**5th International Conference
on
Wind Turbine Noise
Denver 28 – 30 August 2013**

Assessment of wind turbine noise in immission areas

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Summary

A synthetic study program on wind turbine noise titled "Research on the evaluation of human impact of low frequency noise from wind turbine generators" has been performed over the three years from the 2010 fiscal year sponsored by the Ministry of the Environment, Japan. In this study program, field measurements and social surveys in the immission areas around 34 wind farms across Japan and laboratory experiments on the psycho-acoustical effects of wind turbine noise have been performed. Among them, the methods of measurement and analysis of wind turbine noise are discussed in this paper. It includes a prototype of wide-range sound level meter, wind-screen to prevent the wind-noise at the microphone, practical method of on-site measurement, statistical assessment method of amplitude modulation sound, measurement method of residual noise and indicators for the assessment of wind turbine noise.

1. Introduction

As a fundamental research for preparing scheme of Environmental Impact Assessment of wind turbine noise (WTN) in Japan, a study program has been conducted for the past three years from the 2010 fiscal year sponsored by the Ministry of the Environment, Japan. The main topics of this study are physical research by field measurements, social surveys on the response of nearby residents, and audibility experiments on the physiological and psychological effects of wind turbine noise (see Fig. 1). By putting emphasis on the field measurement of WTN among these topics, measurement instrumentation, practical methods of measurement and measurement results are introduced and discussed in this paper.

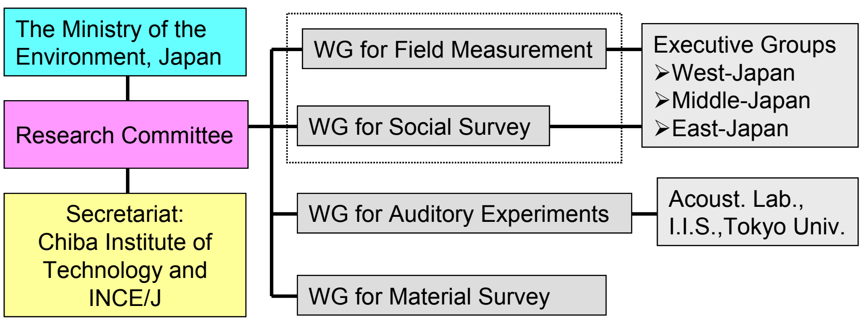


Figure 1: Organization of the research groups and main topics in the study program.

2. Measurement instrumentation

In the problem of WTN, the effect of low frequency components including infrasound is an important matter of controversy and therefore the measurement instrumentation was contrived by paying attention to the measurement in low frequency range as mentioned below.

2.1 Wide-range sound level meter

A prototype of wide-range sound level meter was manufactured to meet the requirements of the measurement frequency range from 1 Hz to 20 kHz, recording function of sound pressure signal built in the body (48 kHz sampling, 16 bits, WAVE-format), *etc*. This instrument meets IEC 61672-1, class 1 (JIS C 1509-1, class 1) in the frequency range from 10 Hz to 20 kHz [1,2].

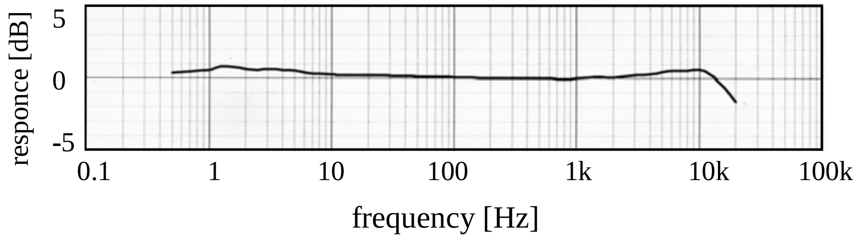


Figure 2: Frequency response characteristic of the wide-range sound level meter.

2.2 Wind-screen set

In the noise measurements in the open, the noise generated by wind at a microphone often deteriorates sound pressure measurement, especially at low frequencies. To prevent such a problem, various contrivances have been made so far. In this study, a prototype of wind-screen set shown in Fig. 3 was devised by considering not only the wind-shielding effect but also water-resistant effect and convenience in conveyance and practical field measurements [1,2].

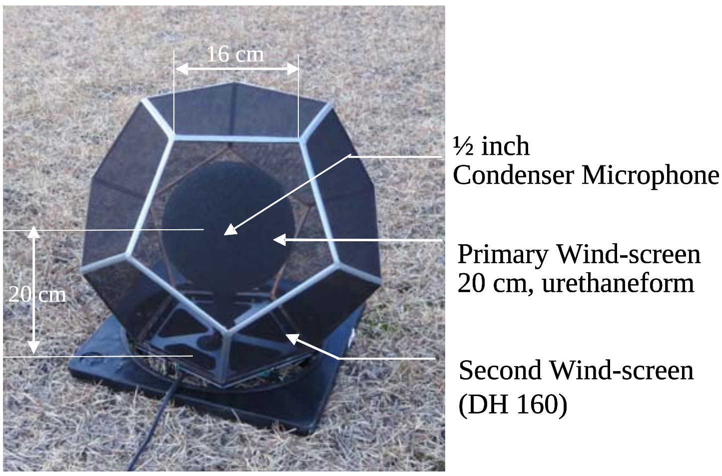


Figure 3: Double wind-screen set for the measurement of WTN in immission areas.

