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Assessment of tonal components contained in wind turbine noise in immission areas

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Summary

Tonal components contained in wind turbine noise are apt to increase psycho-acoustical annoyance and the method of objectively assessing the effect should be established for the wind turbine noise problem. In Japan, a nationwide field measurement of wind turbine noise was conducted over the three years from fiscal year 2010 and a lot of data (recordings of sound pressure) have been obtained. For these data, tonality assessment was tried according to the international standard IEC 64100-11:Ed.3 (2012). In addition, an auditory experiment was performed in order to investigate the effect of tonal components in wind turbine noise on auditory impression using artificially synthesized noises containing tonal components with varying frequencies and levels. From these investigations, the standard method for assessing the tonality of wind turbine noise in immission areas is discussed.

1. Introduction

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. To investigate the actual conditions of this new type of environmental noise problem and to find the ways for assessing the wind turbine noise (WTN), a research project entitled “Research on the evaluation of human impact of low frequency noise from wind turbine generators” has been conducted over the three years from fiscal year 2010, funded by a grant from the Ministry of the Environment, Japan. In this research project, nationwide field measurement [1], social survey [2], laboratory experiments on the audibility of low-frequency components in WTN [3], the

applicability of the A-weighted sound pressure level to WTN [4], and the psycho-acoustic effect of amplitude modulation [5] have been investigated.
Besides these problems, tonal components with discrete frequencies are often contained in WTN which are generated by mechanical vibration of rotating mechanism of wind turbine such as gearbox, generator and cooling fans [6] and they are apt to increase psycho-acoustical annoyance [7, 8].

In the nationwide field measurement in the research project, WTN data were obtained at 29 wind farm sites. At each site, one measurement point was positioned close to a wind turbine (reference point) and seven measurement points were distributed in the residential (immission) area around the wind farm. The sound pressure signals 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). Using these data, the authors have been investigating the method of assessing the effect of tonal components. In this paper, the application of the assessment method of “Tonal Audibility” (TA) specified in IEC 61400-11: 2012 to WTNs observed in immission areas around wind farms was investigated.

In addition, the change of auditory impression by tonal components contained in WTN was examined in a laboratory experiment using artificially synthesized noises containing tonal components with varying frequencies and levels. From the results of these investigations, the standard method for assessing the tonality of WTN in immission areas is discussed.

2. Tonality assessment

As the standards for the assessment of tonality, ISO 1996-2:2007 and DIN 45681:2005 are specified for general environmental noises and IEC 61400-11:2012 specifies the method of assessing TA of WTN in emission measurements. The basic concepts of these standards are similar, but the terminologies and concrete procedures for the calculation of tonality indicators are different because of the difference of respective aims. In this study related WTN in immission areas, the assessment method of TA specified in IEC 61400-11:2012 is mainly applied.

2.1 Analysis procedure

According to IEC 61400-11:2012, the calculation program for the assessment of TA was implemented in this study as shown in Fig. 1. To detect short-term variation of WTN influenced by wind condition, it is specified in the standard that the short-term values of TA are firstly calculated for every 10 s from the sound pressure record and they are averaged for more than 100 s as the value of TA to be finally reported. In the calculation in each time period (10 s), TA is calculated according to the following procedure.

(1) In the A-weighted narrow-band spectrum, the local maxima are detected and the possible tones are identified.
(2) The critical band is calculated centred on the maxima and spectral lines are classified as “tone”, “masking” or “neither”.
(3) As the difference between “tone level” and “masking noise level” in the corresponding critical band, “Tonality” is calculated.
(4) By adding the frequency dependent “auditory criterion” (“masking index” in ISO 1996-2:2007) to the value of Tonality, TA is determined.

Regarding the process (1), the method for detecting possible tones is not specified definitely in IEC 61400-11:2012 and therefore the Savitzky-Golay smoothing and 2nd order differentiation filter was applied when detecting local maxima. In this process, the threshold was tentatively set at -0.35 [dB/f^2] which was decided empirically after many trials. In the case where a tone was identified in more than 20% of the analysis time interval and had TA equal to or higher than -3 dB, the energy average was calculated as the representative value of TA.

