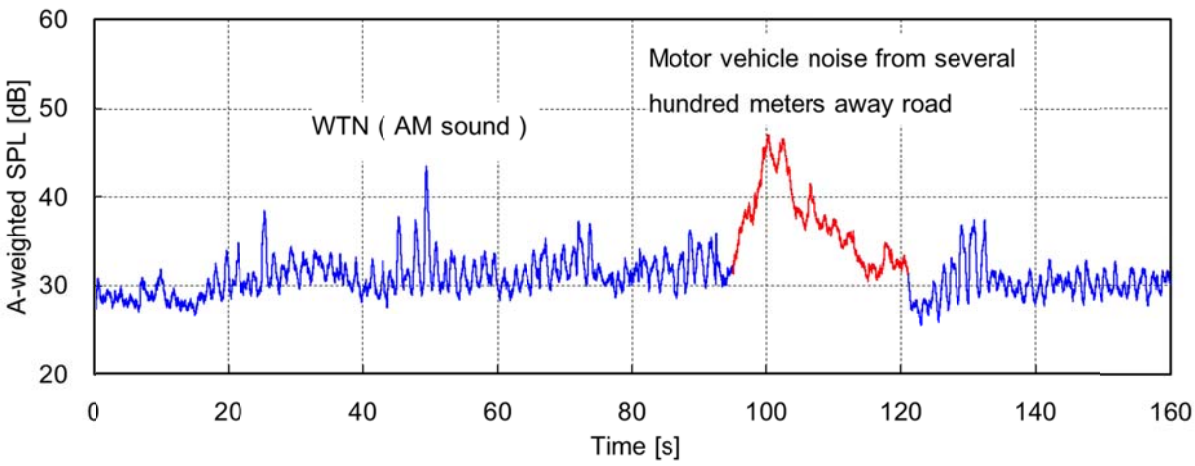
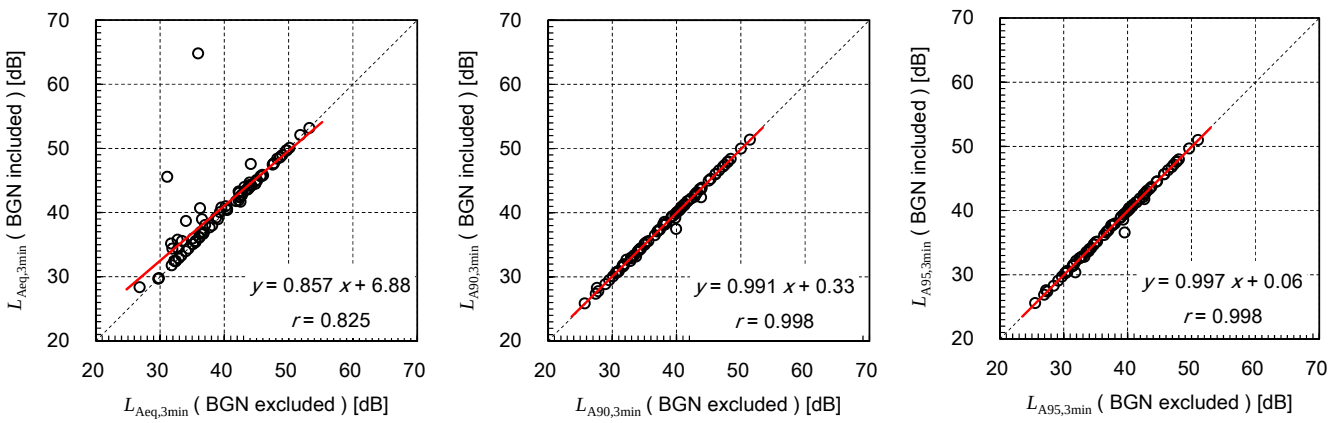


Figure 1 – An example of A-weighted SPL of WTN including background noise.

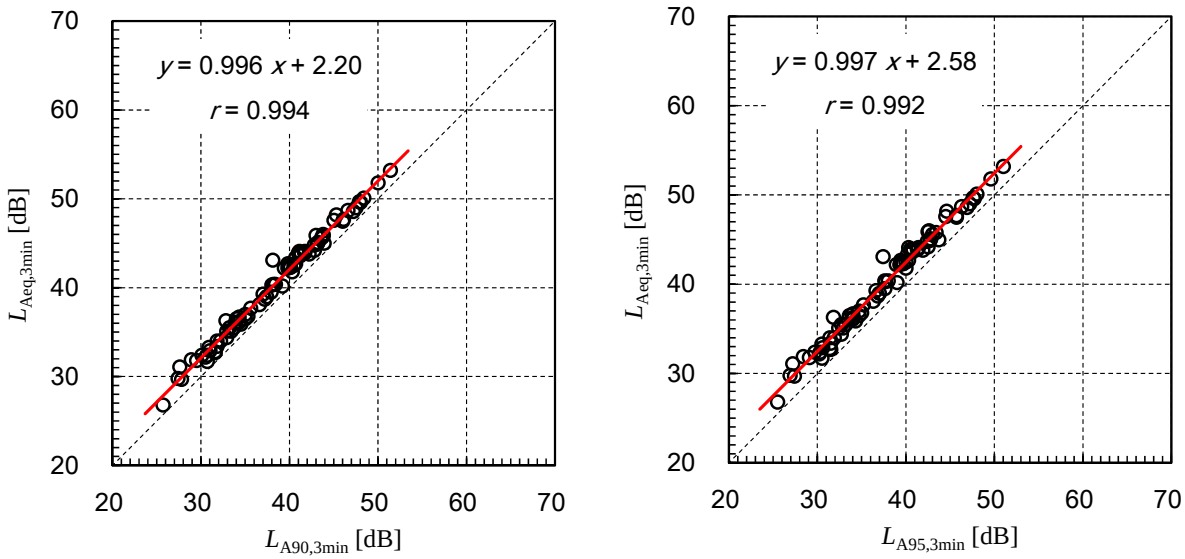


(a). $L_{Aeq,3min}$ (b). $L_{A90,3min}$ (c). $L_{A95,3min}$

Figure 2 – Effect of eliminating background noise for L_{Aeq}, L_{A90} and L_{A95}.

