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Study on the evaluation index of the tonal noise components generated from small fan

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ABSTRACT

There are various cooling methods, but small fans are generally used in order to cool information equipment such as personal computers, projectors and others. The noise generated from small fans contains tonal components, which are mainly caused by the flow temporal variation, the motor's electromagnetic force and others. It's known that these tonal components contribute to not only the overall sound pressure level but also the harsh sound. Although several indices for evaluating tonal components have been proposed, it cannot be said that these are able to be evaluated small fans appropriately. In this study, the new evaluation indices have been proposed. These are named Total Tone-to-Noise Ratio and Total Prominence Ratio based on tonal components evaluation indices Tone-to-Noise Ratio and Prominence Ratio defined in the annex such as ECMA-74. These evaluation indices are total values of TNR or PR of each tonal component included in the noise. Therefore, it is possible to evaluate multiple tonal components individually or comprehensively. In our previous study, it has been confirmed that these new indices are effective for subjective annoyance in small axial fan or small centrifugal fan. This study is attempted to determine their subjective evaluation thresholds with the sensory test.

Keywords: Small fan, Fan noise, Tonal components evaluation

1. INTRODUCTION

In recent years, the information technology equipment such as personal computers, projectors and others have become as necessities for modern life. The amount of heat generated due to high integration of electronic components is increasing along with the high performance or miniaturization of these equipment. Although there are various methods of cooling, the small fans that are very efficient and low-cost are generally used in order to cool them. The noise reduction of the small fan advances and A-weighted sound pressure level itself is kept low, but even that slight sound may be felt annoying in a quiet living environment.

As for the influence of tonal components on the sense of hearing, the evaluation indices called Tone-to-Noise Ratio (hereinafter, referred to as TNR) and Prominence Ratio (hereinafter, referred to as PR) are defined in such as ISO 7779 (1), ECMA-74 (2) and ANSIS 1.13 (3). These are the evaluation indices for evaluating individual tonal components contained in noise and are not the evaluation indices for overall evaluating multiple tonal components contained in noise. Therefore, we have proposed the new indices called Total Tone-to-Noise Ratio (hereinafter, referred to as T-TNR) and Total Prominence Ratio (hereinafter, referred to as T-PR) for evaluating the noise in which multiple tonal components are contained. On the other hand, the psychoacoustic approach to detect the tonal feeling has been also developed and the index such as Tonality has been used for the evaluation of the overall tonal feeling.

The effectiveness of T-TNR and T-PR for annoying was verified with the sensory test by sound sources processed a small axial fan noise and a small centrifugal fan noise or sound sources synthesized white noise and sine wave by Minorikawa et al. (4, 5). The previous study concluded that T-TNR and T-PR could be used as a simple calculation procedure to evaluate noise with multiple

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tonal components and could be effective as a method to evaluate tonal components when there was not enough deviation in Tonality. However, it was the relative result obtained by the paired comparison method, the absolute threshold level of T-TNR or T-PR has not been obtained yet.

The purpose of this study is to determine the threshold levels which has not been determined in the previous study for annoyance in T-TNR or T-PR with the sensory test (the method of adjustment) by sound sources processed small axial fan noises. Furthermore, the effectiveness of the determined threshold levels is verified with actual small fan noises.

2. NOISE CHARACTERRISTICS OF SMALL FAN

2.1 Mechanism of fan noise generation

The noise generated from fan includes the aerodynamic noise that temporal fluctuation of flow becomes sound source, the mechanical noise that mechanical vibration becomes sound source, the electromagnetic noise that electromagnetic force fluctuation of motor becomes sound source and others. Among them, the aerodynamic noise is dominant in the operating state of a normal fan and it can be classified into the rotational noise and the turbulent flow noise from its sound source characteristics. In fan noise, it is known that the noise including high tonal components is felt more annoyance even if the overall level is the same. (6)

The rotational noise is generated by periodic pressure fluctuations accompanying the passage of the impeller. In the case of a centrifugal fan, it has tonal components on the product of the number of blades and the number of rotations and on their harmonics. In the case of an axial fan, it has tonal components on the product of the number of rotor blades and the number of rotations and on their harmonics. It becomes very annoying sound because it has high contribution to the overall of A-weighted sound pressure level. Therefore, it is firstly important to reduce the rotational noise for measures of fan noise. This noise is caused by two types of unsteady flow. One is called the potential interference noise caused by the pressure distribution around the impeller and the other is called wake interference noise induced by the separated flow from the trailing edge of the impeller. In case of the small axial fan, the unsteady flow interfere the obstacles and large noise is generated, when the obstacles such as stators and spokes are located just behind the impeller. (6)

The turbulent noise is caused by the random turbulent 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. (6)

2.2 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 supports the motor. The frequencies of tonal components are shown as the following formula:

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

where,

i : order of harmonics ($i = 1,2,3,\ldots$) Z_r : number of rotor blades

n : rotational speed per second

2.3 Tonal components of centrifugal fan

The rotational noise from centrifugal fans is caused by the interference between the periodic flow from the impeller blade and the tongue of the fan casing. The frequencies of tonal components are shown as the following formula:

$$f_{r,i} = i \cdot Z_r \cdot n \quad \text{(Hz)} \tag{2}$$

where,

i : order of harmonics ($i = 1,2,3,\ldots$) Z_r : number of blades

n : rotational speed per second

3. EVALUATION METHODS OF TONAL COMPONENTS

3.1 Tone-to-Noise Ratio and Prominence Ratio

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 centered at the frequency of the tone. In the existing standards such as the ISO 7779 (1), ECMA-74 (2) and ANSI S1.13 (3), the evaluation methods of the certain prominent discrete tone in information technology equipment are prescribed as TNR and PR, in the very similar manners. In this study, the methods of Annex D of ECMA 74 were referred for determining TNR and PR of each tonal component of interest.

