

**Proposal of new
parameters, T-TNR and
T-PR for total
evaluation of multiple
tones**

Technical
Report



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Introduction

The existing methods for detecting prominent discrete tone are standardised by several *de dule* standards, such as ECMA-74, ISO 7779^[11], ANSI S1.13^[14] etc. These conventional methods state the parameters named as TNR (tone-to-noise ratio) and PR (prominence ratio). And, these parameters, however, commonly focus to each discrete tone in the noise emission of interest.

On the other hand, in the existing real product noise emissions, there are many audible discrete tones in the noise spectrum. In some situations, empirically the existing parameters (TNR and/or PR) are not enough to detect prominent discrete tones. To resolve such situations, new parameters are proposed in this Technical Report. The parameters are called T-TNR (total tone-to-noise ratio) and T-PR (total prominence ratio), which are based on the existing procedure for TNR and PR, respectively, but, integrate contributions from all discrete tones.

In the early stage of development of these parameters, some scientific papers are presented in technical conferences, such as InterNoise and ICSV in world wide, NoiseCon in USA. However, the styles of definitions of each proposed parameter are not exact to those fit to technical standards.

In this Technical Report, the dedicated symbols for T-TNR and T-PR^[9] are proposed for the purpose of standardisation.

This Ecma Technical Report was developed by Technical Committee 26 and was adopted by the General Assembly of June 2019.

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Proposal of new parameters, T-TNR and T-PR for total evaluation of multiple tones

1 Scope

This document describes new methodologies to physically evaluate the tonal prominence of noise emitted by small air-moving devices.

The parameters proposed are T-TNR (total tone-to-noise ratio) and T-PR (total prominence ratio), which are based on TNR (tone-to-noise ratio) and PR (prominence ratio) defined in ECMA-74 Annex D, respectively.

The existing parameters, TNR and PR focus single discrete tone in the noise spectrum of interest. On the other hand, T-TNR and T-PR calculate their values by power summation of the values of TNR and PR of all discrete tones, respectively.

In the technical study of this Technical Report, the proposed methodology applies to both real sample data of small fan noise and their simulated test sound. It is anticipated, however, that users can use the proposed parameters to any other kind of noise emissions, provided that the noise can be analyzed by the procedures for TNR and PR stated in ECMA-74.

2 References

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ECMA-74:2012 12th edition, *Measurement of air-borne noise emitted by information technology and telecommunications equipment*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1

critical band

band of frequencies on either side of a specified frequency within which the presence of sound at a second frequency will interfere with the detection of sound at the specified frequency

[SOURCE: ISO 18405:2017 ^[12], 3.7.2.5]

3.2

loudness,

S

numerical designation of the strength of a sound which is proportional to its subjective magnitude as estimated by normal observers.

NOTE 1 to entry: One sone is the loudness of a sound whose loudness level is 40 phons.

NOTE 2 to entry: Loudness is expressed in sones.

[SOURCE: Modified from ISO 532:1975 ^[10], 3.3]

4 Abbreviations

AMD	air-moving device
FFT	Fast Fourier Transform
PR	prominence ratio
TNR	tone-to-noise ratio
T-PR	total prominence ratio
T-TNR	total tone-to-noise ratio

5 Noise characteristics of small fan

5.1 Fan noise generation mechanism

The noise generated from fan includes

- (1) the aerodynamic noise due to temporal fluctuation of air flow,
- (2) the structure-borne noise due to mechanical vibration of the structure containing fan,
- (3) the electromagnetic noise due to electromagnetic force fluctuation of motor, and so on.

The aerodynamic noise (1) is dominant in the operating state of a normal fan. From view point of sound source characteristics, it can be classified into

- the rotational noise (1-A) and
- the turbulent flow noise (1-B).

The rotational noise (1-A) is caused by periodic pressure fluctuations accompanying the passage of the impeller and the axial flow fan has the discrete components at the blade passing frequency which is the product of the number of rotor blades Z_r and rotational speed n and its harmonics. It becomes very annoying sound because it has high contribution to the overall of A-weighted sound pressure level.

This noise is caused by two types of unsteady flow^[1] one is called the potential interference noise caused by the pressure distribution around the impeller and the other is called the wake interference noise induced by the separated flow from the trailing edge of the impeller.

In case of small axial fan, the unsteady flow interferes the obstacles and large noise is generated, especially when the obstacles such as stators and spokes are located just behind the impeller.

On the other hand, the turbulent flow noise (1-B) is caused by the unsteady flow generated by the fan. The noise source consists of the pressure fluctuations induced by the turbulent boundary layer on the surface of the impeller, the fluctuation of lift caused by the vortex shedding from the trailing edge of the impeller and so on. It has broadband frequency components, though the energy is smaller than the rotational noise energy and the contribution to the overall of A-weighted sound pressure level is secondary. In fan noise, the noise with high tonal components is more annoying even if the overall of A-weighted sound pressure level is the same.