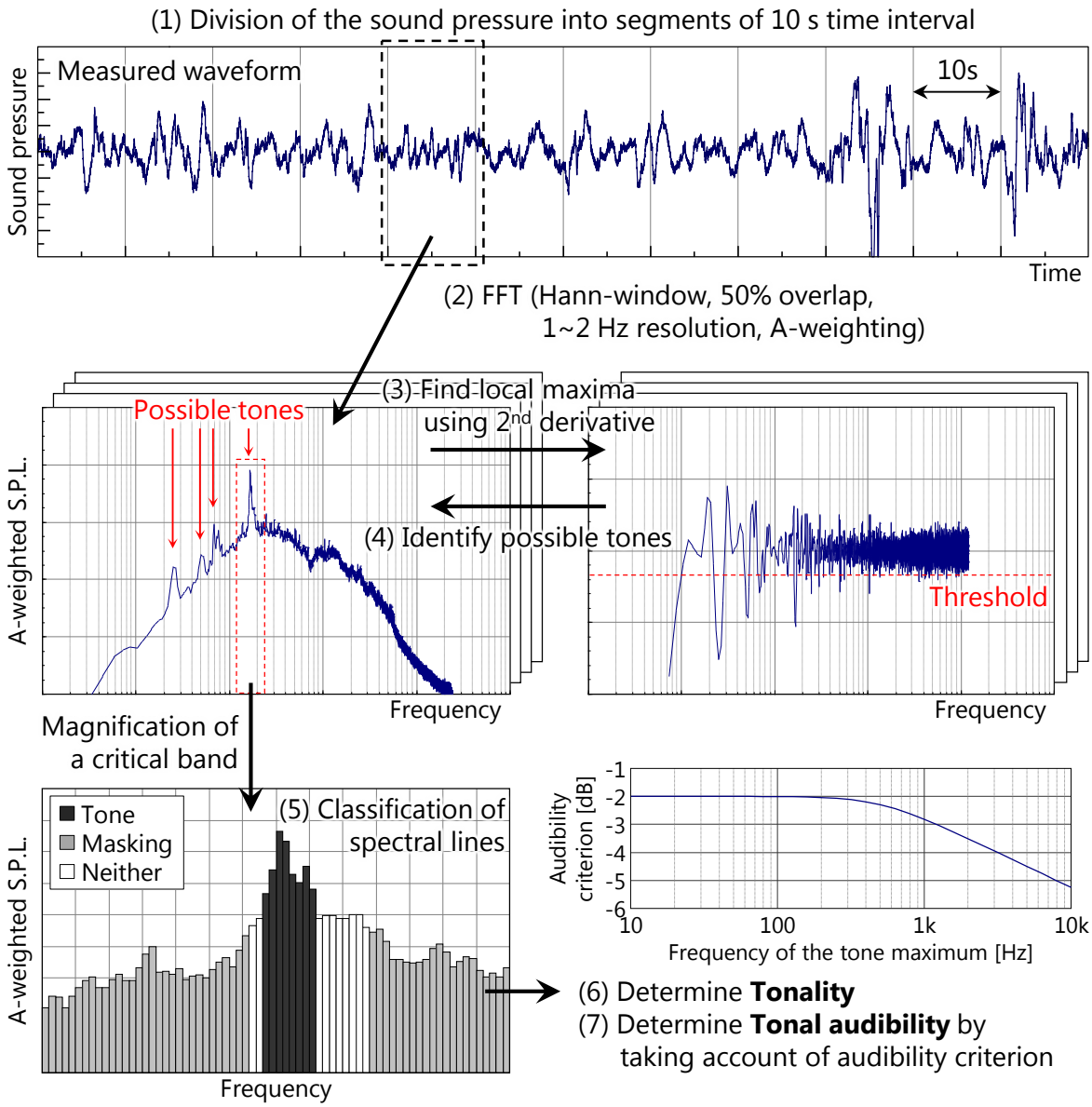
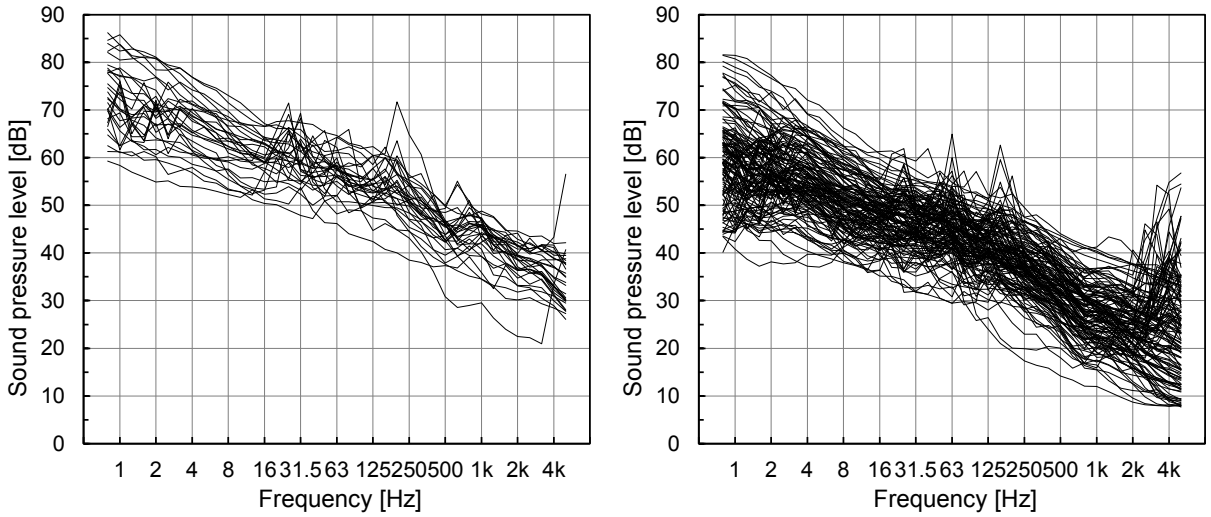


Figure 1 Calculation procudure of “Tonal Audiblity” according to IEC 61400-11: 2012.

