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A comparison of standardized methods for prominence analysis of tonal components

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Summary

Tonal components contained in wind turbine noise are apt to increase psycho-acoustical annoyance. Reduction techniques of tonal noise emission caused by mechanical system of wind turbine generators are well developed in recent years, however, not small amount of wind turbines which emitting tonal noise are still working through the country and its tonal components are often observed around residential areas. Therefore, the method of objectively assessing the psycho-acoustical effect caused by tonal components should be established for the wind turbine noise problem. There are some international standards to determine the prominence of tonal components contained in various type of noise, such as IEC 61400-11 (2012), ISO 1996-2 Annex C (2007), ISO 1996-2 Annex K (2017), ISO/PAS 20065 (2016), DIN 45681 (2005), ECMA-74 15th Edition (2018) and so on. In this paper, principles of these analysis methods are compared and problems to be solved are discussed in order to apply to penalty assessment in immission area. Relationships among metrics determined by these analysis methods are also investigated by using artificially synthesized noise and wind turbine noise actually measured.

1. Introduction

Since tonal components contained in wind turbine noise are apt to increase psycho-acoustical annoyance, authors have been investigated the actual conditions of tonal components contained in wind turbine noise by filed measurements and psycho-acoustical annoyance to tonal components by subjective experiments [1, 2]. Tonal noise resulting from mechanical excitation could be reduced by damping or isolating the vibration at the source [3], however, a certain amount of wind turbine which emitting tonal noise is already exists and the impact of annoyance caused by its tonal noise to people living around the wind turbine cannot be neglected. As an international movement, IEC 61400-11-2 entitled “Measurement of wind turbine noise characteristics in receptor position” is currently under development and is expected to include an analysis method of tonal components. Meanwhile, in Japan, tonal components generated by not only wind power generating facilities but also water heating system based on electric heat pump also have been become a problem, some researches are currently being carried out [4].

Although there are some international standards specifying an analysis method of tonal components contained in environmental noises, there are few papers comparing among these analysis methods despite such a circumstance. This paper organizes concepts of analysis principles for various analysis methods of tonal components specified in international standards, and advantages and disadvantages of each method are described. And then, relationships of calculated results obtained by applying these methods to artificially synthesized noise and actually measured wind turbine noise were investigated.

2. Standardized methods for prominence analysis

There are several international standards as a method of determining tonality or prominence of tonal components contained in noise. Among them, following methods may be applicable to environmental noises and it could be categorized into three kinds of frequency analysis methods.

- FFT based method
  - ✓ ISO 1996-2 Annex C (2007) (hereinafter referred to as ISO method)
  - ✓ IEC 61400-11 (2012) (hereinafter referred to as IEC method)
  - ✓ DIN 45681 (2005) (hereinafter referred to as DIN method)
  - ✓ ISO/PAS 20065 (2016) (hereinafter referred to as PAS method)
- 1/3 octave band based method
  - ✓ ISO 1996-2 Annex K (2017) (hereinafter referred to as ISO survey method)
  - ✓ NZS 6808 (2010) (hereinafter referred to as NZS survey method)
- Loudness based method
  - ✓ ECMA-74 15th Edition (2018) (hereinafter referred to as Psychoacoustic tonality)

Algorithms were implemented into computer program by authors in order to investigate the advantages and disadvantages of those analysis methods. The results are described below.

2.1 FFT based method

Each FFT based method is based on the concept of the masking index described in reference [5]. The masking index was obtained from a psychoacoustic experiment on level difference between a UEN (uniform excitation noise) and a sinusoidal tone when a sinusoidal tone become just-audible, in which UEN is a broadband noise with the same intensity in each critical band. The masking index is shown in Fig. 1.

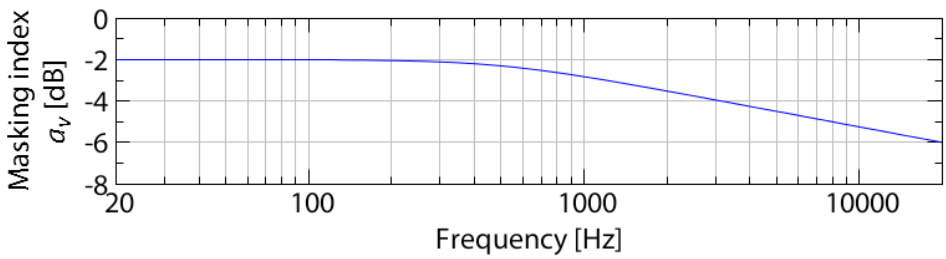


Fig.1 Masking index as a function of a frequency of tonal components

In each standard, the masking index is used to estimate how much the tonal components contained in a noise protrude from just-audible sound pressure level. That is the Tonal Audibility (hereafter referred to as TA) and is calculated by the following formula in any of the standards.

$$\Delta L = L_{\mathrm{T}} - L_{\mathrm{G}} - a_v \tag{1}$$

where, ΔL is the tonal audibility [dB], L_{T} is the total power of tonal components contained in a critical band [dB], L_{G} is the total power of masking noise contained in a critical band centred on a frequency of a tonal component [dB] and a_v is the masking index at a frequency of a tonal component [dB].

As apparent from formula (1), the tonal audibility is calculated from the relative level difference between the tonal component and the masking noise. That is, the absolute sound pressure level does not affect the calculated value.