5.2 Tonal components of centrifugal fan

The rotational noise (1-A of 5.1) from centrifugal fans is caused by the interference between the periodic flow from the impeller blade and the tongue of the fan casing^[1]. The frequency of tonal components f_r in hertz is shown as the following formula:

$$f_{r,i} = i \cdot Z_r \cdot n \text{ (Hz)} \quad (1)$$

where,

- i : order of harmonics (1, 2, 3, ...)
- Z_r : number of rotor blades, and
- n : rotational speed per second.

5.3 Tonal components of axial fan

The rotational noise from axial fans is caused by the interference between the periodic flow from the impeller and the stator or the spoke which support the motor. In general, the number of the blades and the spokes should be the prime number so as not to occur the interference of the blades and the spokes at the same time, so the frequency components are more complicated matter than that of centrifugal fan. The frequency of tonal components f_r in hertz is shown as the following formula:

$$f_{r,j,k} = \frac{j \cdot Z_r \cdot n}{j \cdot Z_r + k \cdot Z_s} \text{ (Hz)} \quad (2)$$

where,

- j : integer index (...-2, -1, 0, 1, 2...),
- k : integer index (...-2, -1, 0, 1, 2...),
- Z_r : number of rotor blades ,
- Z_s : number of spokes, and
- n : rotational speed per second.

In both cases, the shape of the wake is not exact sinusoidal, so the harmonic components are appeared at the same time in FFT (Fast Fourier Transform) spectrum. In addition, these components are influenced by the frequency response function of the fan system. The typical noise spectrum of the small axial fan is shown in Figure 1.

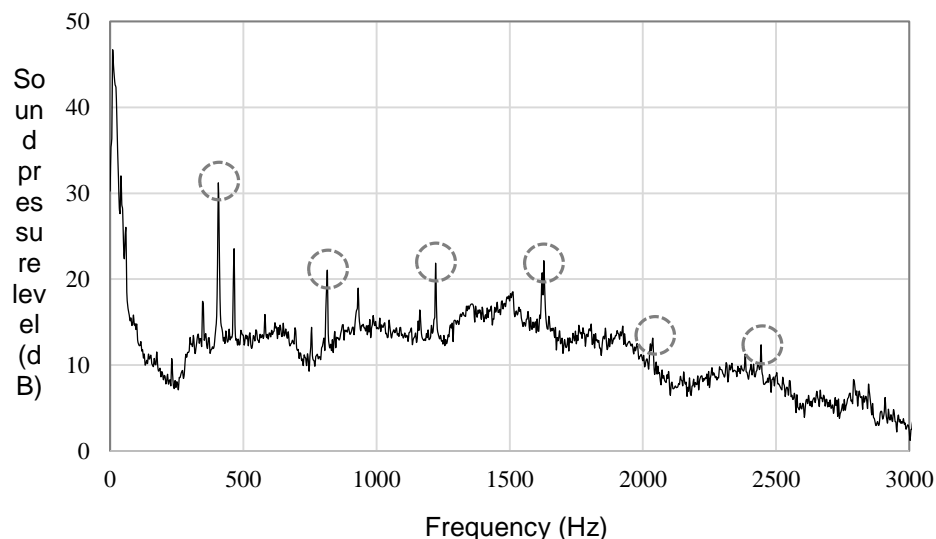


Figure 1 – Typical noise spectrum of small axial fan

6 Evaluation methods of tonal components

6.1 Tonality

Tonality, T is widely known as the metrics that indicate the tonal perception of the sound. This metrics is provided by Terhardt or Aures^[2]. It is calculated as the product of the various weighted functions to the tonal components such as the influence of masking by other tones, the ratio of tonal components and noise, the influence of hearing threshold and is applicable to the evaluation of subjective tonality for the object sound.

$$T = c \cdot w_T^{0,29} \cdot w_{Gr}^{0,79} \text{ (tu)} \quad (3)$$

where,

- c : constant that makes tonality 1 with 1 kHz/60 dB of pure tone.
- w_T : weighting function for tonal components
- w_{Gr} : weighting function for tone and noise

6.2 Tone-to-Noise Ratio (TNR) and Prominence Ratio (PR)

In general, the prominence of a tonal component is determined by the physical relationships between the tonal component level and the surrounding band noise level which is masking the tonal component. The frequency band of the surrounding is so called the critical band that is centred at the frequency of the tone. In the existing standards such as the ISO 7779^[7], ECMA-74 and ANSI S1.13^[9], the evaluation methods of the certain prominent discrete tone in information technology equipment are prescribed as the Tone-to-Noise Ratio (TNR) and the Prominence Ratio (PR), in the very similar manners. In this technical study, the methods of Annex D of ECMA-74:2012 were referred for determining TNR and PR of each tonal component of interest.

In ECMA-74:2012, the TNR (tone-to-noise ratio), ΔL_T is defined as the decibel value of the ratio of the power of tonal component and other noise component in the critical band.

$$\Delta L_T = 10 \lg \left(\frac{W_t}{W_n} \right) \text{ (dB)} \quad (4)$$

where,

- ΔL_T : tone-to-noise ratio according to ECMA-74:2012 (dB)
- W_t : power of tone (Pa²)
- W_n : power of other components in critical band (Pa²)

In ECMA-74:2012, when TNR exceeds by 8 dB at 1 kHz or higher, the tonal component is classified as prominent discrete tone. In case that multiple peaks exist in the same critical band or the noise levels adjacent to the critical band is considerable, TNR vales tends to show bigger or smaller.