2.2 Analysis using the field measurement data of WTN in immission areas

TA analysis was performed on the sound pressure data obtained at 164 measurement points at 29 wind farm sites in Japan. In the field measurements, WTN was recorded for 5 days at each measurement point. From the recordings, the data for representative 10 minutes when the wind turbines were under a rated operation condition was chosen and TA was assessed in the way as mentioned above. In this analysis, the effect of the background noise was eliminated as far as possible. As a result, Figs. 2(a) and 2(b) show 1/3-octave-band spectra of WTN in emission areas (a) and those in immission areas (b). In the emission areas, TA was detected (≥ -3 dB) at all of the measurement points (29). As for the immission areas, TA was detected at 129 points among the total 164 points. The distributions of frequency (horizontal axis) and TA (vertical axis) for each identified tone are shown in Fig. 3, in which it is seen that tone frequency ranged from about 50 Hz to 1,000 Hz and TA ranged from -3 dB up to 14 dB.

Figure 4 shows an example of the change of TA with time measured at four points around a wind turbine (1.5 MW). In this case, it is seen that TA of the dominant tonal component (around 160 Hz) at the measurement point M01 (370 m) in the residential area was greater than that observed at the point M00 (100 m) in the emission area and TA values measured at other immission points M02 (380 m) and M03 (540 m) much decreased.



(a) In emission areas (29 points) (b) In immission areas (129 points)

Figure 2 1/3 octave band spectra of WTNs with Tonal Audibility larger than -3 dB.

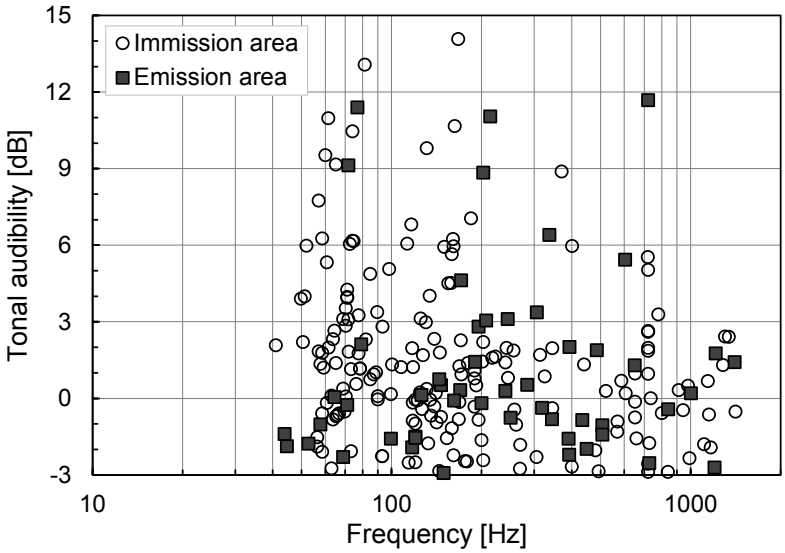


Figure 3 Distribution of Tonal Audibility identified at 158 measurement points.