Table 1 – SPL differences between L_{Aeq} and L_{AN} [dB]

SPL index	Average	Standard deviation	Maximum value	Minimum value
L_{Aeq} - L_{A90}	2.1	0.64	5.0	1.0
L_{Aeq} - L_{A95}	2.5	0.75	5.7	1.2



(a). L_{Aeq} vs. L_{A90} (b). L_{Aeq} vs. L_{A95}

Figure 3 – Correlation between L_{Aeq} obtained by eliminating the background noise and L_{AN} of WTNs.

countries. So, the relationship between L_{Aeq} obtained by eliminating the background noise and L_{A90} or L_{A95} were investigated as shown in Table 1 and Figure 3. The difference between L_{Aeq} and L_{A90} was 2.1 dB on average and the standard deviation was 0.64 dB (correlation coefficient: 0.994) and the difference between L_{Aeq} and L_{A95} was 2.5 dB on average and the standard deviation was 0.75 dB (correlation coefficient: 0.992).

Theoretically, the difference between L_{Aeq} and L_{A90} or L_{A95} ought to depend on the extent of AM. However, the relationship between L_{Aeq} and L_{A90} or L_{A95} is in fairly high correlation as mentioned above and therefore L_{Aeq} can be estimated from L_{A90} or L_{A95} with fairly high accuracy.

3. Assessment of amplitude modulation

Figure 4 shows the time-traces of the A-weighted SPL measured at four points around a wind farm, in which temporal fluctuation of about 1 s period corresponding to the Blade-Passing-Interval (BPI) is clearly seen in all of the traces. The time-trace observed at the measurement point M0 (close to a wind turbine) was relatively stable and fluctuating between 50 to 57 dB,

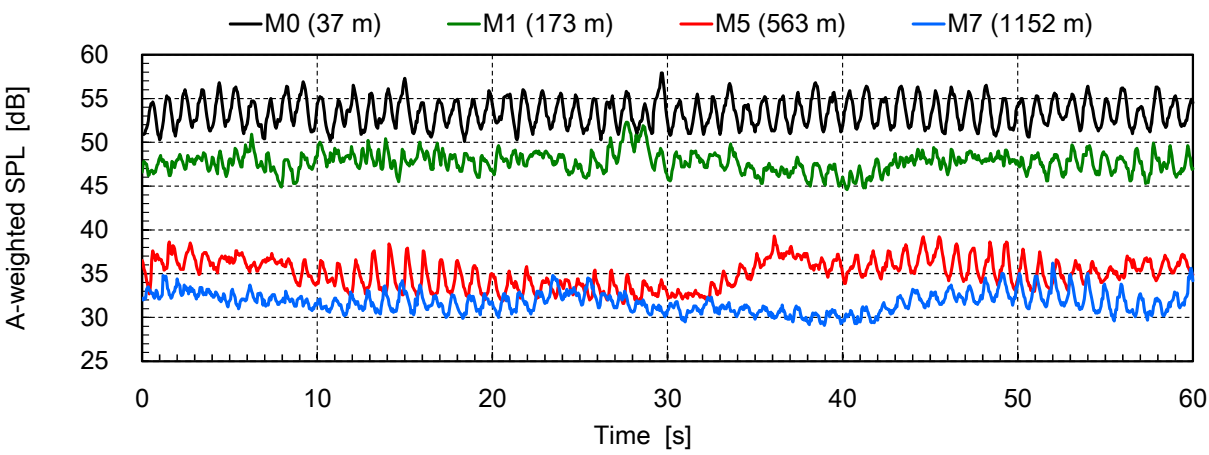


Figure 4 – Recordings of the A-weighted SPLs of WTN (rated power output : 1.95 MW, number of WT : 1).

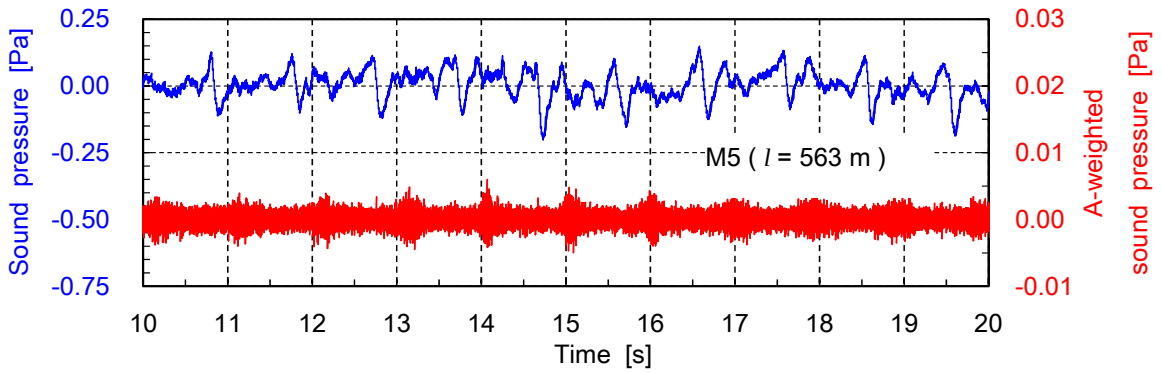


Figure 5 - Examples of sound pressure wave forms of WTN at point M5.