The PR (prominence ratio), ΔL_p is defined as the decibel value of the ratio of the critical band power including the tonal component and the average of the adjacent critical band power on both sides.

$$\Delta L_p = 10 \lg \left[\frac{W_M}{(W_L + W_U)/2} \right] \text{ (dB)} \quad (5)$$

where,

- ΔL_P : prominence ratio according to ECMA-74:2012 (dB)
- W_M : power of middle critical band (Pa^2)
- W_L : power of lower critical band (Pa^2)
- W_U : power of upper critical band (Pa^2)

In ECMA-74:2012, when PR exceeds by 9 dB at 1 kHz or higher, the tonal component is classified as prominent discrete tone. Figure 2 is the schematic view of calculating TNR and PR, respectively.

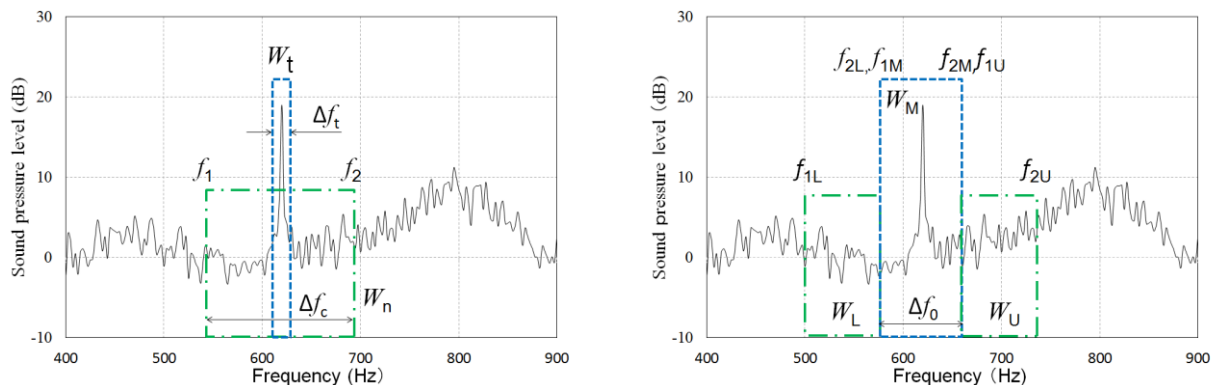


Figure 2 – Schematic view of TNR and PR calculation (Left: TNR, Right: PR)

6.3 Total TNR (T-TNR) and Total PR (T-PR)

In fan noise evaluation, it is important to identify and quantify the tonal components for the product quality control, the detection of noise source and the noise reduction. In Tonality, the method of calculation is a little bit complicated and it is difficult to identify which tonal components have high contribution. On the other hand, TNR and PR can be the indicators for the prominent discrete tone of each tonal component. However, they still don't consider relationship between the multiple tonal components.

In this TR, the new evaluation parameters called T-TNR and T-PR are presented. The individual levels of TNRs or PRs are determined for each of multiple tonal components in the noise spectrum of interest, by the calculation methods of TNR or PR, and the power summation thereof is defined as an evaluation parameter as T-TNR or T-PR, respectively.

$$\langle L_T \rangle = 10 \lg \left(\sum_{i=1}^n 10^{\frac{\Delta L_{Ti}}{10}} \right) \text{ (dB)} \quad (6)$$

$$\langle L_P \rangle = 10 \lg \left(\sum_{i=1}^n 10^{\frac{\Delta L_{Pi}}{10}} \right) \text{ (dB)} \quad (7)$$

where,

- $\langle L_T \rangle$: T-TNR (total tone-to-noise ratio) (dB)
- ΔL_{Ti} : TNR (tone-to-noise ratio) for i -th tonal component (dB)
- $\langle L_P \rangle$: T-PR (total prominence ratio) (dB)
- ΔL_{Pi} : PR (prominence ratio) for i -th tonal component (dB)
- n : number of tonal components of the noise spectrum of interest

Figure 3 is the schematic view of calculation of T-TNR and T-PR, respectively.

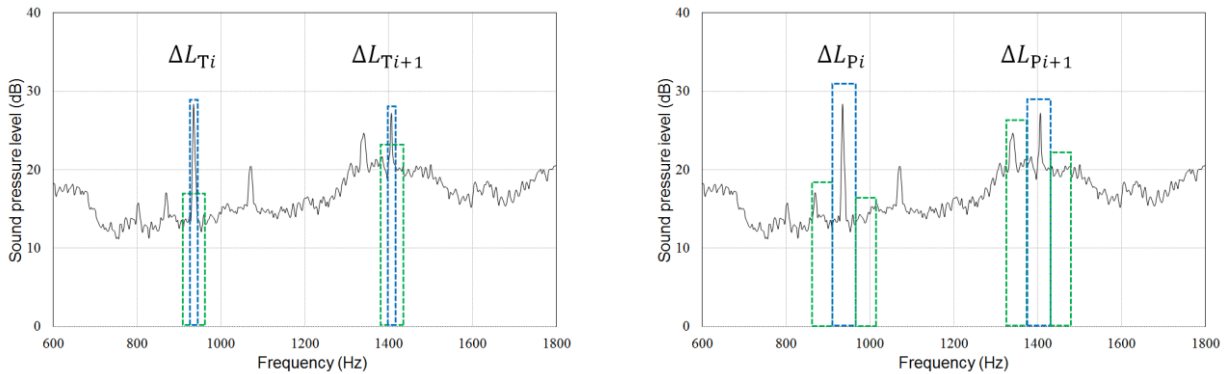


Figure 3 – Schematic view of T-TNR and T-PR calculation (Left: T-TNR, Right: T-PR)