In order to determine the tonal audibility, it is needed to calculate right-hand members of formula (1) according to the following procedure:

- ✓ Identify possible tonal components contained in noise
- ✓ Calculate critical band width centred on the frequency of tonal component
- ✓ Extract tonal components and masking noise by classifying FFT lines in a critical band
- ✓ Calculate the power ratio of tonal components to masking noise within a critical band

Differences between each analysis method are summarized in Table 1. As for the FFT based method, it can be seen from Table 1 that technical specifications such as usable frequency range, evaluation time duration, classification method of the masking noise and expression of the critical band width are slightly different. These technical differences among analysis methods lead to differences in the calculation results of the tonal audibility, which depends on identification accuracy of the tonal component and estimation accuracy of the masking noise level. Since the difference between PAS method and DIN method is substantially only the lower frequency of the usable frequency range, DIN method will not be dealt with individually in this paper.

Table 2 shows overviews of determination methods for the masking noise components within a critical band. L_{G} is derived using a first order linear regression for lines classified as noise in the ISO method, while that is derived from the results of energy summation for lines classified as masking noise using the 70th percentile value of the lines within a critical band in the IEC method. As for the PAS method, L_{G} is derived using an iterative procedure. The procedure commences with the energy averaging of lines with in a critical band with the exception of the line centred on the critical band. In the subsequent steps, energy averaging is performed for lines excluding lines with levels exceed the energy mean value determined beforehand by more than 6 dB. If energy mean value approximately equals to that of previous iteration step, the iterative procedure is discontinued. Then L_{G} is derived by multiplying energy mean value and the critical band width.

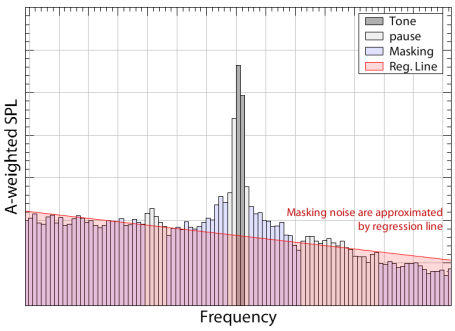
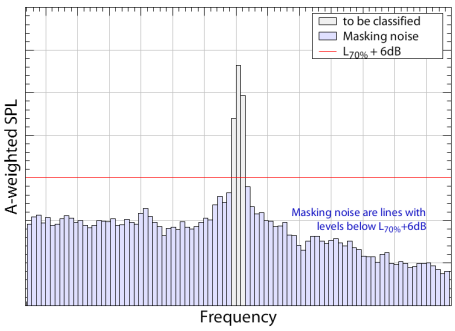
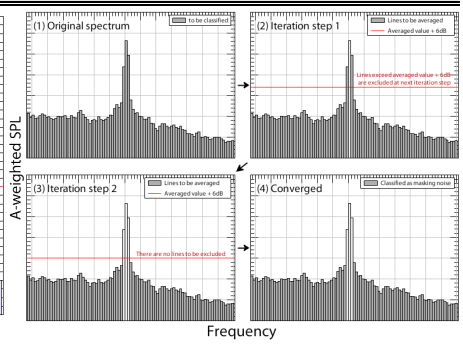
For each determination method of masking noise, good classification result is obtained if shape of masking noise components is approximately flat. However, errors contained in classification result may be large when shape of masking noise components has a steep slope especially in the frequency range below about 100 Hz. The factor for the shape of masking noise component with a steep slope is caused by not only the characteristics of the noise itself but also the influence of the A-weighting filter.

Table 1 Comparisons between analysis methods of the tonal audibility

Standards	ISO 1996-2 Annex C	IEC 61400-11	DIN 45681	ISO/PAS 20065
A-weighted spectrum	Yes	Yes	Yes	Yes
Frequency range [Hz]	from 50	from 20	from 90	from 50
Frequency resolution [Hz]	$\Delta f_{\mathrm{eff}} < 0.05 \times \Delta f_{\mathrm{T}}$	1 to 2	1.9 to 4.0	1.9 to 4.0
Critical band width Δf_{C} [Hz]	$0.2 f_{\mathrm{T}}$ $(f_{\mathrm{T}} > 500)$ 100 $(f_{\mathrm{T}} \leq 500)$	$25 + 75 \cdot (1 + 1.4 \cdot [f_{\mathrm{T}}/1000]^2)^{0.69}$		
Cut-off freq. of CB	$f_{\mathrm{T}} = 0.5 \times (f_{\mathrm{H}} + f_{\mathrm{L}})$		$f_{\mathrm{T}} = \sqrt{f_{\mathrm{H}} \times f_{\mathrm{L}}}$	
Estimation of masking noise	Linear regression	Statistical method	Iterative method	Iterative method
Evaluation time duration	60 s (or about 10 s)	at least 10 s × 10 spectra	at least 3 s × 12 spectra	
Penalty K_{T}	Specified	Not specified	Specified	Specified in ISO 1996-2:2017 Annex J
Sample source code	Not provided	Not provided	Provided	Provided

f_{eff}: Effective analysis bandwidth [Hz]
f_{T}: Frequency of a tonal component [Hz]
f_{L}: Lower cut-off frequency of the critical band [Hz]
f_{H}: Higher cut-off frequency of the critical band [Hz]

Table 2 Overview of determination methods of masking noise components

Linear regression (ISO method)	Statistical method (IEC method)	Iterative method (DIN/PAS method)
		