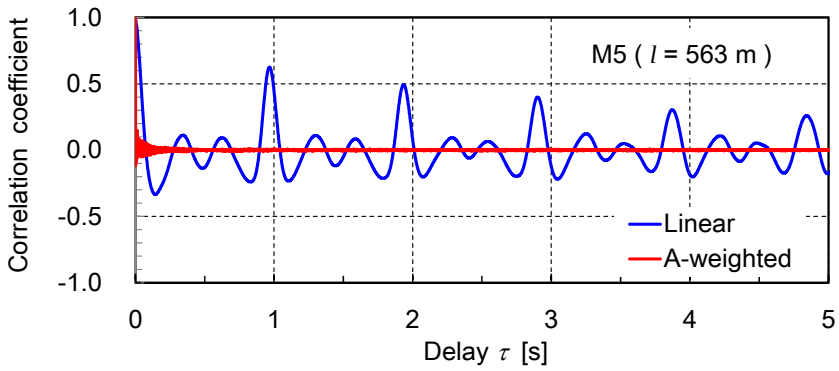


Figure 6 – Examples of measured auto-correlation coefficients of WTN at point M5.

whereas in the patterns observed at other measurement points in the residential area, not only the periodical fluctuation due to blade passing but also a slow temporal variation (drift) is seen.
Figure 5 shows the wave-forms of the linear sound pressure (0.8 Hz to 20 kHz) and A-weighted sound pressure of the WTN measured at the point M5 shown in Fig. 4. In the wave-form of the linear sound pressure, impulsive variations corresponding to BPI of the wind turbine are seen, whereas in that of the A-weighted sound pressure, the amplitude is fluctuating periodically corresponding to the BPI. The auto-correlation functions of the linear and A-weighted sound pressures are shown in Fig. 6. In the result of the linear sound pressure, peaks are seen at an interval of 0.97 s, whereas in the result of the A-weighted sound pressure, such periodical peaks are not seen. This means that the A-weighted sound pressure is an incoherent broad-band noise modulated by the Blade-Passing-Frequency (BPF).
As shown in Fig. 4, not only periodical amplitude fluctuation (amplitude modulation: AM) but also slow temporal level variation (drift) can be contained in WTN. In addition, the width of the AM is not necessarily constant and varies temporally. In the assessment of the AM component in WTN, therefore, the strength of AM should be detected by eliminating the drift.
To objectively quantify the strength of AM, several methods have been proposed [7-12], in which the frequency and magnitude of the envelope of AM are detected by applying the signal processing techniques as Hilbert transform and Fourier transform. As another method, the authors proposed a very simple and practical method calculating the level difference $\Delta L_A(t)$ between A-weighted SPL with FAST time-weighting, $L_{A,F}(t)$, and that with SLOW time-weighting, $L_{A,S}(t)$, (F-S method) [7].

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

Then, the width of the 90% range of the level difference is obtained as a measure indicating the AM depth.

$$D_{AM} = \Delta L_{A5} - \Delta L_{A95} \tag{2}$$

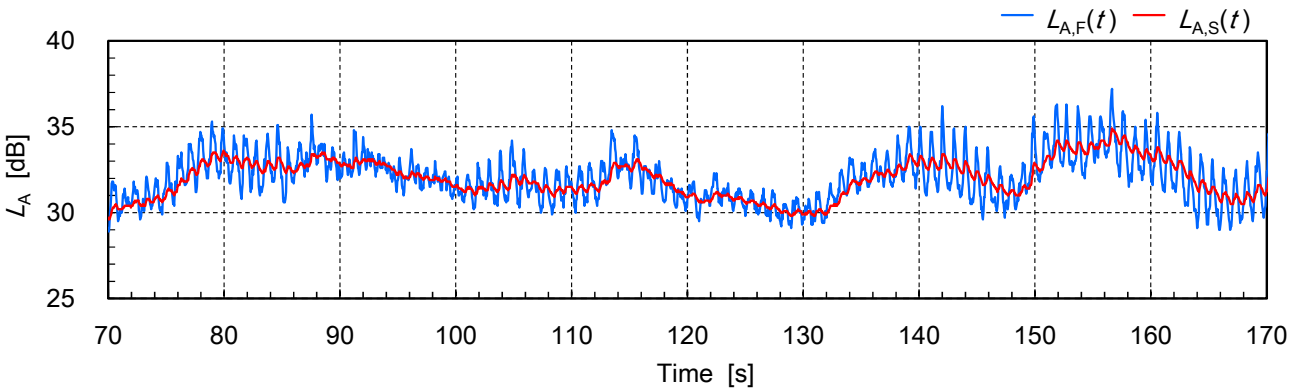
where, D_{AM} is the AM depth in dB, and ΔL_{A5} and ΔL_{A95} are the 5% and 95% levels of $\Delta L_A(t)$, respectively.
Figure 7 shows an example of the A-weighted SPLs of WTN for 40 s recorded with FAST and SLOW time-weightings and the level difference $\Delta L_A(t)$ between them. The data were measured

at a point 1,152 m from a 1.95 MW wind turbine (see Fig. 4). Figure 8 shows the probability density of the instantaneous value of $\Delta L_A(t)$, which can be regarded as the probability density of a normal distribution (the red curve in the figure). This result was obtained from the instantaneous values of $\Delta L_A(t)$ for 3 min for the data shown in Fig. 7. This holds true in almost all cases. Here, the theoretical base of the F-S method is considered. In this case, D_{AM} assessed in the way mentioned above was 2.8 dB. The instantaneous A-weighted SPL evaluated using a time-weighting function with a time constant of τ is described as

