Fact-finding survey for the legislation of wind turbine noise assessment

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ABSTRACT

Wind turbine noise has become a serious environmental noise issue, also in Japan. To investigate this problem, a research project has been conducted over the three years from fiscal year 2010 funded by a grant from the Ministry of the Environment, Japan. This project consisted of three main subjects: physical research on WTN by field measurement, a social survey on the response of nearby residents, and auditory experiments on the human response to noises containing low frequency components. From the research works conducted in this project, the results of the field measurements of WTN are reported and some suggestions for the legislation of wind turbine noise assessment are given in this paper.

1. INTRODUCTION

Wind power generation is a promising means of utilizing renewable energy and numerous wind generation plants have been constructed worldwide. In many countries, however, the noise generated by wind turbines has become a serious problem in the areas around generation plants and the psycho-acoustical effect of wind turbine noise (WTN) has been intensively investigated. Also in Japan, since the commencement of large-scale construction of wind generation plants in about 2000, serious complaints have arisen from nearby residents regarding noise pollution. This problem has often been reported by the mass media as a low frequency noise issue which has increased residents' anxiety about its adverse effect on health.

Regarding this new type of environmental noise problem, scientific knowledge is insufficient and no standard methods for measuring and assessing the noise have been established in Japan. To improve this situation, 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. This project consisted of three main subjects: (1) physical research on WTN by field measurement, (2) a social survey on the response of nearby residents, and (3) auditory experiments on the human response to noises containing low frequency components. Figure 1 shows the organization of the research groups and the main subjects in the project. The Research Committee consisted of 19 experts in acoustics, mechanical engineering,

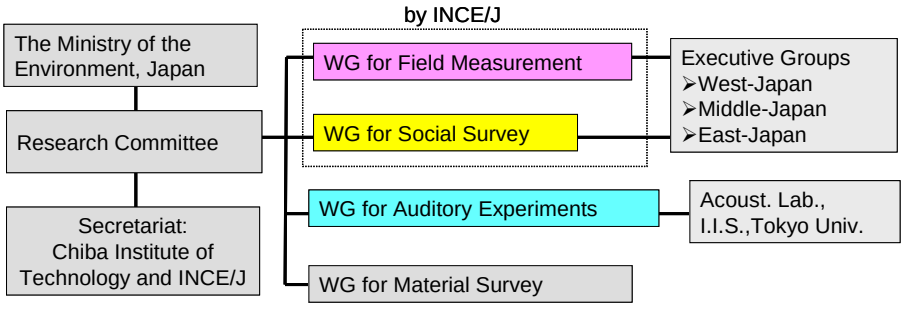

Fig. 1 Organization of the research groups and the main subjects

psychology, and medical science who discussed the course of the project and the details of each research subject. From the research works conducted in this project, the methodology and the results of the field measurements of WTN are reported in this paper. In addition to this work, interview-based social surveys (Kuwano *et al*. 2013; Yano *et al*. 2013) and a series of auditory experiments on the audibility of low frequency noise (Tachibana *et al*. 2012; Yokoyama *et al*. 2012; Yokoyama *et al*. 2013; Sakamoto *et al*. 2013) were conducted in this project and the results have been reported at international congresses.

2. MEASUREMENT INSTRUMENTATION

Regarding the WTN problem, the effect of low frequency components is an important matter of controversy, and a prototype wide-frequency-range sound level meter was manufactured by RION Co. 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).

In outdoor noise measurements, the noise caused by wind at a microphone often interferes with sound pressure measurement, particularly at low frequencies. To prevent this problem, various devises have been made so far. In this study, a prototype wind-screen set, shown in Fig. 2, was devised. This wind-screen set is of the double-skin type consisting of a globular wind-screen of 20 cm diameter made of urethane foam (RION, WS-03) and a newly designed dodecahedral second screen (DH-160) consisting of twelve pentagons with a side of 16 cm covered with a thin cloth (nylon 90% and polyurethane 10%;opening ratio: 60%) with high elasticity (Tachibana *et al*. 2013).