2.2 1/3 octave band based method

As mentioned before, the tonal audibility is determined by classifying lines within a critical band into tonal components or masking noise components in the FFT based method. Since the critical band width and the 1/3 octave band width are approximately same as shown in Fig. 2, classification of components within a critical band cannot be performed using the 1/3 octave band analysis. Therefore, what can be done using the analysis results of 1/3 octave band analysis is to compare the sound pressure level of a band which have a possibility of containing tonal components with the sound pressure level of both sides. That is the method used in the ISO survey method and the NZS survey method, and it is very useful when surveying the presence or absence of tonal components in residential areas. The difference between the two methods is that the ISO survey method requires that both level differences between a band of interest and its neighbouring bands exceed the threshold value, while the NZS survey method requires that arithmetic mean of level differences between a band of interest and its neighbouring bands exceeds the threshold value. The threshold value is described in table 3. Since wind turbine noise has a spectral slope of -4dB/octave [7], this fact yields level difference between a band and its neighbouring bands whether tonal components exists or not exists. Examining an arithmetic mean of level differences between a band of interest and its adjacent lines used in NZS survey method seems to be more suitable for wind turbine noise problems.

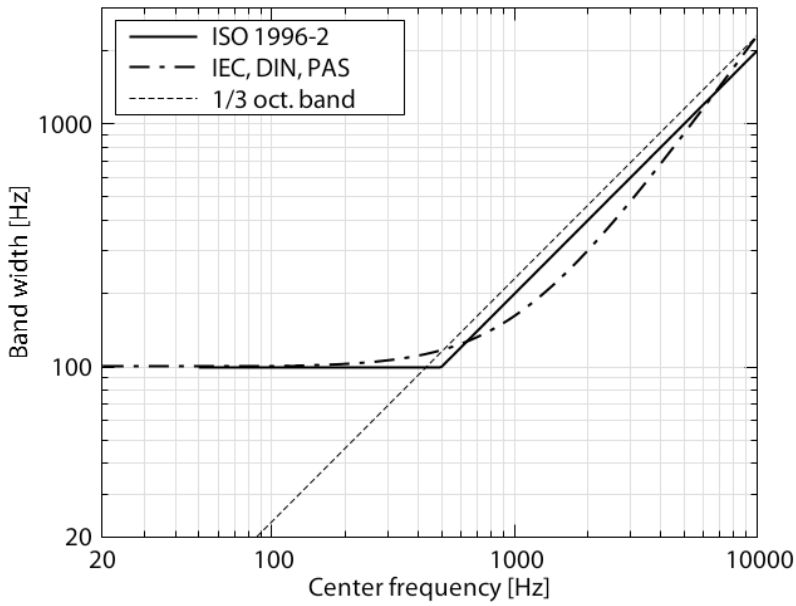


Fig. 2 Comparison between critical band width and 1/3 octave band width

Table 3 Level difference specified in ISO 1996-2:2017 or NZS 6808:2010

Frequency	Level difference
Low frequency (25 Hz to 125 Hz)	15 dB
Middle frequency (160 Hz to 400 Hz)	8 dB
High frequency (500 Hz to 10000 Hz)	5 dB

2.3 Loudness based method

Psychoacoustic tonality calculation method specified in the ECMA-74 is “a perception-model-based procedure for determining whether or not noise emissions contain prominent tonalities, and if present” [6]. Although the standard containing this method targets tonal components emitted by information technology and telecommunications equipment, it is seemed to be applicable to tonal components contained in environmental noise by reason of analysis method described below. To make a long story short, it is a method to analyse by paying attention that tonality perception and the partial loudness of tonal sound components have a strong correlation. As show in Fig. 3, this method uses waveforms divided into 53 critical bands by using auditory filter bank. From this filtered waveforms, loudness contributions of tonal components and noise components to the specific loudness for each critical band are determined. Separation of each contribution to the specific loudness is estimated by using auto-correlation function. The unit of calculated results is given in tu_{HMS}, but it seems close to sone in terms of dimension of a quantity. This psychoacoustic tonality takes account of psycho-acoustical effects such as threshold in quiet, loudness-level-dependent masking and frequency-dependent, therefore, it may have a better relationship between the calculated value and subjective response to the tonal component comparing to both the FFT based method and the 1/3 octave band based method.