In the double wind-screen set, the second screen “DH-160” is in dodecahedral shape consisting of twelve pentagons with a side of 16 cm and covered with thin cloth (nylon 90% and polyurethane 10%, opening ratio: 60%) with a high elasticity. It is used to cover a commercial-base windscreen with a diameter of 20 cm made of urethane foam (RION WS-03). To examine the wind-noise reduction effect of wind-screen set is considerably difficult because it needs extremely low background noise condition down to low frequency region and a wide range wind-speed condition. We tried the measurement several times so far. Recently, we could have conducted a considerably sufficient measurement. As shown in Figure 4, the measurement was performed in a plain in Akita Prefecture, Japan, and the shielding condition for a 1/2 inch condenser microphone was varied in four kinds: (a) naked, (b) with a urethane-foam wind-screen of 7 cm diameter, (c) with that of 20 cm diameter and (d) with the double wind-screen set as shown in Figure 4. Some examples of the measurement results of wind-noise generated at each microphone arrangements are shown in Figures 5 to 8.

Figure 4: Experimental arrangement in the field measurement

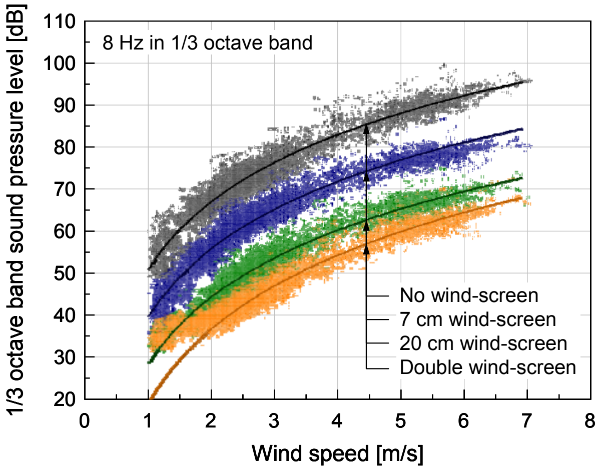


Figure 5: Wind-noise vs. wind speed
(at 8 Hz in 1/3 octave band)

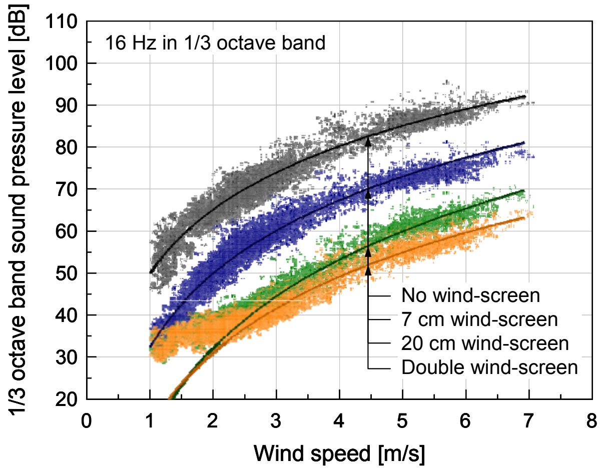


Figure 6: Wind-noise vs. wind speed
(at 16 Hz in 1/3 octave band)

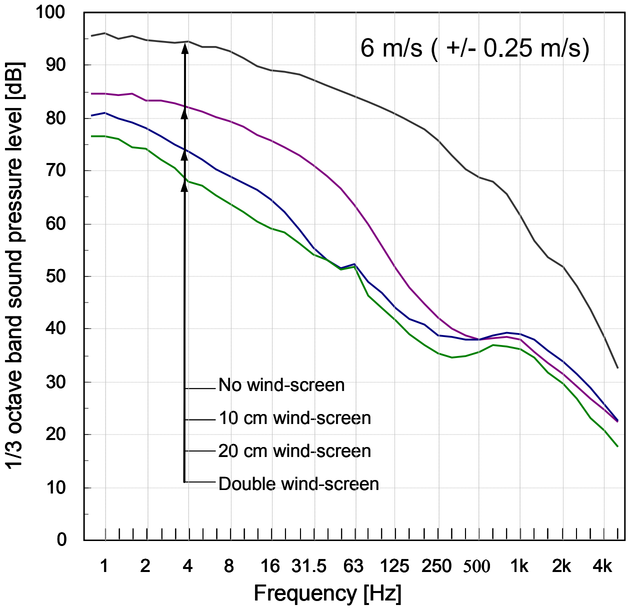


Figure 7: 1/3 octave band SPLs of wind-noise
(wind-speed : 6 m/s(+/- 0.25 m/s))