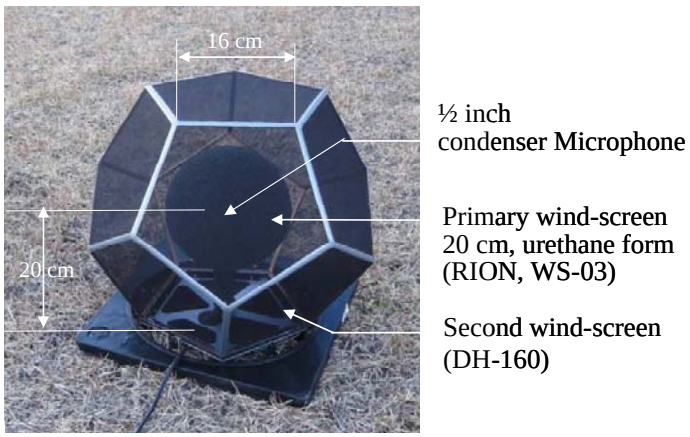

Fig.2 Double-skin type wind-screen set

3. FIELD MEASUREMENTS

To investigate the actual conditions of WTN in Japan, nationwide field measurements were conducted for 34 wind farms from Hokkaido to Okinawa Prefecture in this research project. Moreover, to investigate the actual state of residual noise in quiet rural districts, similar measurements were also conducted in 16 control areas which were not affected by WTN. At the same time as the field measurements, interview-based questionnaires were also conducted both at the wind farm sites and in the control areas to investigate the effect of WTN on nearby residents.

Fig. 3 An example of field measurement of WTN

Although the effect of WTN is severe indoors, disturbing residents' sleep at night, acoustic measurement indoors is very difficult from a physical viewpoint and can invade residents' privacy. In the field measurements in this project, therefore, we decided to perform the measurement facing the nearest wind turbine in the yard of the residence under investigation, and the microphone of a sound level meter covered with the double wind-screen set was placed on the ground so that the center of the microphone was located 20 cm above the ground. Figure 3 shows an example of the setup of a field measurement. The height of the measurement point was decided in order to minimize the effect of wind on the microphone and to avoid various difficulties in keeping the microphone at a high position for a long time.

In the field measurement around each wind farm, seven measurement positions were uniformly distributed in the residential area within a distance of about 100 m to 1 km from the nearest wind turbine.

The field measurement was performed continuously for 5 days at each measurement site and the sound pressure was recorded on an SD card installed in the sound level meter.

4. DATA ANALYSIS

Data were analyzed by putting priority on nighttime as the reference time interval, since the effect of WTN is generally most severe at night. At the reference time interval, the recordings for 10 min of every hour during which the wind turbines were under a rated operation condition were reproduced, and 1/3-octave-band sound pressure levels and A-, C-, and G-weighted time-averaged sound pressure levels were obtained. When carrying out the analysis, the effect of background noises such as road traffic noise, aircraft noise, and the sounds of various creatures was carefully examined and the data contaminated by these background noises were not adopted. In cases where the sounds of insects were dominated, high-cut filtering was applied to eliminate the frequency components higher than 1.25 kHz in 1/3-octave-band.

As the representative values of the 1/3-octave-band and frequency-weighted sound pressure levels for the reference time interval ($L_{peq,night}$), the energy-mean values of the respective sound pressure levels over every 10 min ($L_{peq,10min}$) were calculated.

For residual noise in the control areas, 95 percentile levels of A-, C-, and G-weighted sound pressure levels over 10 min of every hour at night were obtained, and the representative values were calculated as the energy-means of the respective sound pressure levels over every 10 min.

5. MEASUREMENT RESULTS

The field measurements were conducted for 34 wind farms across Japan. Among them, however, the measurement was unsuccessful in the areas around four coastal wind farms where WTN could not be extracted from the background noises of sea waves and windbreak. Another measurement was for investigating the emission characteristics of a wind turbine. Excluding these data, time-averaged 1/3-octave-band sound pressure levels measured at 164 points around 29 wind farms are given in Fig. 4. Brief description of the 29 wind farms is as shown in Table 1. In Fig. 4, it can be seen that almost all WTNs have similar spectral characteristics, which can be approximated by a slope of - 4 dB/octave in band spectrum, with tonal components observed in some of the measurement results.