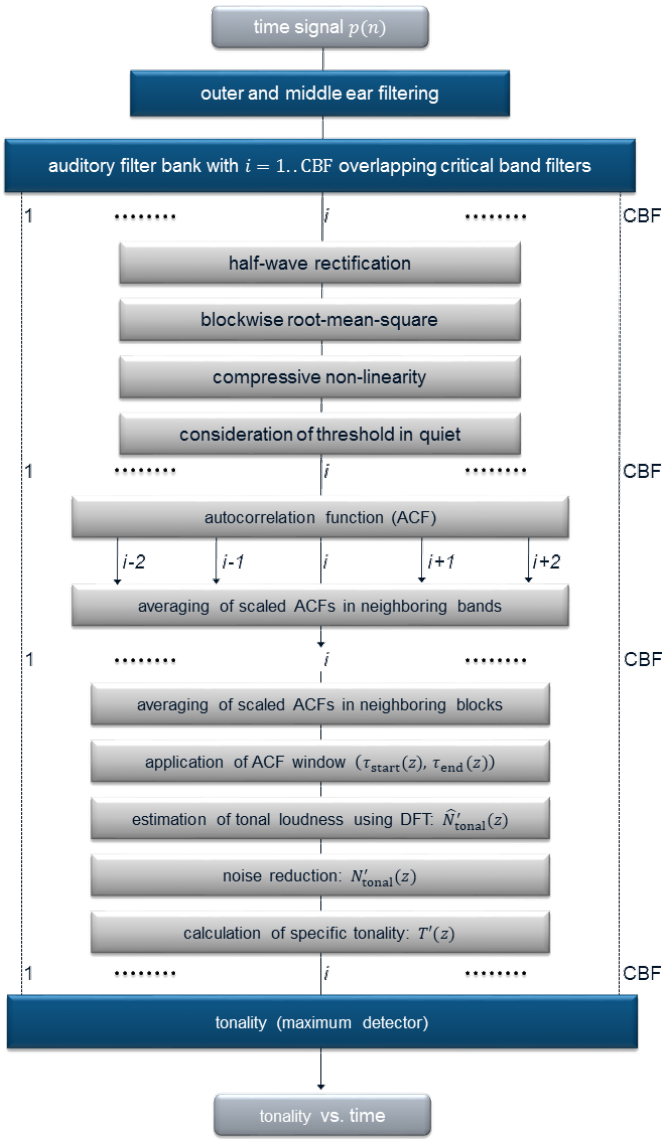


Fig. 3 Analysis scheme of psychoacoustic tonality method (adopted from [6])

3. Relationship among each method for synthesized noise

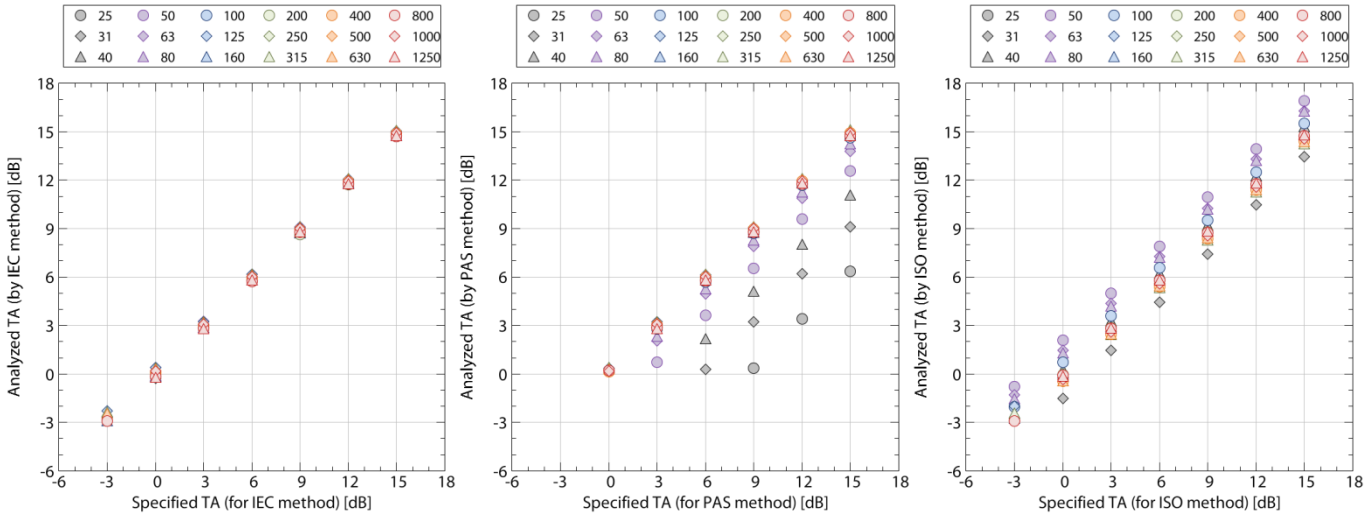
Although each method is originated from different frequency analysis method as described before, it is also important to examine the relationships among these methods and applicable range of each method. In this chapter, various analysis methods are compared by using artificially synthesized noise. This artificial noise is a broadband noise having a frequency characteristic of -4dB/octave, which is based on the filed measurements of wind turbine noise [7] and is referred to as modelled noise hereinafter. Test signals are generated by superposing a sinusoidal tone on the modelled noise such that TA is in the range from -3 dB to 15 dB in 3 dB steps. A-weighted sound pressure levels of modelled noise are set to 3 conditions of 35 dB, 45 dB and 55 dB. Sound pressure level of a sinusoidal tone to be superposed was determined by using formula (1), in which L_{G} is determined from pre-synthesized modelled noise before sinusoidal tone is superposed. This method enables to generate a test sound with exact TA conditions which does not depend on the classification method of the masking noise component. Frequency of sinusoidal tone is in range from 25 Hz to 1250 Hz in terms of the center frequency of the 1/3 octave band. Conditions of test sound are summarised in table 4.