6.4 The threshold level for prominent discrete tone

TNR and PR can be easily calculated from the result of frequency analysis, but these values are invalid below the lower threshold of hearing (LTH)^[13]. Therefore, it is necessary to exclude them from the calculation when their values are less than LTH. Details about this are shown in ECMA-74:2012.

On the other hand, it is considered that it is also effective to find the threshold level for prominent discrete tone in T-TNR and T-PR just as the threshold levels of prominent discrete tone in TNR and PR have been found. In this Technical Report, we also report the examination results.

7 Effectiveness of T-TNR and T-PR for fan noise

In the study by Yamaguchi et al. (2014)^[6], the effectiveness of T-TNR and T-PR for the subjective annoyance was verified by using real noise samples of axial fans and centrifugal fans generally and widely used for cooling IT equipment. The test sounds were adjusted to suit the test conditions based on the real noise samples. In addition, jury test was carried out based on the Scheffe's paired comparison method (Ura's version)^[3].

In their study, it was concluded that T-TNR and T-PR were highly correlated with the subjective annoyance and it was effective to use these parameters to evaluate fan noise having high tonal components. Furthermore, it also said that even though the OASPL (overall sound pressure level) or Loudness which was the measure of the subjective loudness stayed constant, these parameters could be the annoyance index.

However, it was not possible to obtain the threshold levels of harsh feeling since the jury test was the evaluation by paired comparison method.

8 Jury test

8.1 Test sound

As already stated, the aerodynamic noise is dominant in the operating state of a normal fan and from view point of sound source characteristics, it can be classified into the rotational noise (tonal component) and the turbulent flow noise (broadband components).

In this Technical Report, we use the synthesized sound (pseudo fan noise) with white noise as broadband components and sine waves as tonal components for jury test.

8.2 Paired comparison method

The paired comparison method is the methodology for estimating the intensity of each stimulus by presenting two different stimuli in pairs, being made to judge the relative magnitude of paired stimulus, and being performed this procedure for all combinations. The Scheffe's paired comparison method (Ura's version) used in this experiment is the method that each jury compares all pairs that are considered the sequence only once, and has the advantage that scores can be calculated by a small number of juries^[4].

The synthesized sounds of white noise and sine wave(s) of which the balance has been changed are used in this study.

Table 1 shows the summary of test sound adjustment methods by each jury.

Table 1 – Test sound patterns

	Methods for coordination
Pattern 1	Adjust the proportion of tonal components and noise components and adjust that the loudness of all test sounds becomes equal.
Pattern 2	Adjust each set of tonal components and adjust that the loudness of all test tones becomes equal.
Pattern 3	Adjust the proportion of tonal components and noise components so that loudness decreases with increasing tone property.

In the test sound pattern 1, peak components equal in level are set at equal intervals at 600 Hz, 1200 Hz, 1800 Hz, 2400 Hz and 3000 Hz, and all the peak components are changed by 1 time to 5 times for each test sound. Test sounds whose peak component is 1 time are defined as "test sound 1", test sounds 2 to 5 are prepared. The loudness of all the test sound is substantially equal.

In the test sound pattern 2, peak components are set at 4 positions of 720 Hz, 1440 Hz, 2880 Hz and 5760 Hz so that they are separated by 2 or more on the Bark scale, and the sound that is set equal of all peak components is defined as "test sound 1". Next, the first peak component is changed from 2 times to 5 times, and the remaining peak components are adjusted so that the loudness in some of all the test sounds are equal, and test sound 2 to 5 are prepared.

In the test sound pattern 3, the peak component is changed in the similar manner as to the test sound pattern 1, and the whole sound volume is adjusted so as to lower the loudness as the peak component becomes high, and a test sound is created.

To obtain sensory relative distance between test sounds for each test sound pattern, the jury test by the Scheffe's paired comparison method (Ura's version) is carried out. In the trials, the adjective-pairs "Annoying – Not annoying" is used as evaluation axis. Two randomly selected sounds from each test sound pattern are listened in random order, the second sound (comparison sound) to the first sound (reference sound) is evaluated in five stages. Also all combinations are presented in order to investigate the effect of sounds presentation order. The correlation analysis is performed the subjective rank order (mean value of subjects) by the paired comparison method and sound quality evaluation index.

The juries are 20 college students who were selected arbitrarily, and had the normal hearing.

Figure 4 shows an example of test sound (Pattern 1) in frequency domain.