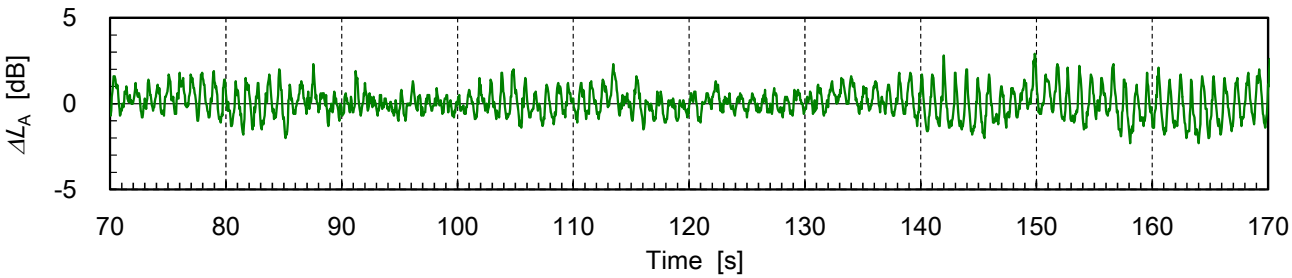
$$L_{A,\tau}(t) = 10 \log_{10} \frac{\hat{p}^2_{A,\tau}(t)}{p_0^2} \tag{3}$$

$$\hat{p}^2_{A,\tau}(t) = \frac{1}{\tau}\int_{-\infty}^{t} p_A^2(\xi) \cdot e^{-\frac{t-\xi}{\tau}} \mathrm{d}\xi \tag{4}$$

where, ξ is time [s], p_0 is the reference sound pressure (20μPa) [13].
When representing the exponential time-weighting function in Eq. (4) as a time-response



(a) Temporal variations of $L_{A,F}(t)$ and $L_{A,S}(t)$ of a WTN



(b) SPL difference of $L_{A,F}(t)$ and $L_{A,S}(t)$

Figure 7 – A-weighted SPLs $L_{A,F}(t)$, $L_{A,S}(t)$ and their difference $\Delta L_A(t)$ at M7 (horizontal distance l : 1152 m).

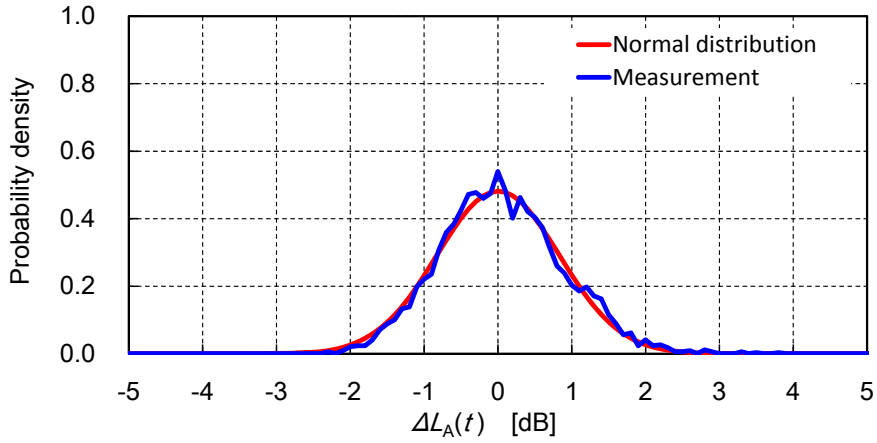


Figure 8 – Example of probability density of AM component $\Delta L_A(t)$ at M7 (horizontal distance l : 1152 m).

function $w(\xi)$ of a low-pass filter as in Eq. (5), Eq. (4) is a convolution between $p_A^2(t)$ and $w(t)$.

$$w(\xi)=\begin{cases} e^{-\frac{t-\xi}{\tau}} & ,\xi\geq 0 \\ 0 & ,\xi<0 \end{cases} \tag{5}$$

The transfer-function $W(f)$ of the low-pass-filter (1st order Butterworth filter) is obtained by the Fourier transform of $w(\xi)$, and its attenuation characteristic $|W(f)|^2$ is expressed as follows.

$$|W(f)|^2=\frac{1}{1+(2\pi f\tau)^2} \tag{6}$$

That is, $L_{A,F}(t)$ and $L_{A,S}(t)$ are the level expressions of the outputs of $p_A^2(t)$ through low-pass filters with time constant of 0.125 s (FAST) and 1 s (SLOW), respectively. Figure 9 shows the response functions of the FAST and SLOW low-pass-filters. The cut-off frequency is 1.27 Hz and 0.16 Hz, respectively.

Figure 10 shows four examples of the power-spectrum of $p_A^2(t)$ measured at points M0, M1, M5 and M7 shown in Fig. 4, in which the BPF of about 1 Hz is clearly seen. BPF of wind turbine is generally around 1 Hz which is within the pass band width of the low-pass-filter of FAST time-constant. On the other hand, 1 Hz is sufficiently outside the path band width of the low-pass-filter of SLOW time-constant and $L_{A,S}(t)$ can be considered to represent the drift. Therefore, the level difference $\Delta L_A(t)$ between $L_{A,F}(t)$ and $L_{A,S}(t)$ can be considered as the strength of the instantaneous fluctuation of AM without the drift.