Table 4 Conditions of test sound used for case study

Noise model	L_{Aeq} of noise	Tone frequency	Tonal audibility
-4dB/octave	35 dB 45 dB 55 dB	25 to 1.25 kHz in 1/3 oct. band interval (18 frequencies in total)	-6, -3, 0, 3, 6, 9, 12, 15

3.1 Comparing among FFT method

In order to compare the property of the masking noise classification method, TA specified at test signal generation and analysed TA was compared for each analysis method. Results are show in Fig. 4. As a result, IEC method has the best correlation between specified TA and analysed TA. ISO method also has a good correlation between specified TA and analysed TA but has a certain amount of variation comparing to the IEC method. This is due to the estimation error of L_{G} especially in the frequency range below about 100 Hz. According to the ISO method, L_{G} is estimated using a first order linear regression of the masking noise component within a critical band even in a frequency range below about 100 Hz where the shape of masking noise components tends to be curved by the A-weighting filter. This causes a deviation between the actual masking noise component and the approximated regression line. As for the PAS method, analysed TAs for tone frequency below 50 Hz are significantly smaller than the specified TAs. This phenomenon is also caused by the estimation method of masking noise components. Frequency range below 50 Hz is out of range and its reason is not described in the PAS method, however, such estimation error is considered to be one of the reasons for the limitation of frequency below 50 Hz.

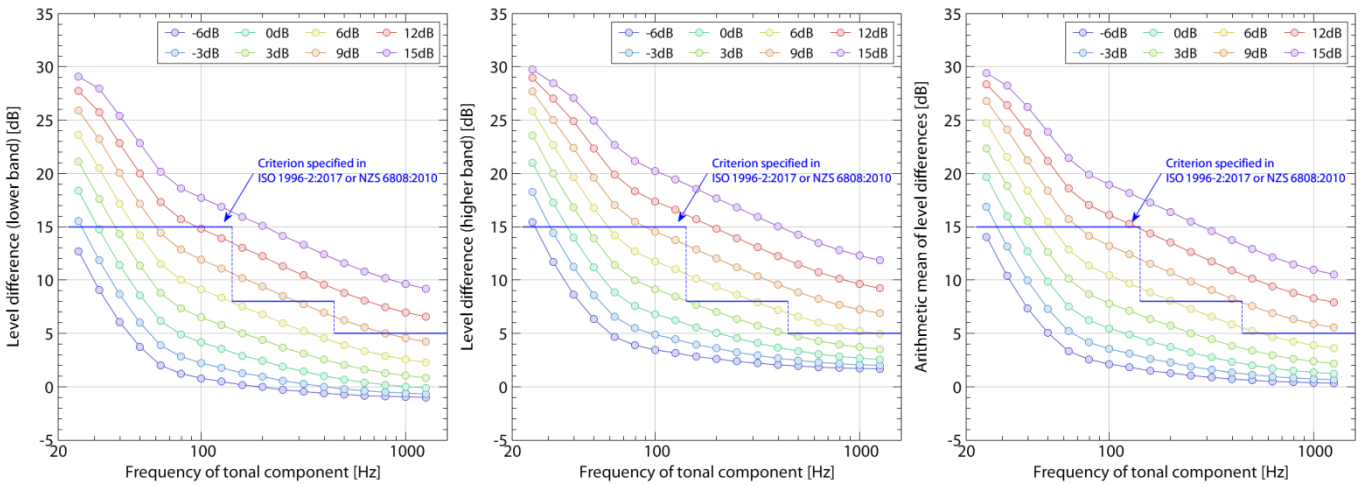


(a) IEC method (b) PAS method (c) ISO method

Fig. 4 Relationship between specified TA and analysed TA

3.2 Comparing between FFT method and 1/3 octave band method

Figure 5 shows examination results of relationships between the level difference based on 1/3 octave band analysis and the TA. Figure 5 (a) and (b) show the level difference between the frequency band containing the tonal component and the adjacent band of the lower frequency band and the higher frequency band, respectively. In the ISO survey method, level differences of both adjacent bands need to exceed the threshold described in table 3, therefore, smaller level difference is used for examination. In this case, judgement is performed using the results of Fig. 5 (a), test signal was judged as prominent tonal component is contained, when TA is 15 dB or more with the tone frequency from 25 Hz to 125 Hz and TA is 12 dB or more with the tone frequency from 160 Hz to 1250 Hz, respectively. As for the Fig. 5 (c),which is based on the arithmetic mean of level differences between the frequency band containing the tonal component and the adjacent bands, tonal component is identified when TA is 12 dB or more with the tone frequency from 25 Hz to 125 Hz and TA is 9 dB or more with the tone frequency from 160 Hz to 1250 Hz, respectively. That is, the NZS survey method is considered to have a better detection ability of the tonal components comparing to the ISO survey method. For details of this discussion, please refer to the literature [8].