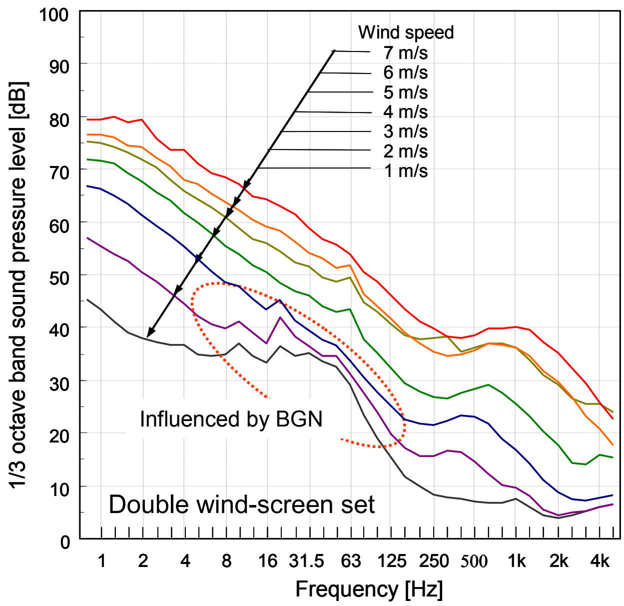


Figure 8: 1/3 octave band SPLs of wind-noise vs. wind-speed
(with the double wind-screen set)

In Figures 5 and 6 which show the wind-noise vs. wind-speed (time-average for 10 s) for 8 Hz and 16 Hz in 1/3 octave band, respectively, the tendency that wind-noise logarithmically increases with the increase of wind-speed in every microphone system but the wind-noise reduction effect is clearly seen in the case of (c) with that of 20 cm diameter and (d) with the double wind-screen set. Figure 7 shows the wind-noise under the wind-speed condition of 6 m/s (+/- 0.25 m/s). Figure-8 shows the 1/3 octave band spectra of the wind-noise for the microphone with the double wind-screen set; the increase of wind-noise due to the increase of wind-speed is seen all over the measurement frequencies. It is seen that the wind-noise reduction effect was limited at the frequencies from about 8 Hz to 100 Hz; it might be due to the background noise in the measurement site.

3. Field measurements

In this study program, WTN measurements have been conducted in 36 areas around 34 wind farms across Japan. Besides, to investigate the actual state of residual noise in quiet rural districts without WTN, the measurements were conducted in the same way in 18 control areas which have similar regional characteristics as in the wind farm areas and not influenced by WTN.

Based on the results of preliminary trials and consideration of the practical conditions at the measurement sites, the following procedures were adopted in the field measurements of this study program.

3.1 Measurement points

Although it is the case that the effect of WTN is serious inside residential buildings, disturbing residents' sleep at night, acoustic measurements inside a building is very difficult from a physical viewpoint [3] and can invade residents' privacy. In the field measurements in this study program, therefore, it has been decided to perform the measurement on the side facing to the nearest wind turbine in the yard of the residence under investigation and the microphone of the wide-range sound level meter covered with the double wind-screen set was set on the ground so that the centre of the microphone located at a height of 20 cm above the ground (see Figure 3). The height of the measurement point was decided in order to prevent the effect of wind on the microphone as far as possible and to avoid various difficulties to keep the microphone at a high position for a long time. Even when using the windscreen-set, the influence of wind can not be completely eliminated and careful attention was needed under a strong wind condition. It was also needed to be careful for heavy rainfall because raindrops noise could affect the measurement.

In the field measurements around each wind farm, seven measurement positions were uniformly distributed in the residential (immission) area supposed to be influenced by WTN within around 1 km from the nearest wind turbine. Besides, an additional measurement point (reference point) was located at a point near a wind turbine and the wind condition was monitored by using an ultrasonic-Doppler-type anemometer set at a height of 4 m above the ground.

3.2 Measurement time interval

A field measurement was performed for continuous 120 hours (5 days) and the sound pressure was recorded on the SD-card installed in the sound level meter. The measurement was performed in an unattended way but the state of affairs such as meteorological conditions (wind and rainfall, *etc.*) and the background noises was checked as far as possible.

4. Data analysis

The sound pressure signal recorded at the measurement sites were analyzed in the ways as mentioned below.

4.1 Reference time interval

Data analysis was performed by putting priority on nighttime as a reference time interval since the effect of WTN is generally most serious at nighttime and the influence of the background noise is generally least in the time zone.

4.2 Sound level data

In the reference time interval, the recordings for ten minutes in every hour during the time when the wind turbines were under a rated operation condition, and A-, C- and G-weighted time-averaged sound pressure levels (SPLs) and 1/3 octave band SPLs were obtained. (Among them, A-weighted SPL was obtained as the main noise indicator and C- and G-weighted SPLs were obtained just for references at the beginning of this study.)