As another way to detect the strength of AM, the method applying Hilbert transform to detect the envelope of modulated sound pressure and Fourier transform to detect the dominant frequency components [14,15] can be applied. This method (Envelope method) and the F-S method were compared as follows.

The data used in this study were the sound pressure signals with a duration time of 3 min recorded at 33 measurement points around 12 wind farms in Japan. They were judged as swishing sounds by auditory test. The signals were convolved with the A-weighting function and processed according to the two methods shown in Fig. 11.

Figure 12 shows two examples of comparison of the power-spectrum $P_{F\text{-}S}(f)$ of the AM component $\Delta L_A(t)$ obtained by the F-S method and the power-spectrum $P_{env}(f)$ of the envelope signal $|p_A(t)|$ detected by the Envelope method. To examine the frequency components around BPFs of wind turbines, all of the results are illustrated as the power relative to the total power of the frequency components between 0.5 Hz and 7 Hz. In all of the results, it is seen that the BPF of the wind turbine is clearly detected as the fundamental frequency (0.85 Hz for W02 and 1.0 Hz for W22). However, the relative power detected by the F-S method is higher than that by the Envelope method. Such comparisons were made for the data obtained at 12 wind farm sites. As a result, the comparisons of relative power at the BPF are shown in Figure 13, in which $P_{F\text{-}S}(f)$ is higher than $P_{env}(f)$ in all cases; this might mean that the F-S method is superior to the Envelope-method in detecting the BPF of wind turbine.

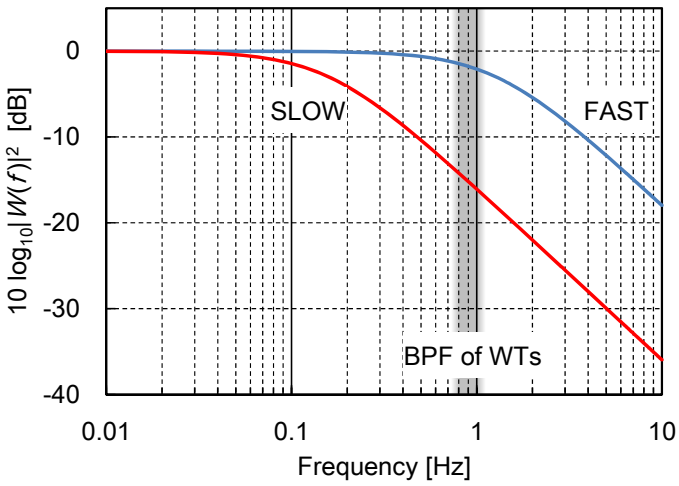


Figure 9 – Attenuation characteristics of time-weighting filter of sound level meter.

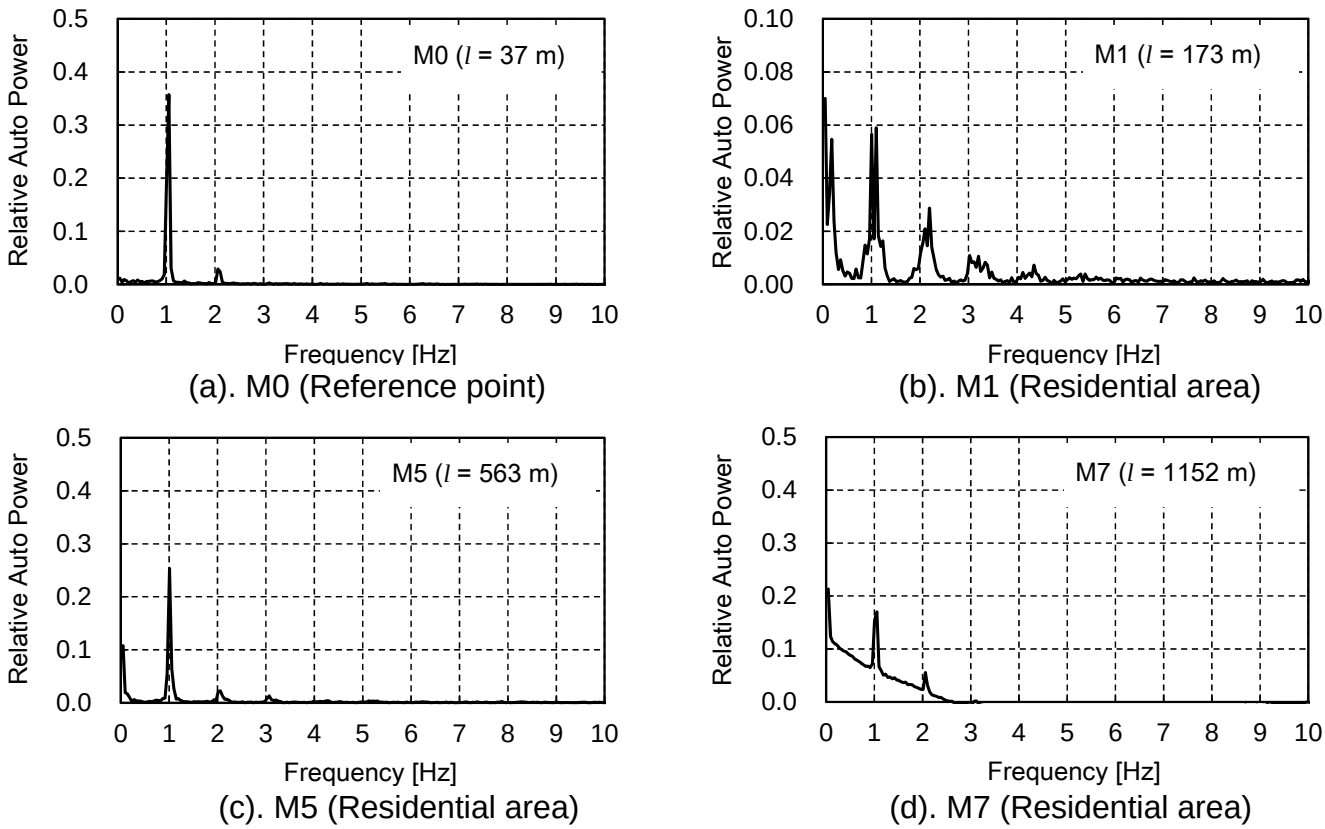


Figure 10 - Auto power spectra of squared A-weighted sound pressure of WTNs.