Table 1 Wind farms under the field measurements

ID	Scale of the wind farms and geographical features	Measurement
W01	1 turbine of 1.98 MW on a hill of a peninsula	Dec. 2010
W02	7 turbines of 2.5 MW in mountainous area	Jan. 2011
W03	10 turbines of 2 MW in mountainous area	Feb. 2011
W04	10 turbines of 1,3 MW in mountainous area	Mar. 2011
W05	9 turbines of 1.5 MW on a tableland	Feb. 2011
W06	6 turbines of 1.5 MW on a tableland	Feb. 2011
W07	9 turbines of 2.3 MW along the ridge of a mountain	Aug. 2011
W08	21 turbines of 2.4 MW in mountainous area	Oct. 2011
W09	9 turbines of 1.5 MW along a coast	Dec. 2011
W10	1 turbine of 1.5 MW in the skirts of a mountain	Dec. 2011
W11	1 turbine of 1.98 MW on a mountaintop along a coast	Jan. 2012
W12	5 turbine s of 1.99 MW in a hilly area	Aug. 2011
W13	1 turbine of 1 MW in a plain	Nov. 2011
W14	17 turbine s of 2 MW along the ridge of a mountain	Dec. 2011
W15	15 turbines of 2.5 MW along the ridge	Jan. 2012
W16	5 turbines of 3 MW along a coast	Jan. 2012
W20	2 turbine s of 400 kW, 4 turbines of 600 kW and 2 turbines of 1.5 MW in flat farmlands	Oct. 2011
W22	1 turbine of 1.95 MW on a mountaintop	Aug. 2012
W23	1 turbine of 1.955 MW in a plain along a coast	Aug. 2012
W24	10 turbines of 1.3 MW on a mountaintop	Sep.-Oct. 2012
W25	8 turbines of 1.3 MW along the ridge of a mountain	Oct. 2012
W27	20 turbines of 1 MW, 5 turbines of 1.5 MW and 14 turbines of 1.65 MW in a vast grassland	Sep. 2012
W28	5 turbines of 1.5 MW and 1 turbine of 2.5 MW (not operated) on a hill along a coast	Oct. 2012
W29	1 turbine of 1.5 MW in gently sloping mountainous area	Oct. 2012
W30	10 turbines of 2 MW around a gently sloping mountainous area	Nov. 2012
W31	1 turbine of 600 kW on a hill	Jan. 2013
W32	1 turbine of 1 MW between harbor facilities and a coastal park	Sep. 2012
W33	1 turbine of 400 kW in a hilly park	Sep. 2012
W34	10 turbines of 1.95 MW in farmlands	Sep. 2012