When making the analysis, the influence by the background noises such as road vehicle noise, aircraft noise and various creatures' and insects' sounds was carefully examined through level-recordings and hearing check. If the influence by these background noises was serious, the data was scrapped. In cases where the insects' sounds were dominating in summer and autumn seasons, high-cut filtering eliminating the frequency components higher than 1.25 kHz in 1/3 octave band was applied because the A-weighted SPL was determined by these sounds.

As the representative values for the reference time interval ($L_{\text{Aeq,night}}$), the energy-mean values of the time-averaged SPLs and 1/3 octave band SPLs for every ten minutes ($L_{p\text{eq,10min}}$) were calculated.

As for the measurements in the control areas, the 95 percentile levels of A-, C- and G-weighted SPLs ($L_{\text{A,95}}$, $L_{\text{C,95}}$ and $L_{\text{G,95}}$, respectively) in ten minutes in every hour in nighttime were obtained in order to see the levels of residual noise in each area.

4.3 Assessment of amplitude modulation

It is known that the amplitude modulation (AM) sound, so called swish sound, is an important factor when assessing WTN since it has a seriously adverse effect on auditory impression [4]. Regarding this problem, we have conducted a psycho-acoustic experiment and confirmed the seriousness of this sound [5]. Therefore, in physical assessment of WTN the method of estimating the strength of AM component in WTN should be standardized as well as time-averaged SPL. As a method for this aim, we contrived a method using the difference between the A-weighted SPL obtained by FAST time-weighting and that by the SLOW time-weighting ($\Delta L_{\text{A}}(t) = L_{\text{A,F}}(t) - L_{\text{A,S}}(t)$), and calculating the width of the 90 percent range of the level difference as a measure indicating the amplitude modulation depth (D_{AM}) [6].

5. Measurement results

In the study program, the field measurements have been conducted in the residential areas around 34 wind farms and 16 control areas across Japan according to the methods mentioned above. Among the 34 wind farms, the measurement failed in the areas around 5 wind farms in coastal regions where WTN could not be extracted from the background sea wave sound.

5.1 An example of measurement result of WTN around a wind farm

Among the results of the field measurement of WTN, an example is shown here. The wind farm under the measurement consists of seven wind turbines of 2.5 MW rated power and located in a mountainous district.

Figure 9 shows the time-history of the time-averaged A-, C- and G-weighted SPLs during 24 hours measured at a measurement point 328 m apart from the nearest wind turbine (M04 in Table 1). The wind turbines started rotation at around 1 p.m. and continuously operated until in the morning of the next day. According to the specification in this study program, the time-averaged SPLs for ten minutes in every hour during nighttime (8 hours from 22:00 to 06:00) were analysed and their energy-base averaged values were calculated as shown in the figure. Figure 10 shows the time-averaged 1/3 octave band SPLs for the nighttime at respective measurement points (M00 to M07) and Table 1 shows the time-averaged SPLs at these measurement points.

Figure 11 shows the distribution of $L_{\text{Aeq,night}}$ in distance from the nearest wind turbine. In this result, the tendency of level decline in distance is not so clear in the immission area (M01 to M07).

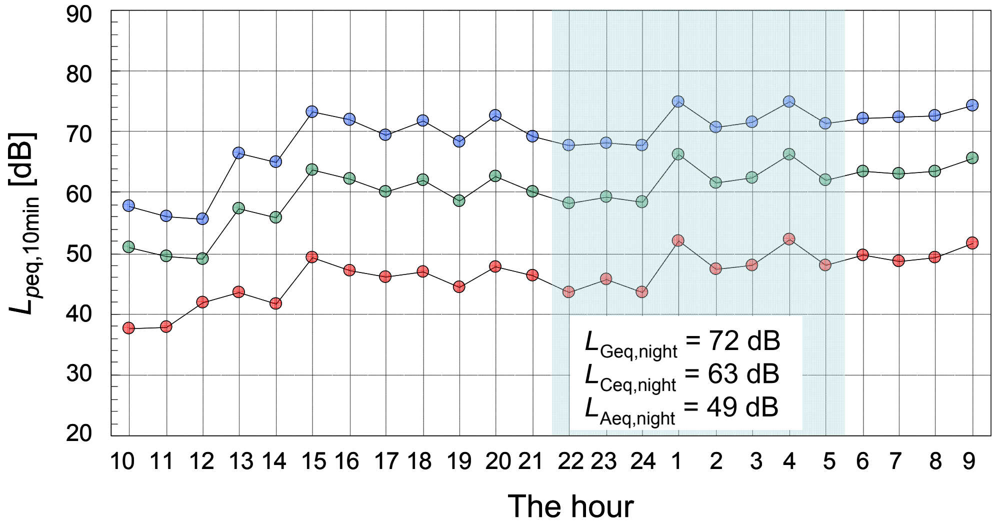


Figure 9: Time history of the time-averaged A-, C- and G-weighted SPLs during 24 hours measured at a measurement point (M04).