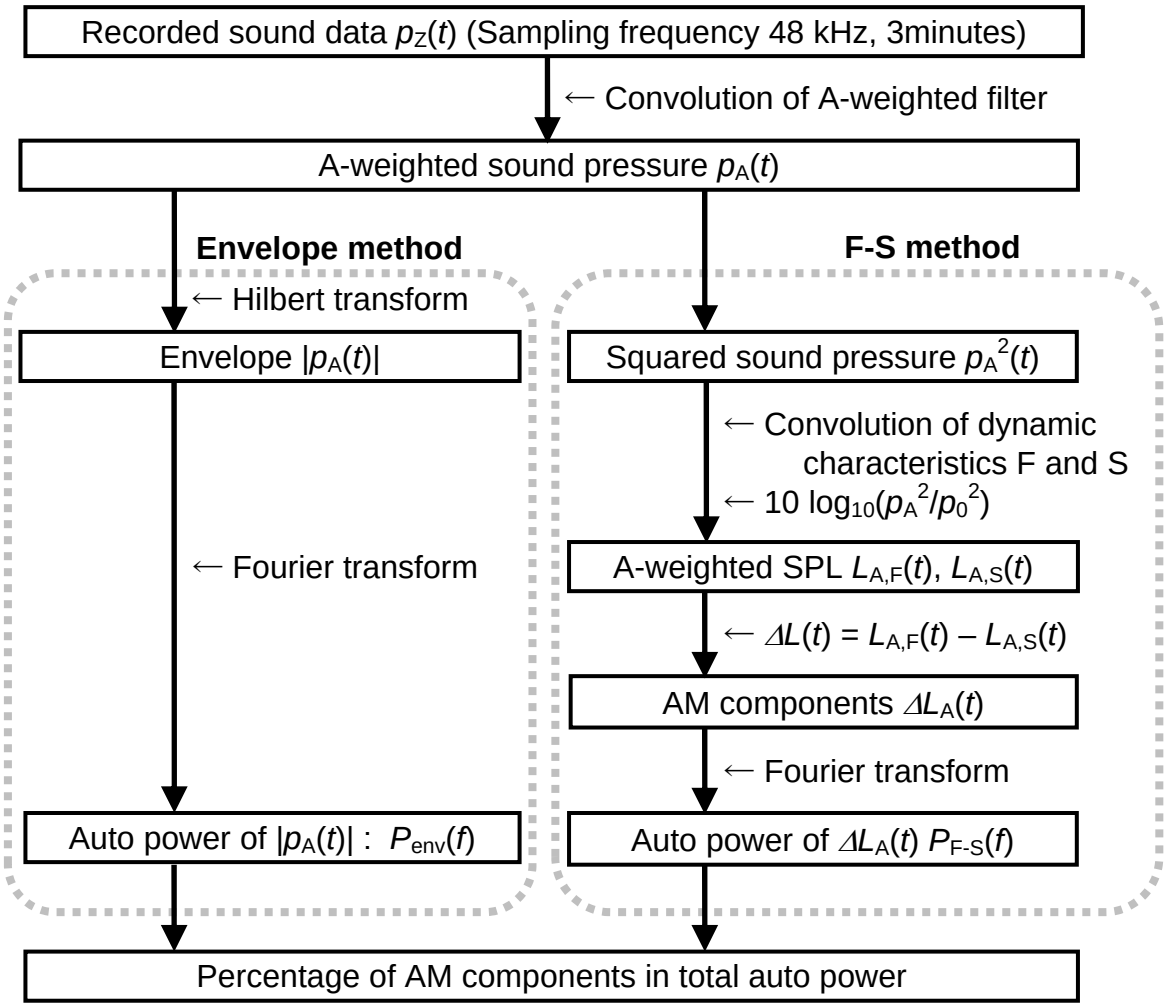
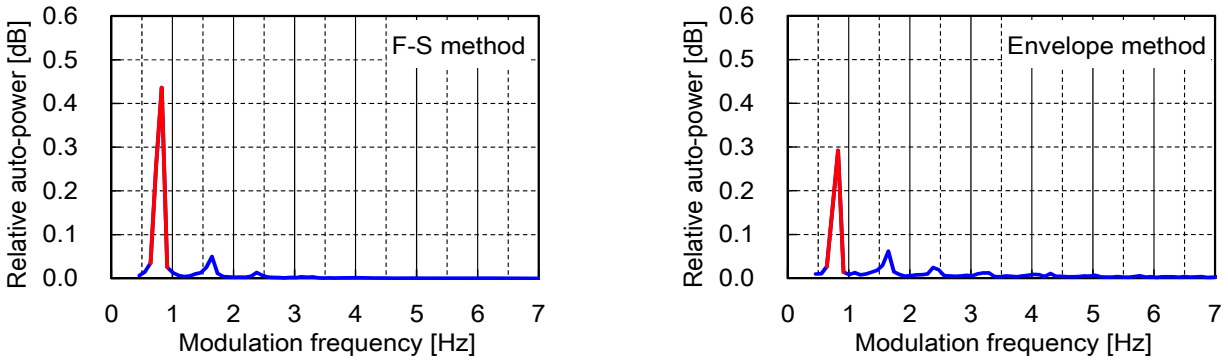
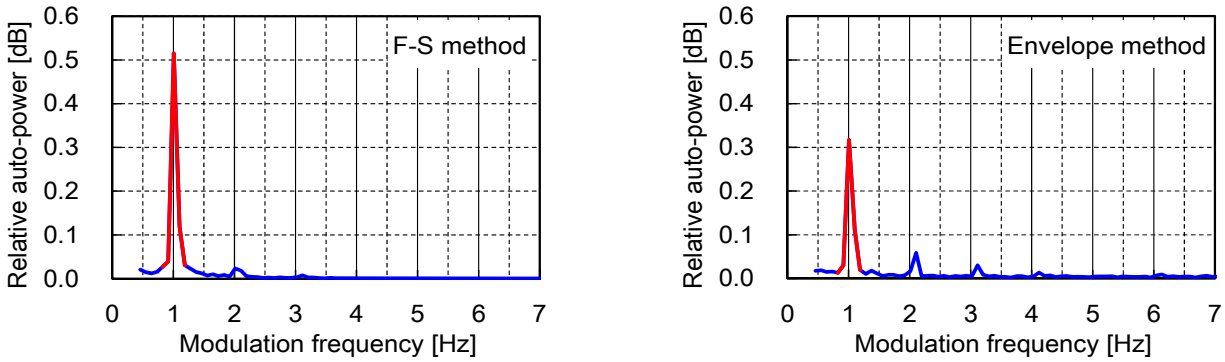