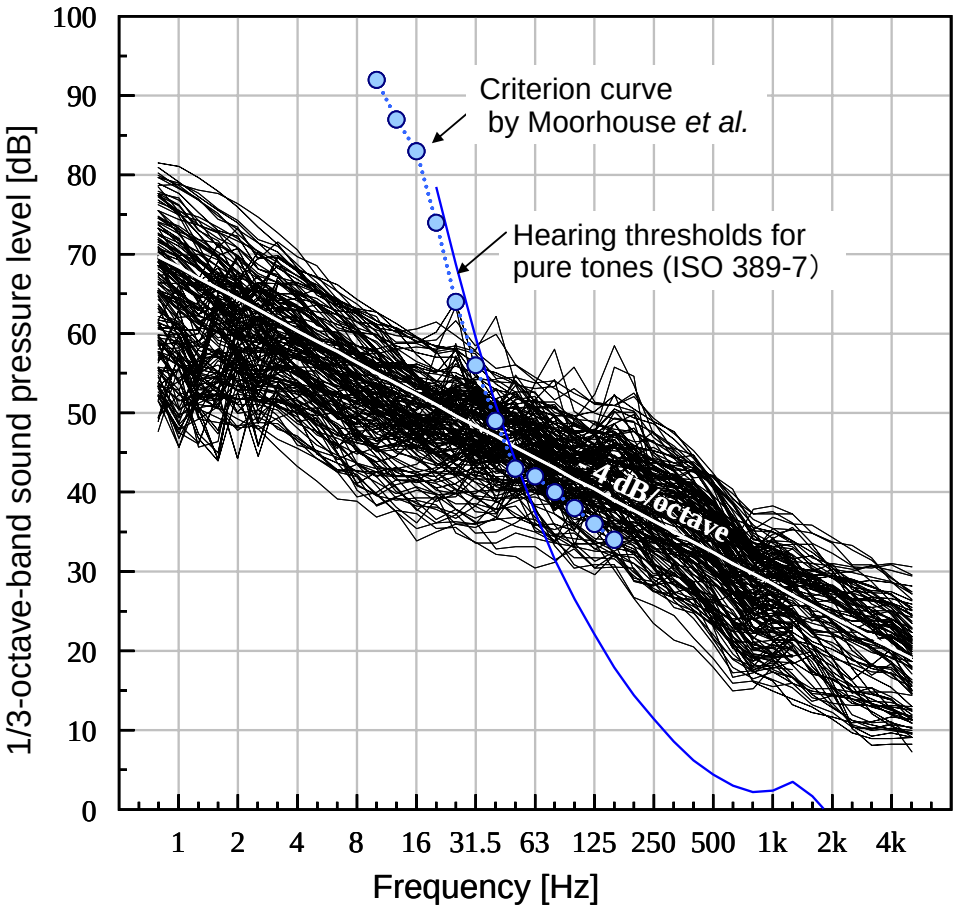

Fig. 4 Measurement result of WTN at 164 points around 29 wind farms.

By comparing the measurement results with the criterion curve for the assessment of low frequency noise proposed by Moorhouse *et al*. (2009), it can be seen that the frequency components below 20 Hz for all the WTNs measured in the immission areas were much lower than the criterion curve. Regarding this criterion curve, its validity has been confirmed by an auditory experiment on the audibility of band limited low frequency noise conducted as a part of this project (Yokoyama *et al*. 2013).

To see the overall features of WTN, all of the measurement results for L_{Aeq} and L_{Geq} are shown in Figs. 5(a) and (b), respectively, in the form of histograms. In these figures, the data of the residual noise level in terms of $L_{A,95}$ and $L_{G,95}$ measured at 33 measurement points in the control areas are also shown for comparison. In Fig. 5(a), it can be seen that L_{Aeq} for WTN was distributed from 25 dB to 50 dB and the modal class is 41-45 dB, followed by 36-40 dB. On the other hand, the residual noise level in the control areas was distributed in the ranges from 20 dB to 35 dB. Thus, there was a difference of 10 dB or more between the WTN in terms of L_{Aeq} in the areas around wind farms and the residual noise in terms of $L_{A,95}$ in the control areas.

In Fig. 5(b), it is clear that the G-weighted sound pressure levels measured in the areas around wind farms were higher than those measured in the control areas. Even in the areas around wind farms, however, the levels were much lower than the infrasound threshold level described in ISO 7196.