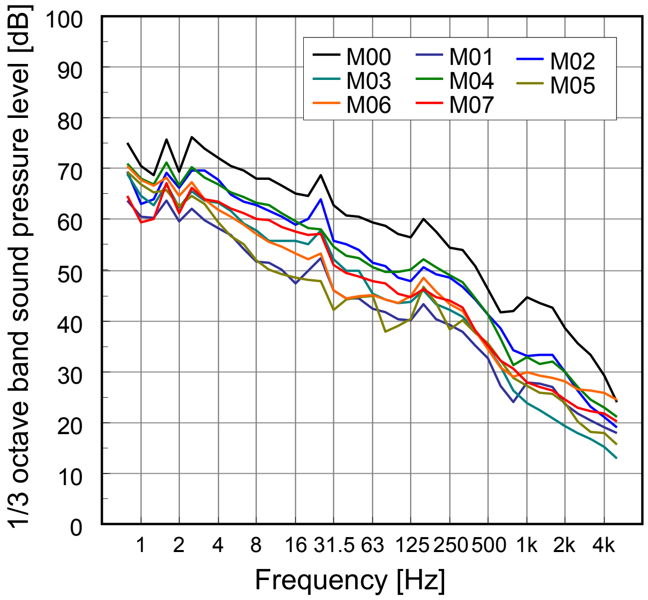


Figure 10: time-averaged 1/3 octave band SPLs for nighttime at respective measurement points (M00 to M07)

Table 1: Time-averaged SPLs for the nighttime at respective measurement points.

Measurement point	Distance [m]	$L_{peq,night}$ [dB]		
		L_{Aeq}	L_{Ceq}	L_{Geq}
M00	136	56	71	80
M01	416	40	54	64
M02	240	48	64	75
M03	409	42	59	69
M04	328	49	63	72
M05	464	42	54	61
M06	397	44	57	66
M07	561	43	60	70

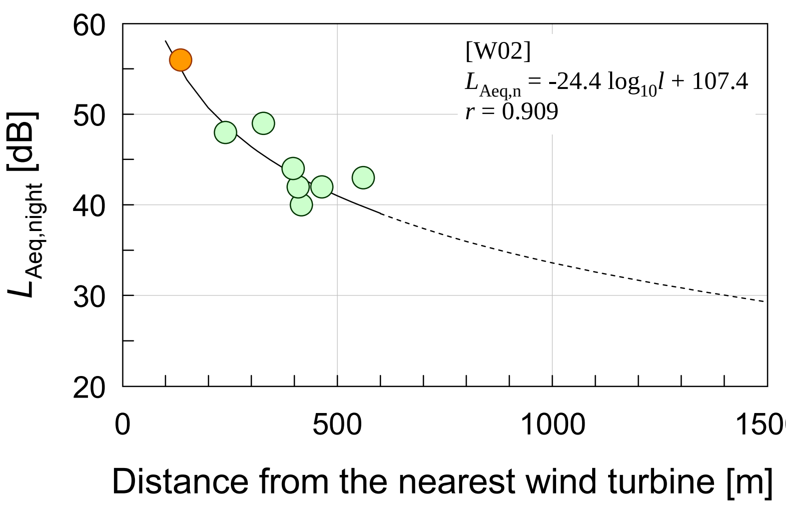


Figure 11: Distribution of $L_{Aeq,night}$ in distance from the nearest wind turbine.

5.2 Measurement results obtained in the area around 29 wind farms

1/3 octave band SPLs measured at 164 points around 29 wind farms are shown in Fig. 12. In the figure, it is seen that almost all WTNs are similar in spectral characteristic which can be approximated by - 4 dB/octave (in band spectrum) as a whole, whereas tonal components are seen in some WTNs. By comparing the measurement results with the criterion curve proposed by A.T. Moorhouse *et al*. [7], it is seen that the frequency components below 20 Hz of almost all WTNs measured in the immission areas are much lower than the hearing/sensation thresholds.