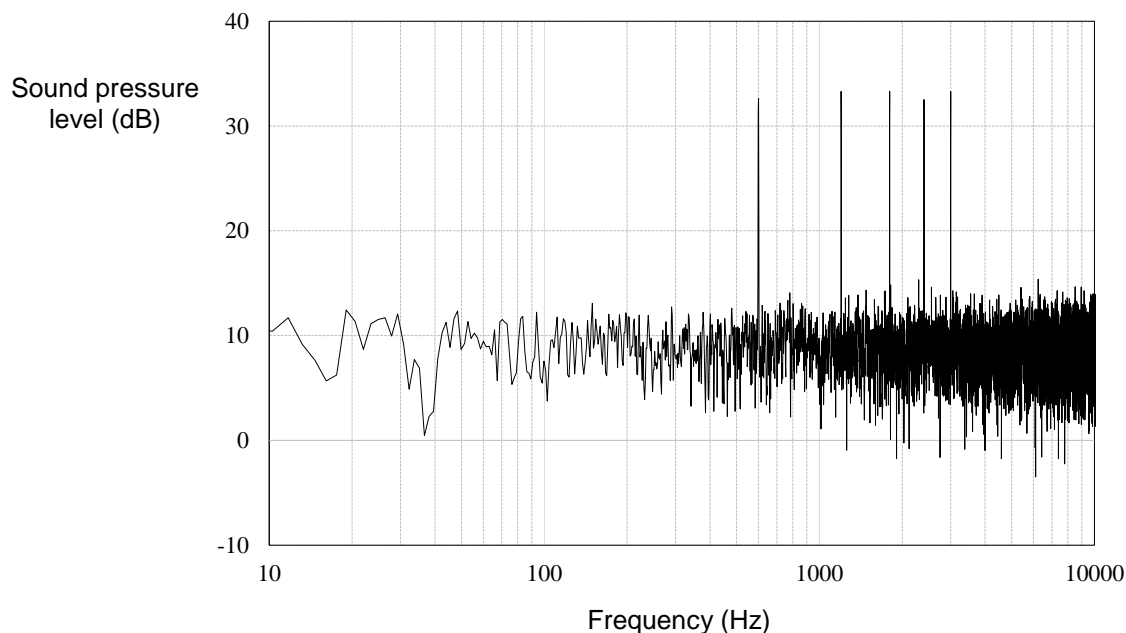


Figure 4 – Example of test sound : Pattern 1

8.3 Method of adjustment

The method of adjustment is a process in which a jury (i.e., an experimenter) freely changes a stimulus to obtain PSE (point of subjective equality) and the like. In this jury test, we selected the method that juries adjust the stimulus^[4].

The jury test with the method of adjustment is carried out to find the threshold levels for the tonal component of single frequency, that is, the threshold levels of TNR and PR or the threshold levels of T-TNR and T-PR. As with paired comparison method, white noise is simulating broadband components and sine wave is simulating tonal component. The sound that is synthesized the tonal components (720 Hz, 1440 Hz, 2880 Hz, 5760 Hz) used in the test sound pattern 2 of the pair comparison method and the white noise is used as the test sound.

The each jury adjusts the white noise level or tonal component levels with control knob displayed on the personal computer screen and decides his or her threshold level about subjective annoyance. Although the defined time limit for judging one sound is not set, each jury is given instructions so as not to spend too much time for one sound before the test. In addition, in order to eliminate series errors, the initial gain of the presentation sound is adjusted so as to be ascending series and descending series.

First, only white noise is played as test sound and the allowable annoying range is estimated by adjusting volume. The adjustment value of white noise level obtained here is applied to all synthetic sounds. That is the average value of ascending series and descent series.

Next, the sound of only single frequency is played as test sound and the allowable annoying range of each frequency is estimated by adjusting volume. The average value of ascending series and descent series of each frequency is applied to the initial value of the synthetic sound.

The synthetic sound based on these results is created and played as test sound, the threshold levels of annoying is detected by freely adjusting volume. In case of the synthetic sound, adjustment of volume is done only for the target one frequency or four frequencies. When the four tone frequencies are adjusted at the same time, their adjustment gains are unified all.

The juries are 10 college students who were selected arbitrarily, and had the normal hearing.