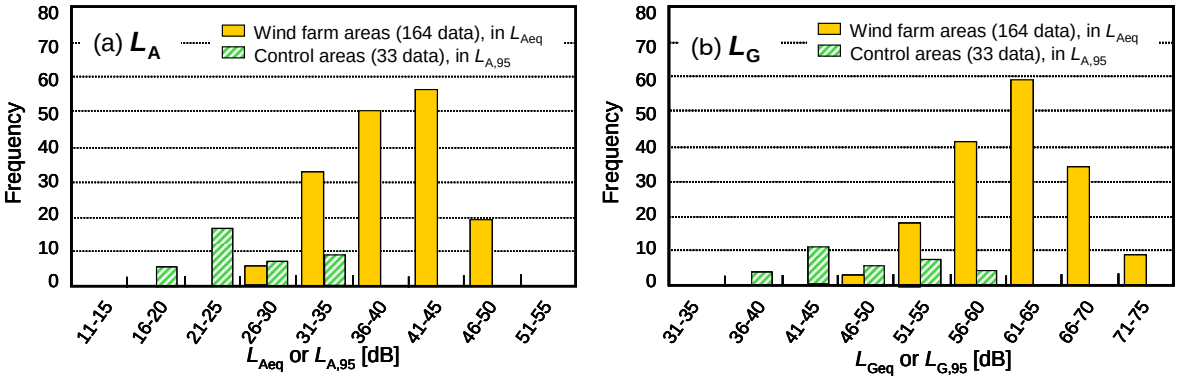

Fig. 5 WTNs and residual noises in the control areas assessed in terms of (a) A- and (b) G-weighted sound pressure levels, measured at 29 wind farm sites and in 16 control areas.

6. ASSESSMENT OF AMPLITUDE MODULATION SOUND

Regarding WTN, the amplitude modulation (AM) sounds (swish sounds) is a serious problem, because they increase psychological annoyance (Moorhoouse *et al*. 2007; Bowdler & Leventhall 2011; Bullmore *et al*. 2011; Bass *et al*. 2012). To objectively quantify the level of AM, the authors contrived a method using the difference between the A-weighted sound pressure level obtained by FAST time-weighting and that by the SLOW time-weighting ($\Delta L_A(t) = L_{A,F}(t) - L_{A,S}(t)$), and calculating the width of the 90 percent range of the level difference as a measure indicating the amplitude modulation depth (D_{AM}) (Fukushima *et al*. 2013).

Figure 6(a) shows an example of the A-weighted sound pressure levels of WTN recorded with FAST and SLOW time-weightings for 40 s, and the level difference $\Delta L_A(t)$ is shown in Fig. 6(b). Figure 6(c) 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 Fig. 6(b) were used. In this case, D_{AM} was 2.8 dB.

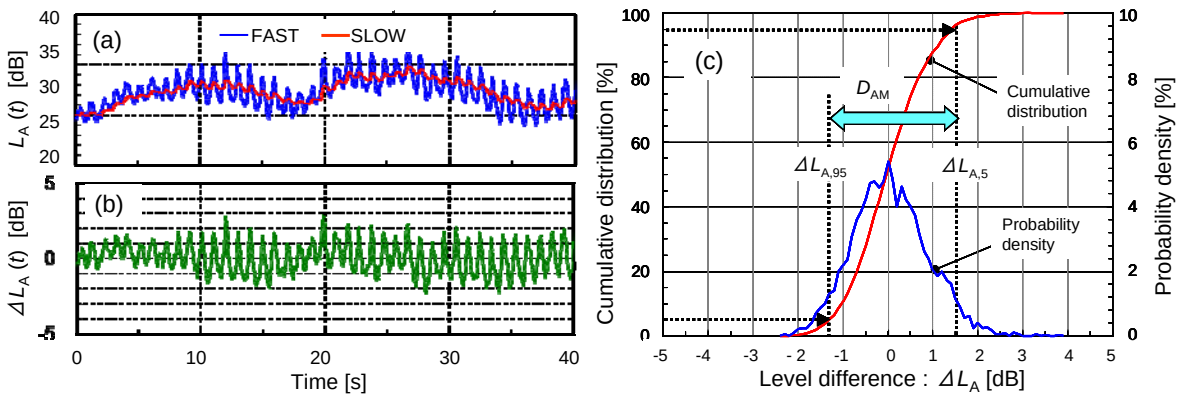

Fig. 6 An example of amplitude modulation in WTN. (a) : A-weighted SPLs recorded with FAST and SLOW time-weightings for 40 s, (b) : the level difference $\Delta L_A(t)$, and (c) : the procedure to determine the amplitude modulation depth D_{AM}.