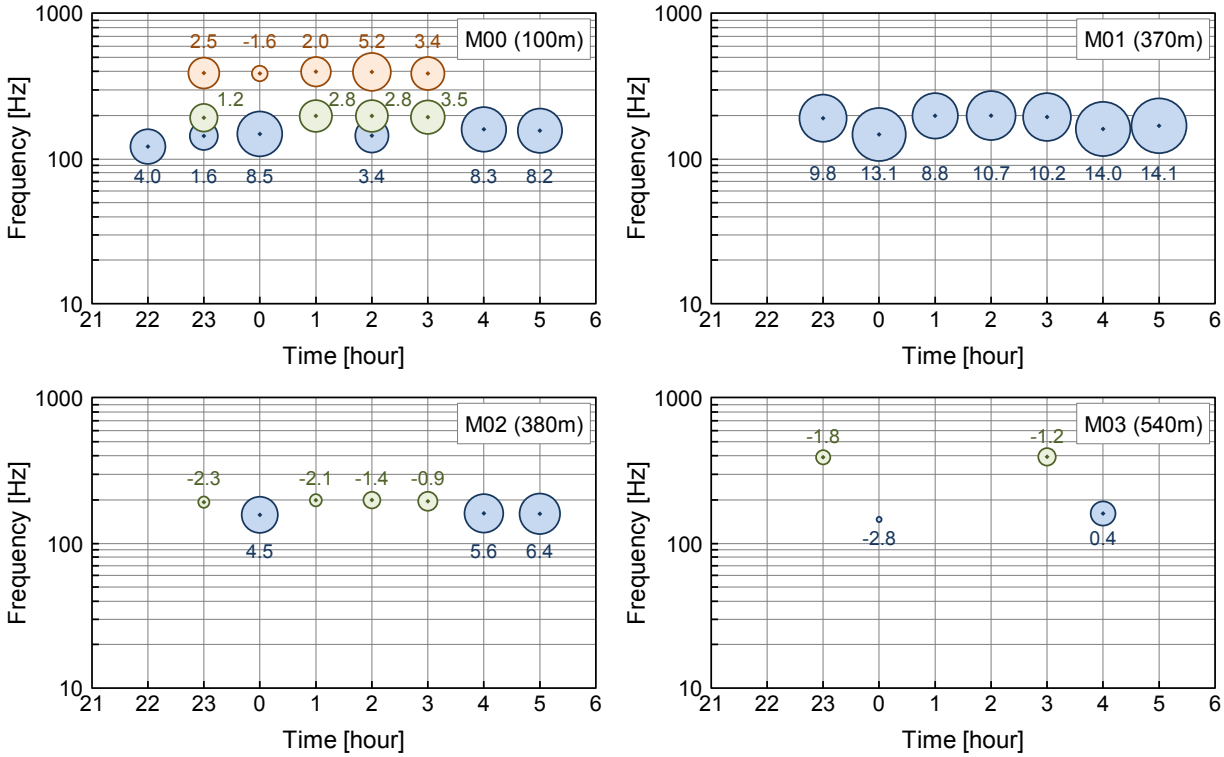


Figure 4 An example of the change of Tonal Audibility with time (around 1.5 MW wind turbine).

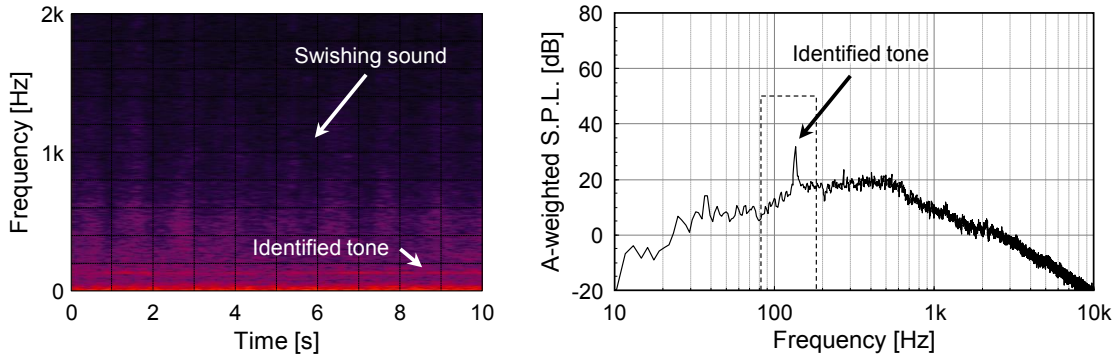
2.3 Case studies

From the data included in Fig. 2, three typical data were chosen as shown in Table 1, in which the data regarding wind turbine(s), the distance from the nearest wind turbine and the measurement point, averaging time for the assessment of TA, centre-frequency of the critical band, and the assessed TA are shown. In this table, the results assessed by ISO 1996-2:2007 are also shown for comparison. In Cases-1 and -2, TA values assessed by IEC 61400-11 are smaller than those assessed by ISO 1996-2. This tendency is pointed out also in reference [8, 9]. In Case-3, TA could not be assessed by ISO 1996-2 as mentioned below. Figures 5, 6 and 7 show the spectrogram (a) and narrow-band spectral characteristic measured for 10 s (b). In Fig. 5 for Case-1, a tone was identified at 135 Hz and its TA was evaluated as 6.1 dB. In this case, a strong amplitude modulation was also observed. In Fig. 6 for Case-2, two tones were identified. In such a case, only the most dominant tone is reported according to ISO 1996-2, while respective tones are reported according to IEC 61400-11. In Fig. 7 for Case-3, it is seen that the frequency of the tone at around 180 Hz shifted with time. In this case, TA could be evaluated according to IEC61400-11 because analysis was performed for every 10 s, while it could not be assessed according to ISO 1996-2 because of the temporal shift of the frequency of the tone.