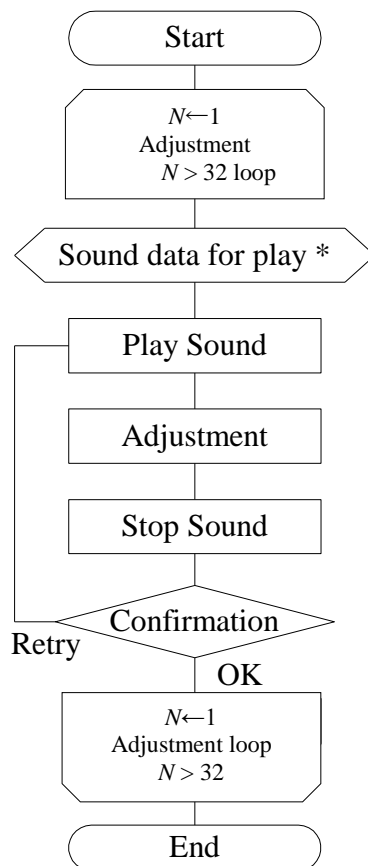


Figure 5 – Jury test for method of adjustment

Table 2 –Test sound patterns

<i>N</i>	Test sound	Series	<i>N</i>	Test sound	Series
1	White noise	Ascending	17	White noise + Sine wave 2880 Hz	Ascending
2	White noise	Descending	18	White noise + Sine wave 2880 Hz	Descending
3	Sine wave 720 Hz	Ascending	19	White noise + Sine wave 5760 Hz	Ascending
4	Sine wave 720 Hz	Descending	20	White noise + Sine wave 5760 Hz	Descending
5	Sine wave 1440 Hz	Ascending	21	White noise + Sine waves (720/2880/5660 Hz)	Ascending
6	Sine wave 1440 Hz	Descending	22	White noise + Sine waves (720/2880/5660 Hz)	Descending
7	Sine wave 2880 Hz	Ascending	23	White noise + Sine wave 720 Hz	Ascending
8	Sine wave 2880 Hz	Descending	24	White noise + Sine wave 720 Hz	Descending
9	Sine wave 5760 Hz	Ascending	25	White noise + Sine wave 1440 Hz	Ascending
10	Sine wave 5760 Hz	Descending	26	White noise + Sine wave 1440 Hz	Descending
11	White noise + Sine waves (720/2880/5660 Hz)	Ascending	27	White noise + Sine wave 2880 Hz	Ascending
12	White noise + Sine waves (720/2880/5660 Hz)	Descending	28	White noise + Sine wave 2880 Hz	Descending
13	White noise + Sine wave 720 Hz	Ascending	29	White noise + Sine wave 5760 Hz	Ascending
14	White noise + Sine wave 720 Hz	Descending	30	White noise + Sine wave 5760 Hz	Descending
15	White noise + Sine wave 1440 Hz	Ascending	31	White noise + Sine waves (720/2880/5660 Hz)	Ascending
16	White noise + Sine wave 1440 Hz	Descending	32	White noise + Sine waves (720/2880/5660 Hz)	Descending

9 Results and discussions

9.1 Paired comparison method

The results for each test sound pattern are shown below. It is found that the subjective annoyance and T-TNR or T-PR have very high correlation (Figure 6). From this, it is considered these evaluation parameters (T-TNR and T-PR) are effective when fan noise having tonal components is evaluated.

It is found that there is high correlation also in the subjective annoyance and Tonality except for the case of Test sound pattern 2 (Figure 7). In the Test sound pattern 2, it is considered that Tonality is calculated almost constant value (slightly decreasing trend at increasing of the subjective annoyance) since the influence of frequency masking is small and the loudness is set almost constant. Therefore, it is considered that it became a negative correlation with the subjective annoyance.

Also, in Figures 6 and 7, the values of T-TNR and T-PR are distributed in some degree of wider range, comparing to the range of subjective annoyance values. In Tables 3 and 4, this tendency is expressed by the variance. Comparing with that of subjective annoyance, those of T-TNR and T-PR are large enough. So, T-TNR and T-PR are effective as the sound quality evaluation index. On the other hand, it is considered that it is difficult to evaluate the subjective annoyance by using Tonality because the variance is smaller than that of the subjective annoyance.

In the Test sound pattern 3, it is found that the correlations of the subjective annoyance and T-TNR or T-PR are very high. However, it is necessary to consider how much change range is effective since the change range of loudness is very small.