The above procedure was applied to the sound pressure recordings made at 81 points at 18 wind farm sites. In this study, D_{AM} was determined from the recordings made for 3 min at each measurement point. As a result, it was found that D_{AM} ranged from 1 dB to 5 dB and that the modal group was 2.0 to 2.4 dB. It has been clarified that the sensation of fluctuation begins at an AM depth of approximately 2 dB (Bowdler & Leventhall 2011). This was confirmed in a recent

auditory experiment (Yokoyama *et al*. 2013) performed as a part of this research project. According to these findings, fluctuation due to AM can be detected at about three-quarters of the measurement points examined in this study.

7. CONCLUSIONS

A summary of the paper is given as follows.

(1) Since the effect of low-frequency components in WTN is a major concern, field measurements were performed using newly manufactured sound level meters covering a wide frequency range including infrasound.

(2) To prevent windnoise generation at the microphone, a double-skin type wind-screen set was devised. The result of a field test confirmed that the wind-shielding effect can be improved down to the infrasound frequency region by adding a second wind-screen to the conventional single wind-screen.

(3) Since the adverse effect of WTN is most serious at night, nighttime was defined as the reference time interval and the data were analyzed while focusing on this time zone.

(4) To obtain a representative value of WTN during the reference time interval, the method to analyze the time-averaged sound pressure levels for 10 min of every hour and to calculate their energy-mean was adopted in this study.

(5) Among 34 wind farms under measurement in this study, WTN could not be measured for four wind farms located in coastal areas owing to the effect of sea wave sound and the noises caused by windbreaks. It is a difficult problem to identify the WTN under such poor signal-to-noise ratio conditions.

(6) From the measurement results of the 1/3-octave-band sound pressure level at 194 points at 29 wind farm sites, it was found that WTN generally has a spectrum characteristic of about - 4 dB/octave in band spectrum. All the 1/3-octave-band sound pressure levels in the infrasound frequency region were below the criterion curve for the assessment of low frequency noise proposed by Moorhouse *et al*.. As a part of this research project, the human audibility of the low frequency components contained in WTNs in immission areas was examined through a laboratory experiment and it was confirmed that the components in infrasound region are not audible/sensible (Yokoyama *et al*. 2012, 2013).These indicate that WTN is not a problem in the infrasound frequency region (Jakobsen 2005).

(7) However, most of the 1/3-octave-band sound pressure levels were above the criterion curve and the pure-tone hearing threshold curve specified in ISO 389-7 in the audible frequency range higher than 20 Hz. This means that WTN should be discussed as an “audible” environmental noise.

(8) All the measurement results of WTN in the residential areas obtained in this study were between 25 dB to 50 dB in the time-averaged A-weighted sound pressure level. These levels are relatively low, but they are audible and might cause serious annoyance in residential areas which are generally very quiet rural districts.

(9) As a part of this research project, the human loudness sensation was investigated through a laboratory experiment using various kinds of environmental noises including low frequency components down to infrasound frequencies, and it was confirmed that the loudness sensation can be more accurately assessed by the A-weighted sound pressure level than by the C-weighted sound pressure level (Sakamoto *et al*. 2013). Therefore, it can be said that WTN can be assessed by the A-weighted sound pressure level as a primary indicator, similarly to general environmental noises.

(10) To assess the extent of amplitude modulation contained in WTN, a simple

statistical method using the difference between the A-weighted sound pressure level with FAST time-weighting and that with SLOW time-weighting was proposed. This method was applied to 81 measurement points at 18 wind farm sites and it was found that the fluctuation sensation by AM sound might be caused at about three-quarters of all the measurement points. Therefore, the effect of AM should be well considered when devising legislation for the assessment of WTN, as specified in Standards New Zealand.

(11) In the measurement results of this study, strong tonal components were found in some cases. Tonality is a serious problem of WTN as well as AM, and the authors plan to investigate this problem by using our measurement data and by referring to previous studies (Cooper et al. 2013; Søndergaard & Pedersen 2013) and international standards (ISO 1996-2:2011 and IEC 61400-11:2012).

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