Figure 8 shows another example of Z-weighted narrow-band spectrum of WTN compared with the hearing thresholds for pure tones specified in ISO 389-7. In this case, TA was assessed to be 1.5 dB at the tone frequency of 51 Hz and it is judged as a tonal component according to IEC 61400-11. As shown in the figure, however, the tone level is lower than the hearing threshold curve by 6.5 dB. In such a case, tonal audibility should be precisely considered from a view point of hearing thresholds for pure tones.

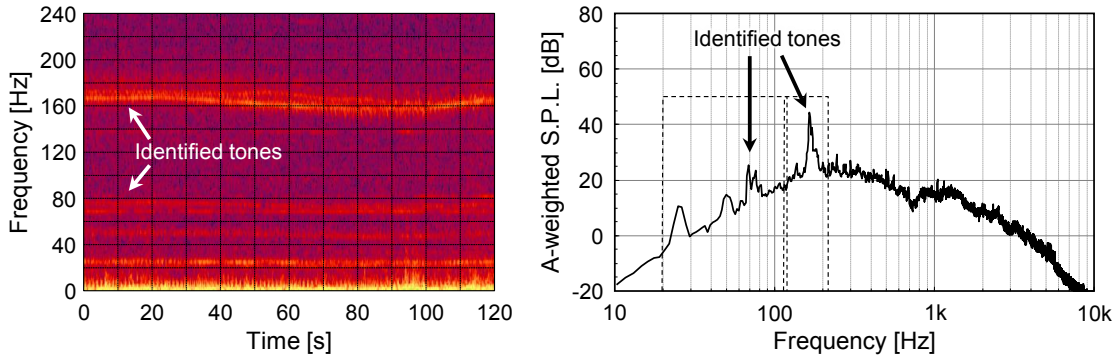
Table 1 Measurement conditions and assessed results of Tonal Audibility in three cases.

		Case-1	Case-2		Case-3
Measurement condition	Rated power [kW]	1,980	1,500		1,500
	Number of WTs	1	5		1
	Distance from nearest WT [m]	273	221		370
IEC 61400-11:2012	Averaging time	10 s×12	10 s×12		10 s×12
	Centre freq. of C.B. [Hz]	134.8~136.2	68.9	156.7~167.0	172.9~194.8
	Tonality [dB]	4.0	-2.1	7.0	9.2
	Tonal audibility [dB]	6.1	-0.1	9.1	11.2
ISO 1996-2:2007	Averaging time	120 s	120 s		120 s
	Centre freq. of C.B. [Hz]	134.8	161.1		178.7
	Tonal audibility [dB]	8.6	11.2		-



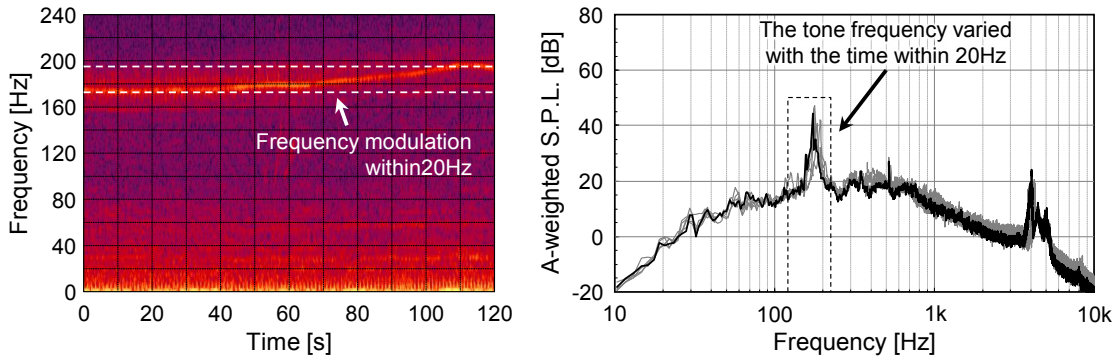
(a) Spectrogram (b) Narrow-band spectrum

Figure 5 Frequency characteristic of case-1.



(a) Spectrogram (b) Narrow-band spectrum

Figure 6 Frequency characteristic of case-2.



(a) Spectrogram (b) Narrow-band spectrum

Figure 7 Frequency characteristic of case-3.