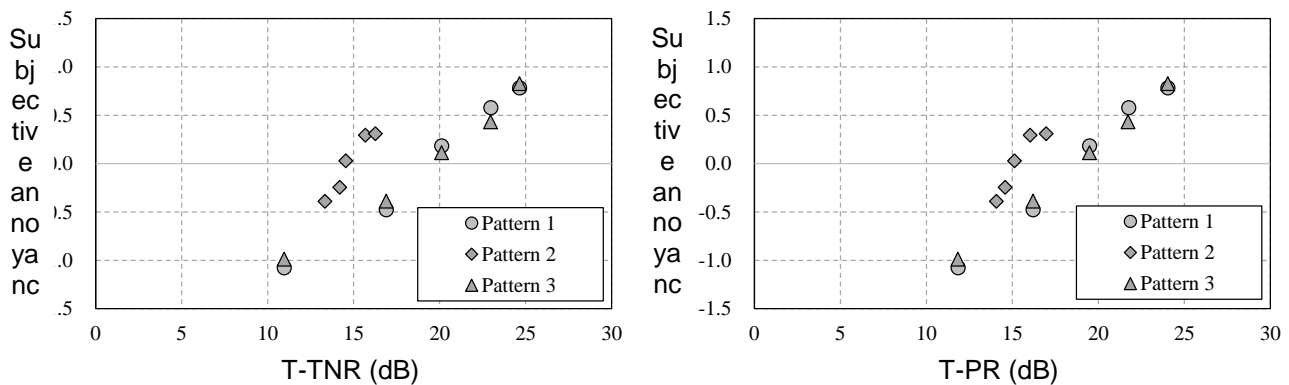


Figure 6 – Relationships between T-TNR or T-PR and subjective annoyance

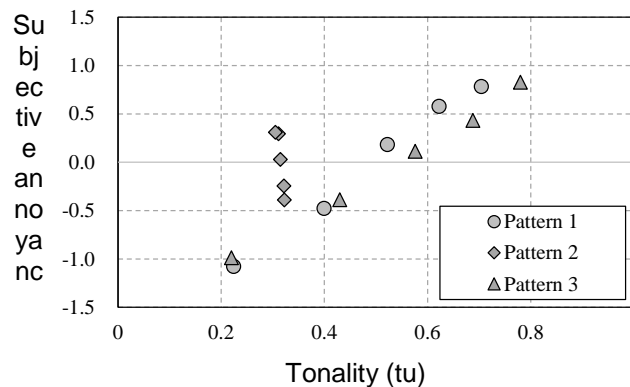


Figure 7 – Relationships between tonality and subjective annoyance

Table 3 – Results of Test sound pattern 1

Sound No.	T-TNR (dB)	T-PR (dB)	Tonality (tu)	Subjective annoyance
1	11,0	11,8	0,224	-1,08
2	16,9	16,2	0,399	-0,48
3	20,1	19,5	0,522	0,19
4	23,0	21,8	0,622	0,58
5	24,6	24,0	0,774	0,79
Variance	2,330	2,189	0,435	0,877
Correlation coefficient	0,993	0,995	0,995	

Table 4 – Results of Test sound pattern 2

Sound No.	T-TNR (dB)	T-PR (dB)	Tonality (tu)	Subjective annoyance
1	13,3	14,1	0,322	-0,39
2	14,2	14,6	0,321	-0,25
3	14,5	15,1	0,315	0,03
4	15,7	16,0	0,311	0,30
5	16,3	17,0	0,305	0,31
Variance	1,084	1,074	0,084	0,561
Correlation coefficient	0,996	0,949	-0,952	

Table 5 – Results of Test sound pattern 3

Sound No.	T-TNR (dB)	T-PR (dB)	Tonality (tu)	Subjective annoyance
1	11,0	11,8	0,220	-0,99
2	16,9	16,2	0,430	-0,39
3	20,1	19,5	0,562	0,11
4	23,0	21,7	0,688	0,43
5	24,6	24,0	0,780	0,83
Variance	2,330	2,189	0,470	0,883
Correlation coefficient	0,992	0,999	0,998	

9.2 Method of adjustment

The threshold of annoyance at each frequency is determined by means of method of adjustment. In addition, the threshold levels for T-TNR and T-PR are obtained from the synthesized sounds white noise is simulating broadband components and sine wave is simulating tonal component.

The threshold of annoyance at each frequency is determined by using the composite sounds of white noise and single frequency tone as shown in Table 2. The threshold of annoyance at each frequency and the reference curve of "Prominent Discrete Tone" (ECMA-74:2012) are compared in Figure 8 and the threshold levels of annoyance at each frequency is shown in Table 6.

It is found from Figure 8 that the threshold levels are higher (the response is dull) than the criterion for the discrete tones less than 2 kHz and are lower (the response is high) than the criterion for the discrete tones higher than 2 kHz.

It is found from Table 6 that as the frequency of tonal component increases, the standard deviation of threshold decreases. It is thought that this is affected the critical bandwidth differs from frequency to frequency and the white noise where the broadband components are uniformly distributed. On the other hand, it can also be considered that the permissible range of each individual is large at low frequencies and it is small at high frequencies.

The threshold levels for T-TNR and T-PR ($\langle L_T \rangle_0$ and $\langle L_P \rangle_0$) are shown on Table 7. It is defined that the thresholds of annoyance in T-TNR or T-PR can be calculated by the sum of TNR or PR. The threshold of annoyance in T-TNR or T-PR did not coincide with the sum of TNR and PR of each frequency. It is considered that the total value of TNR or PR of each frequency did not match the thresholds of T-TNR or T-PR since the adjustment values of four frequencies of synthesized sound for obtaining T-TNR or T-PR are unified. The standard deviations of $\langle L_T \rangle_0$ and $\langle L_P \rangle_0$ are almost the same.