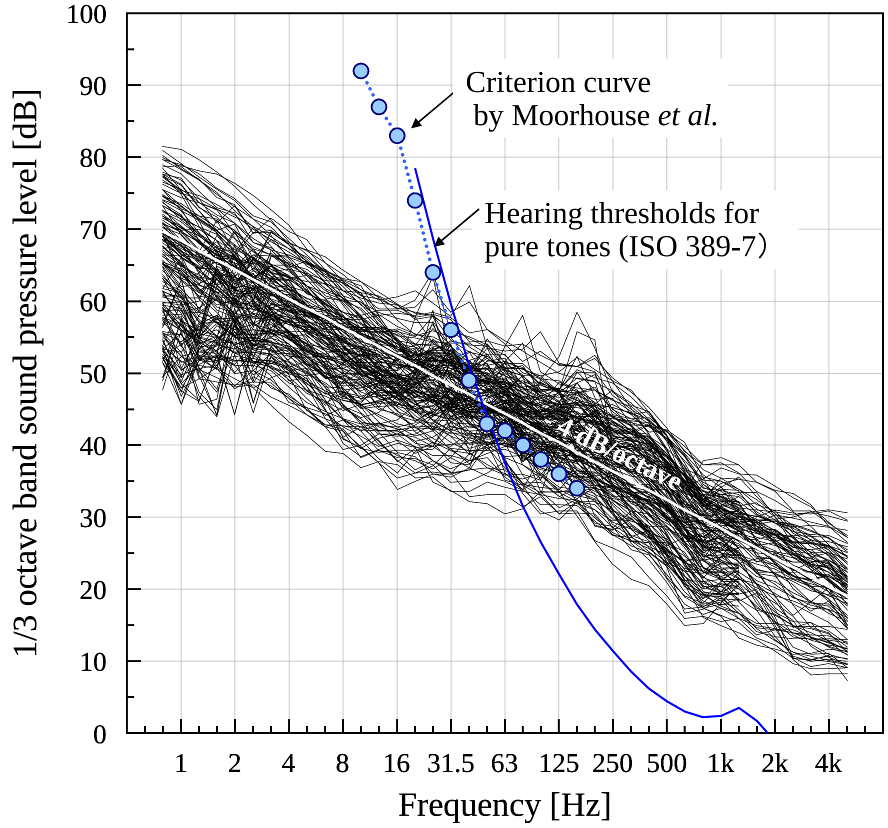


Figure 12: Measurement result of WTN at 164 points around 29 wind farms in Japan

To see the overall feature of WTN, all of the measurement results of L_{Aeq} are shown in Figure 13 in the form of histogram. In the figure, the data of the residual noise level in $L_{A,95}$ measured at 33 measurement points in the 14 control areas are also shown for comparison. In the result, it is seen that L_{Aeq} of WTN distributed from 25 to 50 dBA and the mode is seen in the class of 41-45 dBA, followed by that of 36-40 dBA. On the other hand, the residual noise level in the control areas distributed in the range from 20 to 35 dBA. Thus, about 15 dBA difference was seen between the WTN in L_{Aeq} in the areas around wind farms and the residual noise in $L_{A,95}$ in the control areas.

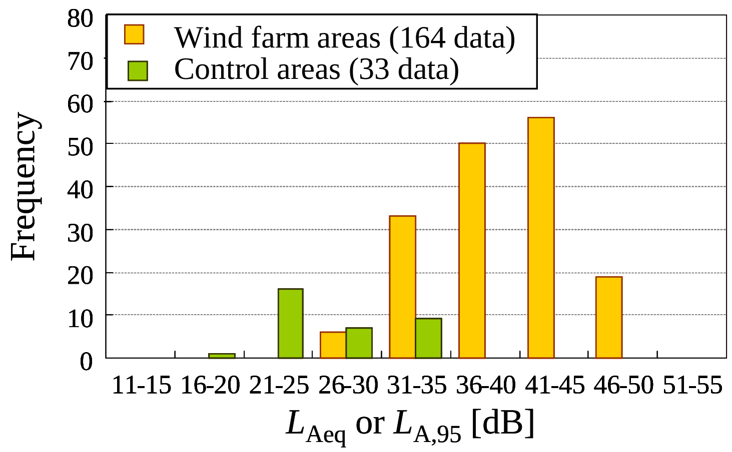


Figure 13: Comparison between L_{Aeq} in the areas around wind farms and $L_{A,95}$ in the control areas.

In the WTN problem, the difference between L_{Ceq} and L_{Aeq} is often discussed. Regarding this point, the relation between the two quantities was examined for the measurement results obtained at the 164 measurement points. The result is shown in Figure 14, in which it is clearly seen that L_{Aeq} and L_{Ceq} are highly correlated.

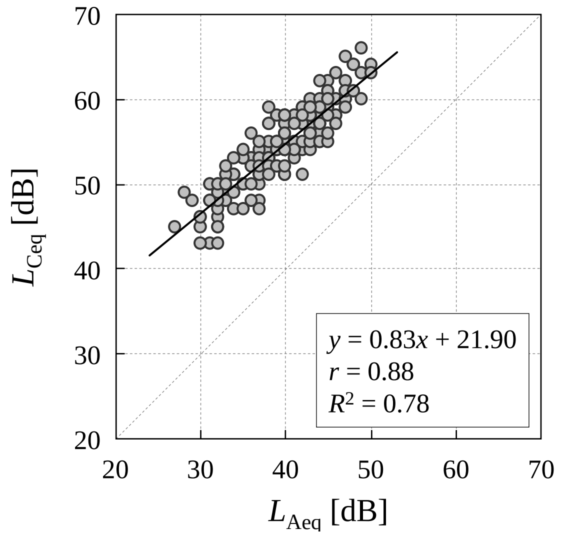


Figure 14: Relationship between L_{Aeq} and L_{Ceq} of WTN.