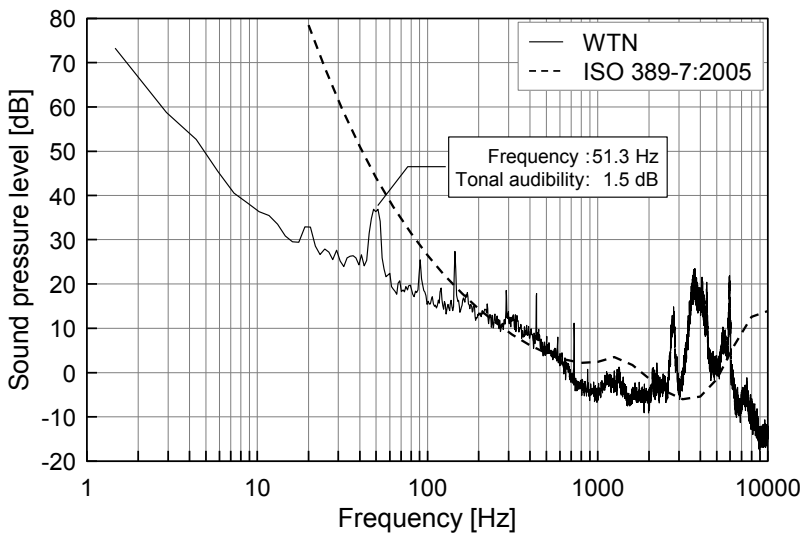


Figure 8 Comparison between a tonal component of a WTN and the hearing thresholds for pure tones (ISO 389-7).

3. Auditory experiment on the effects of tonal components in WTN

As a basic experiment on the effect of tonal components in WTN, the change of auditory impression was examined by varying the frequency and TA of a tonal component.

3.1 Experimental facility

In this study, an experimental facility constructed for auditory experiments on sounds with wide frequency range down to infrasound was used [3]. The facility consists of a pair of rooms with 16 woofers of 40 cm diameter installed on the partition wall between the two rooms. For the production of mid-/high-frequency components up to a frequency of 8 kHz, a full-range loudspeaker of 10 cm diameter was positioned at the centre point of the 16 woofers. The crossover frequency between the two systems was set at 224 Hz. The listening position was located 3.5 m from the centre point of the loudspeaker system. To correct the frequency characteristic of the total reproduction system, the digital inverse-filtering technique was applied using a linear-phase FIR filter calculated from the transfer function from the input of the amplifier to the listening point measured in the frequency range from 4 Hz to 8 kHz in 1/12-octave-bands.

3.2 Test sounds and experimental procedures

To investigate the difference threshold of auditory impression when any tonal component is included in WTN, the constant method was applied. As the standard stimulus (S_S), an artificially synthesized noise modelling the frequency characteristics of general WTNs (-4 dB/octave in band spectrum [1]) was used and its level was fixed at 45 dB in A-weighted sound pressure level. As for the comparison stimulus (S_C), a pure tone (50, 100, 200, 400 or 800 Hz) was superimposed on the model noise so that its TA varies in 7 steps as shown in Table 2. As an example, the FFT spectrum of the test sound containing a tonal component at 200 Hz is shown in Fig. 9, which was measured in the absence of the listener at the listening position where the centre of the listener's head would be.

As the comparison stimuli S_C, 36 sounds in total (5 different tone frequencies times 7 variation of TA, and the same sound as S_S) were synthesized and they were paired with S_S. The duration time was 5 s for both S_S and S_C. 36 pairs of S_S - S_C were randomly arranged and presented to each test subject twice (72 times pair comparisons in total). In the experiment, the subject sat straight on a chair to keep his/her head near the headrest in the test room and he/she was asked to judge the difference of the auditory impression between S_S and S_C according to the following four-category system (in Japanese):

1: They are not different at all.
2: They are slightly different.
3: They are considerably different.
4: They are definitely different.

The total time needed to complete the test on 72 pairs of the test sounds was about 30 minutes including rest times in between. In this experiment, 16 subjects from 21 year-old to 30 year-old (12 males and 4 females) with normal hearing abilities participated.

Table 2 Test sounds used in the experiment.

Stimuli	Tonal Audibility [dB]
Model noise	No tonal components
Model noise + 50 Hz tone	-3, 0, 3, 6, 9, 12, 15
Model noise + 100 Hz tone	-3, 0, 3, 6, 9, 12, 15
Model noise + 200 Hz tone	-3, 0, 3, 6, 9, 12, 15
Model noise + 400 Hz tone	-3, 0, 3, 6, 9, 12, 15
Model noise + 800 Hz tone	-3, 0, 3, 6, 9, 12, 15