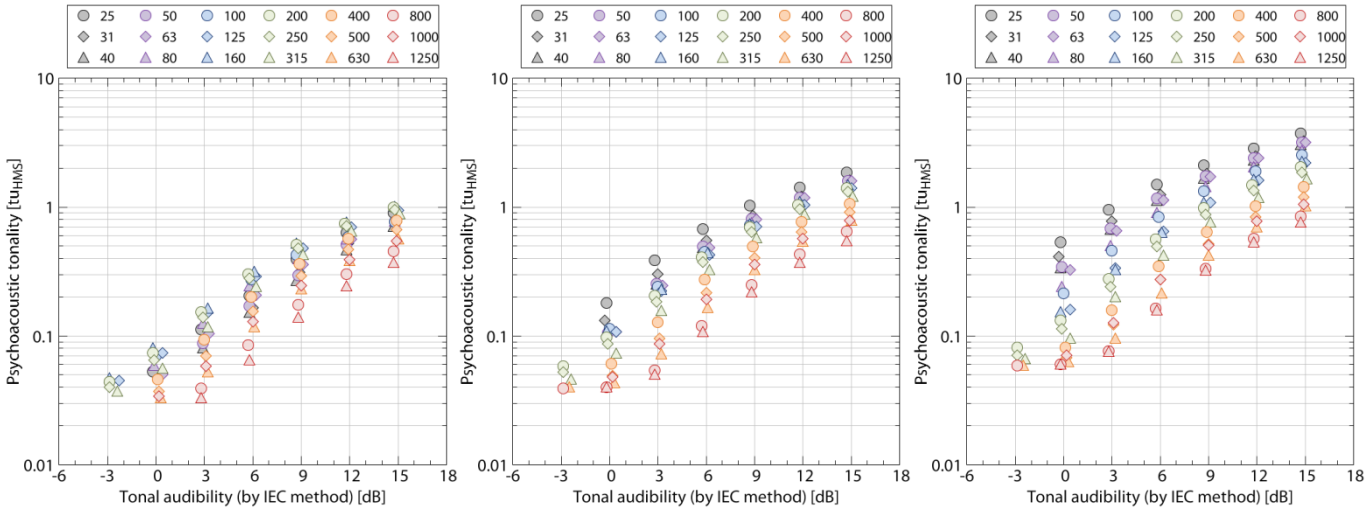


(a) Diff. with lower band (b) Diff. with higher band (c) Average of both differences

Fig. 5 Relationship between TA and level difference for -4dB/octave noise

3.3 Comparing between FFT method and psychoacoustic tonality method

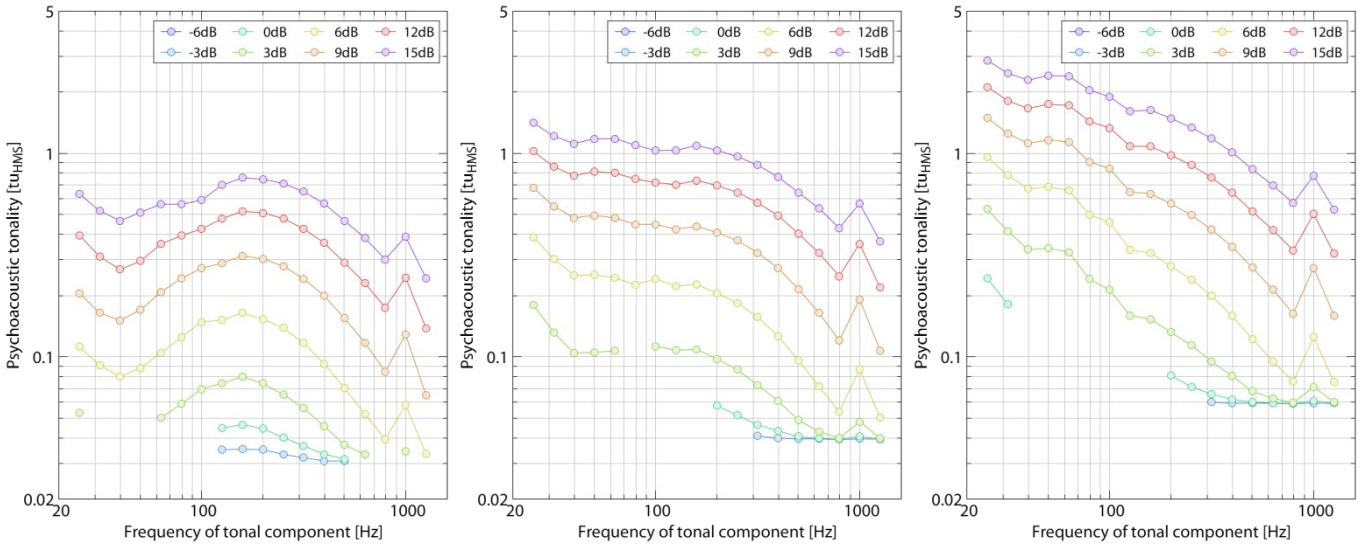
Figure 6 shows results of comparison between the TA calculated by the IEC method and the psychoacoustic tonality for the modelled noise conditions of 35 dB, 45 dB and 55 dB in terms of A-weighted sound pressure level. If the calculation algorithm of the psychoacoustic tonality has a simple dependency on the sound pressure level of interest, calculated results of psychoacoustic tonality is expected to be simply shifted with increase of sound pressure level. However, results shown in Fig. 5 are not simple dependency. This result suggests that the psychoacoustic tonality include the effects of not only sound pressure level but also other factors.



(a) 35 dB (b) 45 dB (c) 55 dB

Fig. 6 Relationship between TA and Psychoacoustic tonality for -4dB/octave noise

Figure 7 show the relationship between the psychoacoustic tonality and the frequency of the tonal component by re-arranging the data shown in Fig. 6. In this result, the shapes of the lines significantly change with increase of sound pressure level of masking noise especially in the frequency range below 200 Hz. Assuming that acoustic model of the psychoacoustic tonality is correct, it has been suggested that it is necessary to carry out a research on the influence on humans by subjective experiment using sound recordings of actual noises or test sound simulating actual sound pressure level and frequency characteristics, when investigating the value of the penalty for environmental impact assessment. In other words, blind use of the penalty value which is not limited the types of noise as specified in ISO 1996-2:2017 may cause evaluation result not reflecting the actual situation.