Figure 11 - Procedures of determining AM components.



(a). W02M07 (rated power output : 2500 kW, number of WT : 7, horizontal distance : 561 m)



(b). W22M07 (rated power output : 1950 kW, number of WT : 1, horizontal distance : 1152 m)

Figure 12 – Auto power spectrum of AM components of WTN.
Frequency interval Δf = 0.0916 Hz.

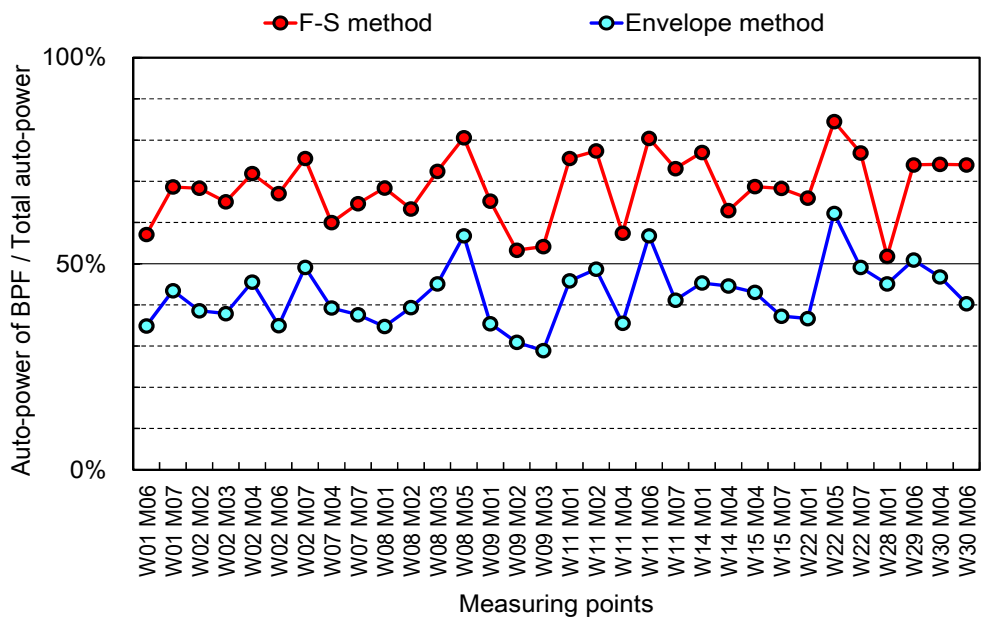


Figure 13 - The ratio of auto-power of BPF to total power.
Total power is defined by the sum of powers of the respective frequencies in the range from 1Hz to 7Hz.

4. Assessment of ambient acoustic condition

Wind power generation facilities are often constructed in quiet rural districts and WTN tends to be audible and cause psycho-acoustical annoyance when no specific noises exist, especially at night. Therefore, the ambient acoustic condition without WTN should be evaluated by the remaining residual noise in the environmental noise impact assessment. Figure 14 shows an example of the time-trace of the A-weighted SPL measured in a rural area without WTN. In this

case, motor vehicle noises come a long way (several hundred meters apart) were included, causing a level difference of about 5 dB between $L_{Aeq,10min}$ and $L_{A95,10min}$ (residual noise). Figure 15 shows the time-traces of $L_{Aeq,10min}$ and $L_{A95,10min}$ of every hour during a day. In the nighttime from 9 pm to 5 am, they were close, whereas they were much separated in the daytime being influenced by the background noises. Thus, the ambient acoustic condition without WTN should be assessed by L_{A95} or L_{A90}.