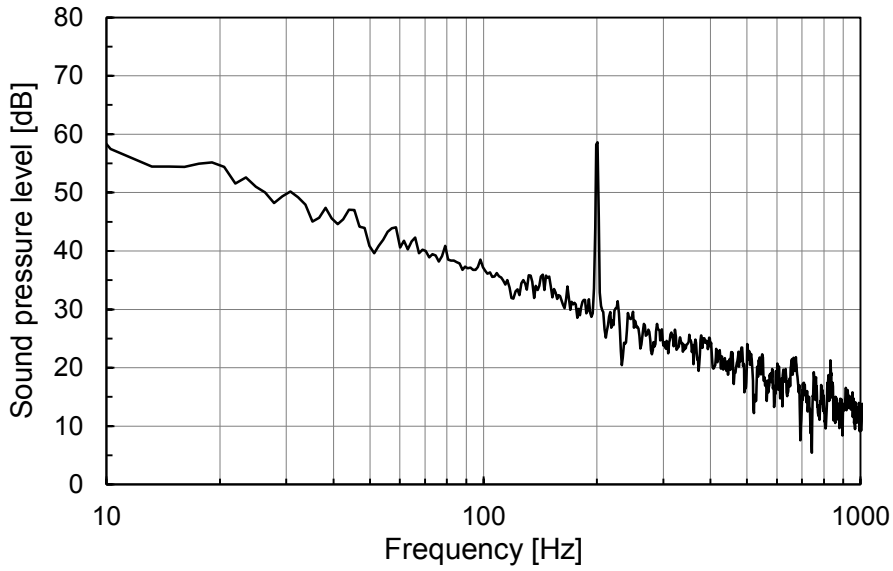


Figure 9 An example of FFT spectrum of the test sound with 200 Hz tone frequency and 15 dB Tonal Audibility.

3.3 Experimental results

From the experimental results, difference threshold of auditory impression was investigated. Figure 10 shows the percentage of the subjects who answered 1 to 4 in the four categories.

In this experiment S_S (model noise) was included as a S_C in order to check the reliability of subjects' judgment. As a result, 12.5% of the subjects' response of 2 (slightly different) was found. This might be attributed to subject's psychology to want to find subtle differences hard.

For all of the tone frequencies, the tendency that positive response monotonically increased with the increase of tone level was found.

To quantitatively assess the experimental results, two steps of positive response regarding the difference between S_S and S_C were assumed: one is categories 2+3+4 (case-1) and the other is categories 3+4 (case-2). For these cases, the difference threshold was calculated by linear interpolation under the assumption of 50% discrimination probability as shown in Fig. 11. In this result, the difference threshold for 400 Hz tone frequency is exceptionally low in both cases, which is inexplicable at present. For other tone frequency, the difference threshold is around 0 dB in case-1 and 6 dB in case-2 in terms of TA.