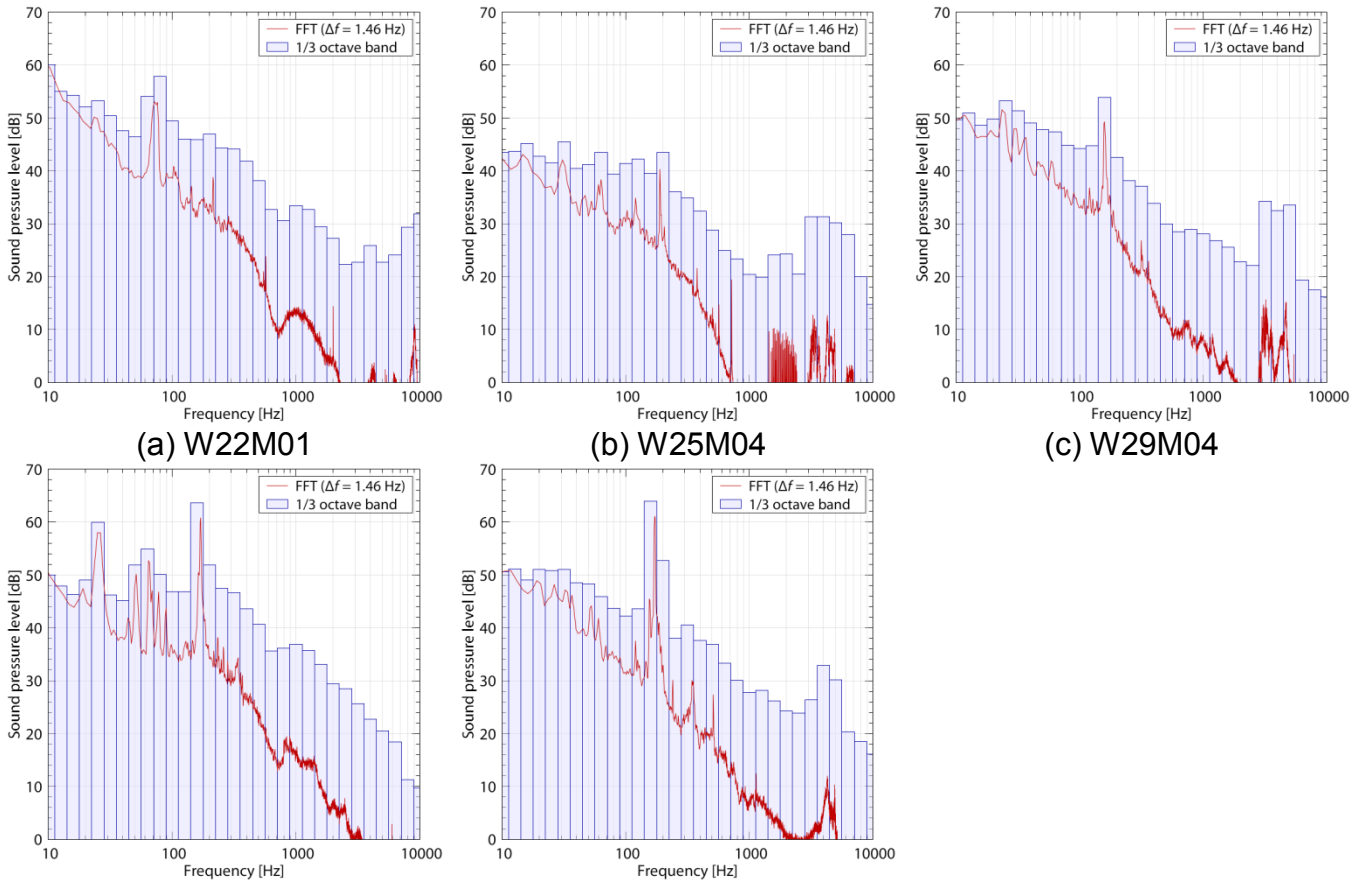


(a) 35 dB (b) 45 dB (c) 55 dB

Fig. 7 Frequency dependence of Psychoacoustic tonality for -4dB/octave noise

4. Relationship among each method for wind turbine noise

In order to examine the before mentioned analysis methods, an analysis was performed for a wind turbine noise containing tonal components actually measured. Figure 8 shows frequency characteristics of sound recording used for analysis. Analysis time duration is 10 s in this case. Tonal components are clearly seen for all of the data used in analysis.



(a) W22M01 (b) W25M04 (c) W29M04

(d) W28M06 (e) W29M01

Fig. 8 Frequency characteristics of wind turbine noise for analysis

Table 5 Calculated results for wind turbine noise containing tonal components

Name	W22M01	W25M04		W29M04	W28M06	W29M01
$L_{Aeq,30s}$	45.9 dB	40.3 dB		44.5 dB	52.7 dB	52.2 dB
Frequency	76.2 Hz	189.0 Hz	720.7 Hz	158.2 Hz	169.9 Hz	171.4 Hz
TA by IEC	5.3 dB	0.9 dB	4.3 dB	6.2 dB	12.2 dB	17.1 dB
TA by PAS	2.5 dB	1.2 dB	4.5 dB	6.3 dB	12.1 dB	19.5 dB
TA by ISO	6.4 dB	0.8 dB	3.8 dB	7.1 dB	11.5 dB	18.7 dB
Frequency band	80 Hz	200 Hz	800 Hz	160 Hz	160 Hz	160 Hz
Average of level diff.	6.1 dB	5.7 dB	0.7 dB	10.2 dB	14.2 dB	15.8 dB
Prominent?	No	No	No	Yes	Yes	Yes
Frequency	(96.9 Hz)	(211.4 Hz)		(159.6 Hz)	(169.6 Hz)	(171.0 Hz)
Psychoacoustic tonality	0.255 tu_{HMS}	0.149 tu_{HMS}		0.564 tu_{HMS}	1.361 tu_{HMS}	1.763 tu_{HMS}