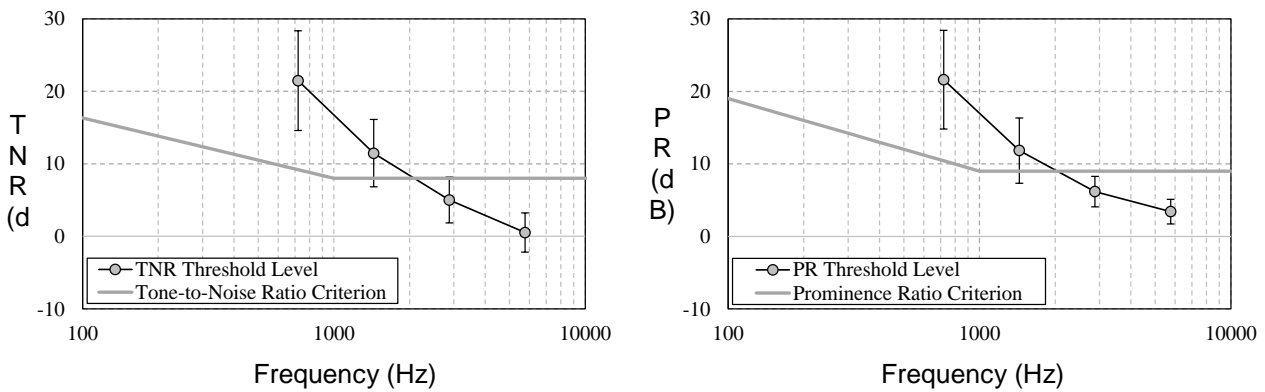


Figure 8 – Average threshold levels of annoyance in TNR and PR

Table 6 – Threshold levels at each frequency

Frequency (Hz)	TNR (dB)	Standard deviation (dB)	Frequency (Hz)	PR (dB)	Standard deviation (dB)
720	21,5	6,9	720	21,6	6,8
1440	11,5	4,7	1440	11,8	4,5
2880	5,0	4,7	2880	6,2	2,1
5760	0,5	2,7	5760	3,4	1,7

Table 7 – Threshold levels for T-TNR and T-PR

	Threshold level (dB)	Standard deviation (dB)
$\langle L_T \rangle_0$	17,8	6,3
$\langle L_P \rangle_0$	18,2	6,0

10 Conclusion

It has been confirmed that T-TNR and T-PR proposed in this study are effective as evaluation parameters of noise with multiple tonal components from the results of both the real noise samples and the synthetic sound samples. In addition, these are considered to be useful also in that they are obtained by relatively simple calculations based on the calculation method of the existing standards (ECMA-74, ISO 7779 etc.).

The annoyance threshold levels of TNR and PR for single tonal component and the annoyance threshold levels of T-TNR and T-PR for multiple tonal components can be determined by using method of adjustment. However, there is a high possibility that these values cannot be directly applied as threshold values since the test sounds are the synthetic sound. Therefore, we would like to examine the method etc. of giving the gain adjustment value of each frequency and conduct additional test. Eventually, we would like to verify the effectiveness of these thresholds for the noise generated from the actual small fan and apply to product evaluation of small fan.

Furthermore, it is expected that T-TNR and T-PR are effective for not only small fan noise but also other noise which consists of tonal components and broadband components. The follow-up research works should be done for applying them to evaluation of various product noise in the future.



Bibliography

- [1] Shoji Suzuki, Masaharu Nishimura, Shinya Kijimoto and Gaku Minorikawa, *Mechanical Acoustical Engineering*, Corona publishing, **1993**
- [2] Ernst Terhardt, Gerhard Stoll and Manfred Seewann, Algorithm for extraction of pitch salience from complex tonal signals, *J. Acoust. Soc. Am* **1982**
- [3] Union of Japanese Scientists and Engineers, Research Committee of Sensory Evaluation, *Sensory Evaluation Handbook*, JUSE Press, **1973**
- [4] Seiichiro Namba and Sonoko Kuwano, *Psychological measuring method for sound evaluation*, Corona publishing, **1998**
- [5] W. Aures, *Procedure for Calculating the Sensory Euphony of Arbitrary Sound Signals*, *Acustica* 59, 130{141, **1985**.
- [6] Takao YAMAGUCHI; Gaku MINORIKAWA; Masayuki KIHARA, *Study on evaluation method of the pure tone for small fan*, Proceedings of inter-noise2014, Melbourne, Australia, **2014**
- [7] Gaku Minorikawa, Takao Yamaguchi, *STUDY ON EVALUATION METHOD OF TONAL NOISE FOR SMALL FAN*, Proceedings of ICSV22, Florence, Italy, **2015**
- [8] NAKANO, T., MINORIKAWA, G. *STUDY ON EVALUATION METHOD OF THE TONAL NOISE COMPONENTS FOR SMALL FAN*, fan2018, Darmstadt, Germany, **2018**
- [9] Kimizuka, I., MINORIKAWA, G. *Ecma TR for New Physical Evaluation Method of Prominent Discrete Tone of Noise Emitted from Air-Moving Devices*, Noise-Con2016, Providence, USA, **2016**
- [10] ISO 532:1975, *Acoustics — Methods of calculating loudness level*, *International Organization for Standardization*, **1975**
- [11] ISO 7779 4th edition, *Acoustics – Measurement of airborne noise emitted by information technology and telecommunications equipment*, *International Organization for Standardization*, **2018**
- [12] ISO 18405:2017, *Acoustics — Underwater acoustics -- Terminology*, *International Organization for Standardization*, **2017**
- [13] ISO 28961:2012 1st edition, *Acoustics – Statistical distribution of hearing thresholds of otologically normal persons in the age range from 18 years to 25 years under free-field listening conditions*, *International Organization for Standardization*, **2012**
- [14] ANSI S1.13 5th Edition, *American National Standard Measurement of Sound Pressure Levels in Air*, American National Standards Institute, **2005**
- [15] ISO/PAS 20065, *Acoustics — Objective method for assessing the audibility of tones in noise — Engineering method*, **2016**