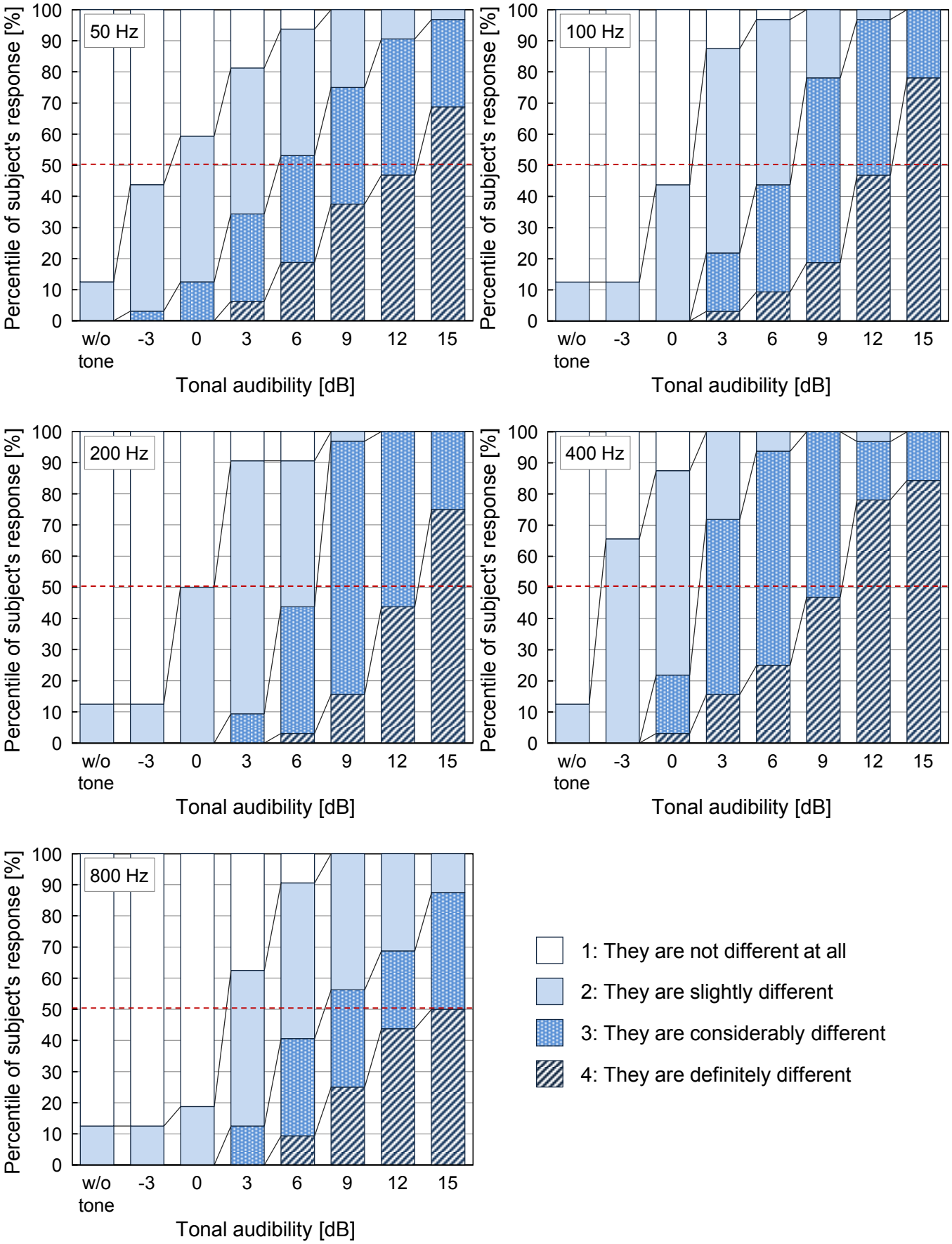


Figure 10 Experimental results of difference threshold of auditory impression.

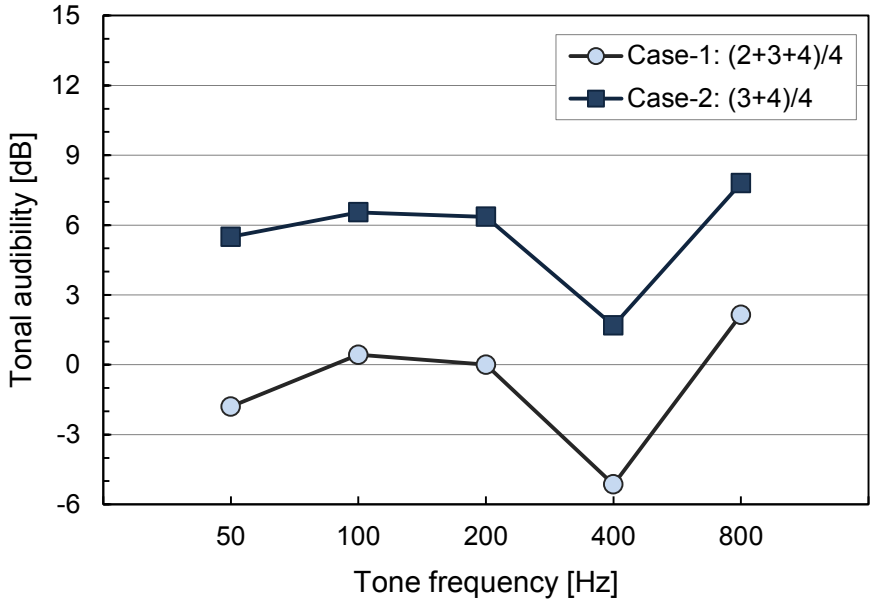


Figure 11 Difference threshold calculated from the experimental results shown in Fig. 10.

4. Conclusions

- Regarding the effect of tonal components contained in WTN, the procedures for identifying TA specified in IEC 61400-11: 2012 was implemented in a software program. To detect possible tones automatically when detecting local maxima, the Savitzky-Golay smoothing and 2nd order differentiation filter was used in the program.
- The software program was applied to the data obtained in the field measurements of WTN conducted at 29 wind farm sites across Japan. The data were obtained not only in the noise emission areas (within about 100 m from the nearest wind turbine) but also in the immission areas (from about 100 m to 1 km from the nearest wind turbine). In the emission areas, TA greater than -3 dB was detected at all of the measurement points (29). As for the immission areas, TA greater than -3 dB was detected at 129 measurement points among the total 164 points. In both areas, it was seen that tone frequency ranged from about 50 Hz to 1,000 Hz and TA ranged from -3 dB up to 14 dB.
- In tonality assessment, especially in immission areas where WTN level is relatively low, the influence of the extraneous noises such as exhaust sound of motor vehicles with illegal mufflers and sing signals of municipal public address systems are often included and close attention is needed to eliminate such noises.
- Three representative data were chosen among the all data, TA was evaluated according to IEC 61400-11: 2012 and ISO 1996-2: 2007. As a result, it was found that these standards provide a bit different identification of TA, which is mainly due to the difference of averaging time interval. A tendency was also found that TA values assessed by IEC 61400-11 are smaller than that assessed by ISO 1996-2.
- To investigate the validity of the numerical assessment method regarding the tonality of WTN, a basic auditory experiment on the difference threshold of auditory impression was tried using a model noise and that including tonal components. As a result, the difference threshold for “considerably different” + “definitely different” was around 6 dB in TA in the cases of tone frequencies of 50 Hz, 100 Hz, 200 Hz and 800 Hz, whereas it was about 2 dB in TA in the case of tone frequency of 400 Hz. Such a discrepancy cannot be explained at present and further investigation is needed.

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