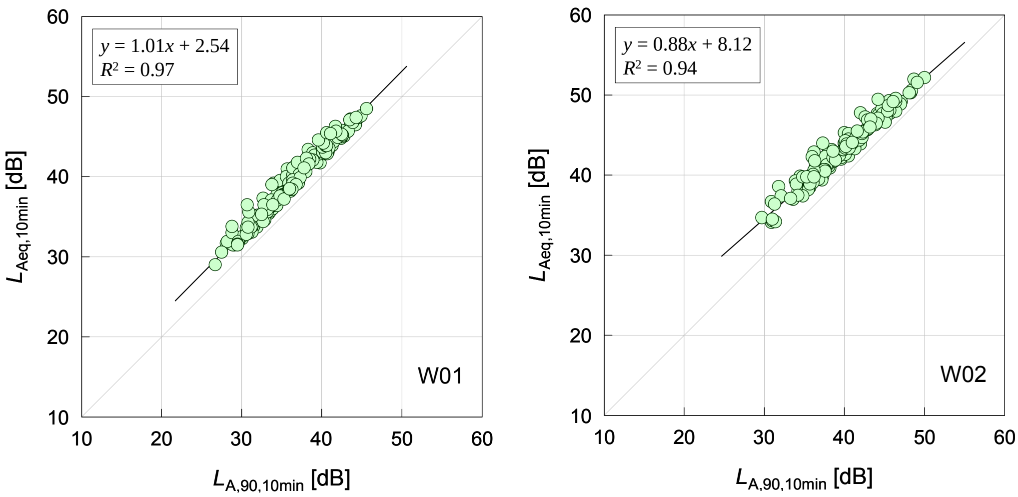
6. Practical methods for determining WTN and residual noise

6.1 Determination of $L_{Aeq,T}$ of WTN

As previously mentioned, the time-averaged SPLs of WTN were obtained by paying close attention to the influence of the background noise in all measurements in this study. This work was very laborious and time consuming and therefore the correspondence between the exact value of $L_{Aeq,T}$ and 90% percent levels $L_{A,90,T}$ or 95% percent levels $L_{A,95,T}$ was examined by using the measurement results obtained in this study. Two examples of the correlation between $L_{Aeq,10min}$ and $L_{A,90,\ 10min}$ are shown in Figure 15, in which highly correlations are seen. Such an investigation was made for the measurement results for 55 points around 8 wind farms and the following relationship has been found.

$$L_{Aeq,10min} \approx L_{A,90,10min} + 2.6 \approx L_{A,95,10min} + 3.1 \text{ [dB]} \qquad (1)$$

Consequently, $L_{Aeq,T}$ of WTN can be estimated by measuring $L_{A,90,T}$ or $L_{A,95,T}$.



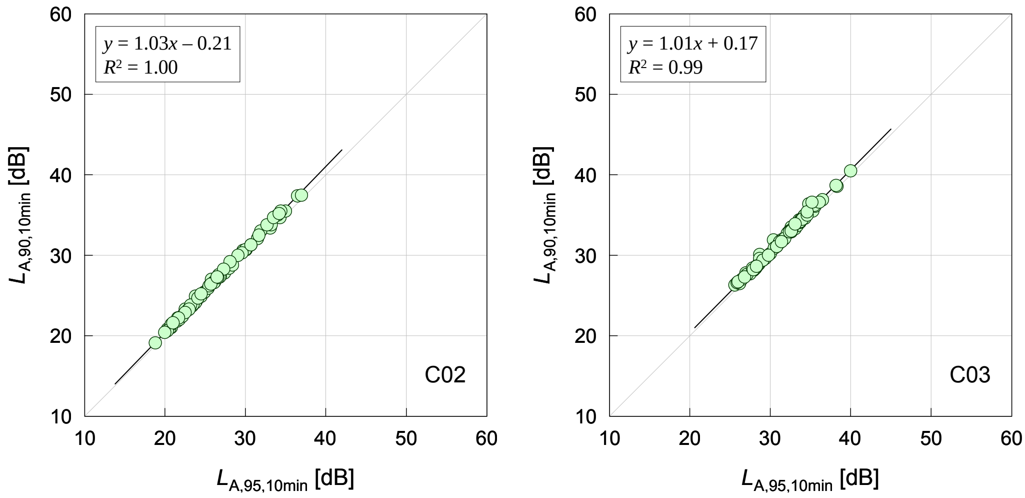
(a) W01 (one 1.98 MW WT) (b) W02 (seven 2.5 MW WTs)

Figure 15: Two examples of the correlation between L_{Aeq} and $L_{A,90}$.