Table 5 shows the calculated results of the tonal audibility and the psychoacoustic tonality for the recording shown in Fig. 7. Since the detected frequency of the psychoacoustic tonality is calculated by arithmetic mean of the frequency with a maximum tu_{HMS} for instantaneous specific loudness calculated at every 0.1 ms interval, it is shown in parentheses for reference in table 5. To see the result, there is no significant difference in the detection ability of the tonal components in the present data among the methods for calculating the tonal audibility, while it is

seemed to be a little varied in the TA for tonal component of 76 Hz. As for the 1/3 octave band based method, tonal components of about 160 Hz, in which TA exceeds about 6 dB, were judges as prominent. This is consistent with the theoretical value show in Fig. 4(c). The tendency was seen that calculated results of the psychoacoustic tonality increased with increase of analysed TA.

An interesting thing in this result is found at the data of W25M04. Tonal component of 720 Hz will be adopted for evaluation by the tonal audibility because TA of 720 Hz is larger than that of 189 Hz. On the other hand, tonal component of 189 Hz was predominant over that of 720 Hz for the psychoacoustic tonality. Tonal component of 189 Hz is 'audible' also in the auditory impression, while that of 720 Hz was hard to hear as if masked. In such a case, validity of simply adopting a maximum TA for the evaluation needs further investigation.

5. Conclusion

In this paper, we investigated various international standards considered to be applicable as an evaluation indicator of the tonal component contained in environmental noise, and summarized the overview of the analysis principles. Each method can be arranged by the frequency analysis method, and the each feature are as follows.

- FFT based method
  - Advantages
    - ✓ Moderately simple algorithm
  - Disadvantages
    - ✓ Does not consider absolute sound pressure levels
    - ✓ Does not consider the hearing threshold
  - Remarks
    - ✓ Need for scientific evidences or open discussions to validate the algorithm
- 1/3 octave band based method
  - Advantages
    - ✓ Extremely simple method
    - ✓ Only need for 1/3 octave band analyser
  - Disadvantages
    - ✓ Cannot detect tonal components of around 'just audible' sound pressure levels
  - Remarks
    - ✓ NZS survey method is better than ISO survey method for environmental noises
- Loudness based method
  - Advantages
    - ✓ Adoption of human auditory mechanisms
    - ✓ Reflection of absolute sound pressure levels
    - ✓ Taking into account of hearing threshold
  - Disadvantages
    - ✓ Complex algorithm to implement into computer programs
    - ✓ High computational load
  - Remarks
    - ✓ Useful for understanding results of subjective experiments
    - ✓ Need for more evidences of relationship to subjective evaluation

Based on the concept of the psychoacoustic tonality, we confirmed that the following points are important. In order to use TA for determining a penalty, it is necessary to investigate relationship to human response by subjective experiment using test sounds in consideration of both actual frequency characteristic and actual sound pressure level. In addition, it is indicated that tonal component with a maximum TA not always has maximum contribution to the auditory impression.

Although the analysis methods of tonal components to be surveyed are publish as international standard, scientific evidences or open discussion results for validity of analysis principle are seemed to be less information. If these analysis methods will continue to be used as part of the wind turbine noise measurement method, more scientific evidences or open discussion is desired.

References

1. T. Kobayashi, S. Yokoyama, A. Fukushima, T. Ohshima, S. Sakamoto, H. Tachibana, “Assessment of tonal components contained in wind turbine noise in immission areas”, 6th International Meeting on Wind Turbine Noise, Glasgow, 2015.
2. S. Yokoyama, T. Kobayashi, H. Tachibana, “Subjective experiments on the perception of tonal component(s) contained in wind turbine noise”, 7th International Meeting on Wind Turbine Noise, Rotterdam, 2017.
3. Colin H. Hansen, Con J. Doolan, Kristy L. Hansen, “Wind Farm Noise: Measurement, Assessment, and Control”, John Wiley & Sons Inc., 2017.
4. M. Yonemura, H. Lee, S. Sakamoto, “Study on subjective evaluation of noise containing low frequency tonal components using rating scale method” (in Japanese), 2019 Spring Meeting of the Acoustical Society of Japan, 2019.
5. E. Zwicker, H. Fastl, “Psychoacoustics: facts and models”, Springer, 1999.
6. ECMA-74, “Measurement of Airborne Noise emitted by Information Technology and Telecommunications Equipment (15th edition)”, Ecma International, 2018.
7. H. Tachibana, H. Yano, A. Fukushima, S. Sakamoto, “Nationwide field measurements of wind turbine noise in Japan”, Noise Control Engineering Journal, 62(2), pp.19-101, 2014.
8. S. Yokoyama, T. Kobayashi, H. Tachibana, “A Practical Method for Estimating a Presence of a Prominent Tonal Component in Wind Turbine Noise”, Inter-noise 2018, Chicago, 2018.