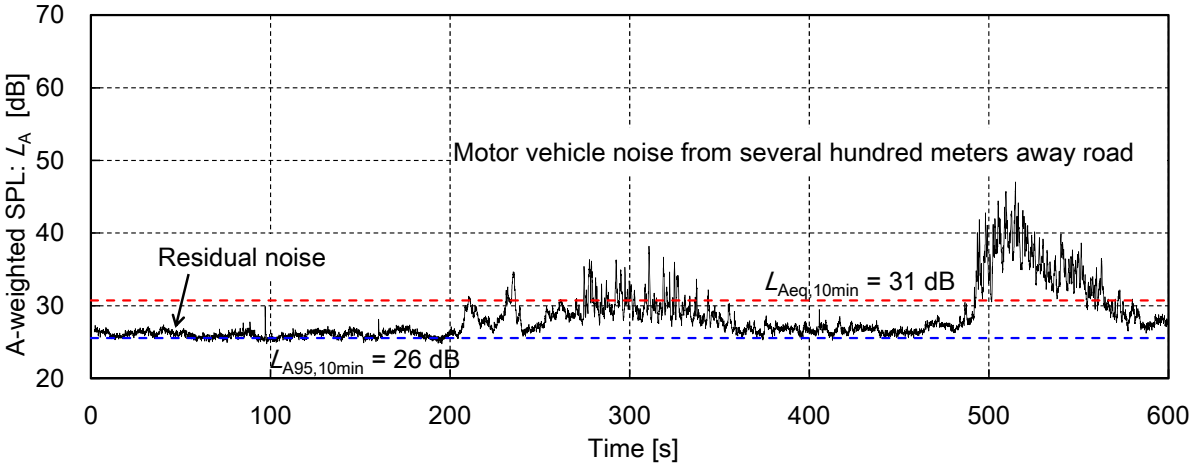


Figure 14 – Example of environmental noise at quiet area.

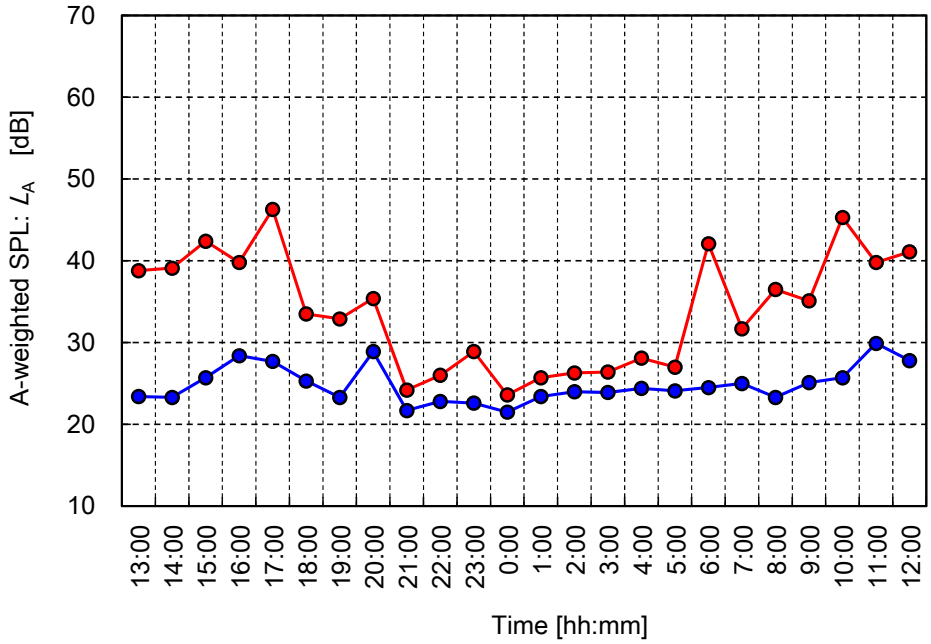


Figure 15 – Time history of L_{Aeq} and L_{A95} during 24 hours measured at control area..

5. Conclusions

Since wind power generation facilities are often constructed in quiet rural districts, WTN tends to be audible and annoying especially at night. The temporal fluctuation (AM) and tonal components contained in WTN increase annoyance. In the quantitative assessment of WTN, such acoustic characteristics should be considered. Regarding this problem, the methods for measuring time-averaged noise level, strength of amplitude modulation, and ambient acoustic condition have been investigated using the sound pressure data recorded at a lot of wind farm sites across Japan. The results of these studies are as follows.

(1) WTN should be primarily assessed by the time-averaged noise level in terms of L_{Aeq}, but L_{Aeq} is apt to be much influenced by the background noises and troublesome processing to eliminate the effect of the background noises is needed. As an alternative method to avoid

this problem is to use L_{A90} or L_{A90} which is robust against the background noises and L_{Aeq} can be statistically estimated from these indicators with high accuracy.

(2) To evaluate the strength of AM components in WTN, we proposed a method to calculate the level difference between the instantaneous A-weighted SPL with FAST time-weighting and that with SLOW time-weighting and obtain the width of the 90% range of the level difference as the AM depth D_{AM} (F-S method). This method was considered using the low-pass-filtering theory and compared with the method applying Hilbert transform and Fourier transform. As a result, it has been confirmed that this method is very simple and practical for the quantitative assessment of the AM components by eliminating the slow temporal variation (drift) of WTN. The FAST and SLOW time-weighting are very universal in general noise measurement.

(3) For the establishment of criteria for WTN and in the noise impact assessment of wind power generation facilities, the ambient acoustic condition without any specific background noise such as traffic noises should be considered as the initial noise condition. In this regard, L_{A90} or L_{A95} should be adopted as an indicator representing the noise floor in the environment.

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