6.2 Determination of residual noise

Also when measuring residual noise level under the condition without WTN, it is laborious and worrying to eliminate the influence of background noise. In such a case, it is convenient and practical to measure either $L_{A,90,T}$ or $L_{A,95,T}$. Two examples of the correlation between the two quantities examined in two control areas are shown in Figure 16. Such an investigation was made for the measurement results for 18 points in 6 control areas and the following relationship has been found.

$$L_{A,90,10min} \approx L_{A,95,10min} + 0.5 \text{ [dB]} \qquad (2)$$



(a) Control area C02 (b) Control area C03

Figure 16: Two examples of the correlation between $L_{A,90}$ and $L_{A,95}$ in the control areas.

7. Other research topics in the study program

7.1 Social survey

At the same time of the field measurements of WTN, questionnaire surveys by interview method have been conducted in the 36 areas around wind farms and the 18 control areas for comparison. The questionnaire contains the items regarding the residents' general conscience about their living environment, annoyance due to WTN, sense of value toward wind turbine facilities, subjective health status and face-sheet.

As a result, it has been found that the effect of WTN is most serious at night, the response of highly annoyed by WTN tends to increase with increasing L_{Aeq} (doze-response relationship) and decreases with increasing the distance from the wind turbines. The details of the survey will be presented in two papers at inter-noise 2013 congress [8,9].

7.2 Auditory experiments on low frequency sounds

In WTN problem, the influence of low frequency components is a matter of controversy. Therefore, a series of laboratory experiments on human audibility of low frequency sounds and psycho-acoustical effects of WTN has been conducted as an important theme in the study program [10-13]. Through these experiments, it has been confirmed that the low frequency components contained in WTNs in immission areas are hardly audible/sensible [11,12], loudness of WTN can be well assessed by A-weighted SPL in the same way as in the assessments of general environmental sounds [13], and amplitude modulation contained in WTN increases noisiness and regular fluctuation sensation occurs when the amplitude modulation depth becomes 2 dB or more [5].

8. Conclusions

To summarize the results obtained in the study program for WTN by putting emphasis on noise measurement and analysis;

(1) In the field measurements, the effect of wind should be reduced as far as possible by using wind-screen with sufficient wind shielding effect. As a system, we devised a double wind-screen set.

(2) The measurement points should be located on the side facing to wind turbine(s) in the yard of the residence under investigation. The microphone should be positioned near the ground so that the effect of wind could be reduced.

(3) Since the operation of wind turbine(s) varies according to the change of natural wind condition, a measurement should be conducted for a long term; at least five days.

(4) Since WTN tends to increase annoyance and cause sleep disturbance in the nighttime, the noise assessment should be made mainly for this time interval.

(5) As the main noise indicator, time-averaged A-weighted SPL should be adopted in principle. At the same time, 1/3 octave band SPLs should be analyzed to examine the contents of tonal components.

(6) In the reference time interval, the recordings for ten minutes in every hour during the time when the wind turbines are under the rated operation condition. As the representative values for the time interval, the energy-mean of the SPL values in every ten minutes should be calculated for the reference time interval.

(7) As a practical method of assessing WTN, 90% percent A-weighted SPL ($L_{\mathrm{A},90,T}$) or 95% percent levels ($L_{\mathrm{A},95,T}$) may be measured. In these cases, $L_{\mathrm{Aeq},T}$ can be approximated by equation (1). In the measurement of residual noise without WTN, $L_{\mathrm{A},90,T}$ or $L_{\mathrm{A},95,T}$ should be measured. The difference between these two indicators can be approximated by 0.5 dB.

(8) In the analysis, background noises such as road vehicle noise, aircraft noise and various creatures' and insects' sounds should be eliminated by paying careful attention. In cases where the insects' sounds are dominating (in summer and autumn), high-cut filtering with 1.25 kHz cut-off frequency should be applied to eliminate high frequency components which is apt to be dominant in the assessment of A-weighted SPL.

(9) Amplitude modulation can increase annoyance of WTN and it should be assessed. As an method for this aim, we contrived a method using the difference between the A-weighted SPL obtained by FAST time-weighting and that by the SLOW time-weighting, and calculating the width of the 90 percent range of the level difference as a measure indicating the amplitude modulation depth. In almost all cases, amplitude modulation is contained in WTN, and therefore the effect of this component should be considered when setting any noise limit for WTN.

(10) In the study program, the effect of tonal components contained in WTNs has not been sufficiently investigated. Regarding this problem, the validity and applicability of ISO 1996-2 should further be examined by psycho-acoustical experiments.

In Japan, Environmental Impact Assessment has become mandatory for the construction of wind power plants from October 2012 and the Ministry of the Environment has began drafting a guideline for the assessment of WTN. The results of this study program will be useful for this work.

Acknowledgement

This study program has been funded by the Ministry of the Environment, Japan.

The authors acknowledge gratefully the members of the Research Committee of the study program for their earnest discussion and thank Mr. Tatsuya Ohta (NEWS Environmental Design Inc.) and Dr. Tomohiro Kobayashi (Kobaysi Institute of Physical Research) for their considerable assistance for this study program.

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