The TNR (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. In ECMA-74, 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. (2)

$$\Delta L_{\mathrm{T}} = 10\log_{10}\left(\frac{W_{\mathrm{t}}}{W_{\mathrm{n}}}\right) \text{ (dB)} \tag{3}$$

where,

ΔL_{T} : tone-to-noise ratio according to ECMA-74 (dB)

W_{t} : power of tone (Pa^2)

W_{n} : power of other components in critical band (Pa^2)

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

$$\Delta L_{\mathrm{P}} = 10\log_{10}\left[\frac{W_{\mathrm{M}}}{(W_{\mathrm{L}} + W_{\mathrm{U}})/2}\right] \text{ (dB)} \tag{4}$$

where,

ΔL_{P} : prominence ratio according to ECMA-74 (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)

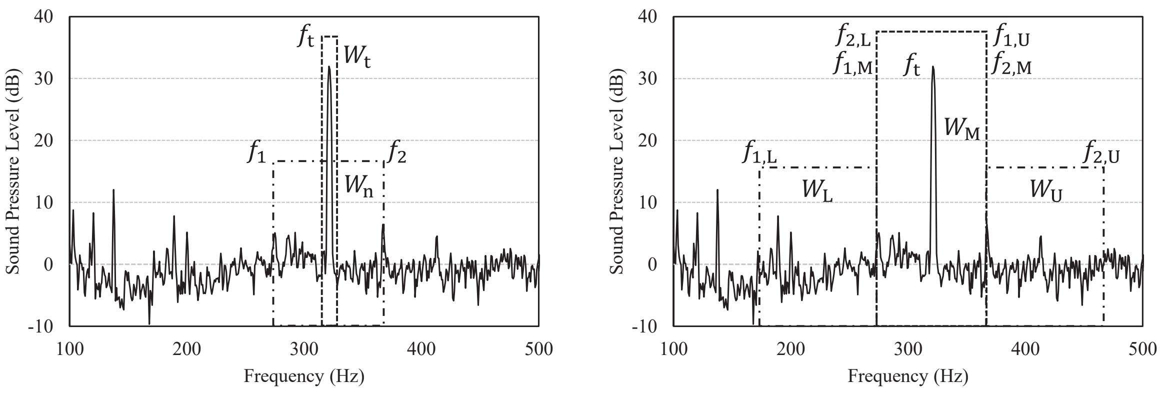

Figure 1 – Schematic view of TNR and PR calculation (Left: TNR, Right: PR)

3.2 Total Tone-to-Noise Ratio and Tonal Prominence Ratio

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 study, the new evaluation parameters called T-TNR and T-PR have been proceed. 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. Figure 2 is the schematic view of calculating T-TNR and T-PR.

$$\langle L_{\mathrm{T}} \rangle = 10\log_{10}\left(\sum_{i=1}^{n} 10^{\Delta L_{\mathrm{T}i}/10}\right) \tag{5}$$

$$\langle L_{\mathrm{P}} \rangle = 10\log_{10}\left(\sum_{i=1}^{n} 10^{\Delta L_{\mathrm{P}i}/10}\right) \tag{6}$$

where,

$\langle L_{\mathrm{T}} \rangle$: T-TNR (dB) $\Delta L_{\mathrm{T}i}$: tone-to-noise ratio for i-th tonal component (dB)

$\langle L_{\mathrm{P}} \rangle$: T-PR (dB) $\Delta L_{\mathrm{P}i}$: prominence ratio for i-th tonal component (dB)

n : number of tonal components of the noise spectrum of interest

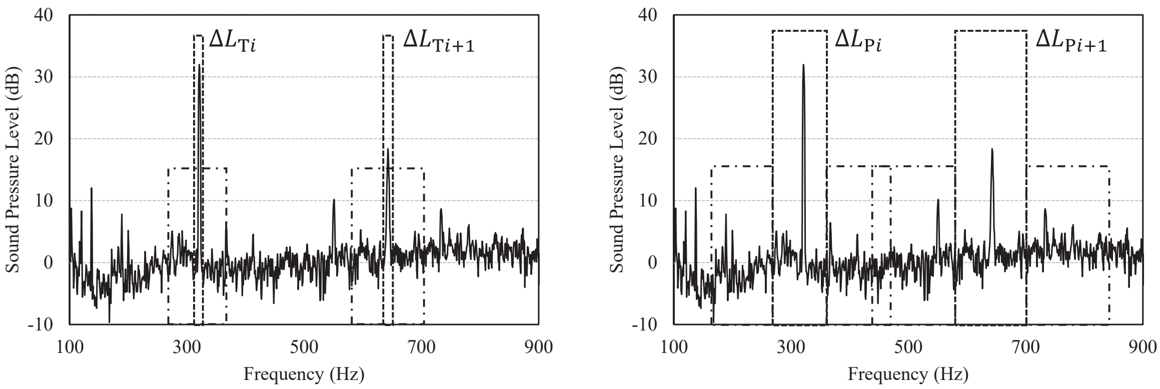

Figure 2 – Schematic view of T-TNR and T-PR calculation (Left: T-TNR, Right: T-PR)

3.3 Tonality

Tonality, T is widely known as the indices that indicate the tonal perception of the sound. This index is provided by such as Terhardt and Aures (7, 8). 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.

3.4 The threshold level for subjective annoyance of T-TNR or T-PR

In order to evaluate whether the fan noise is good or bad, it is necessary to determine the boundary level of T-TNR and T-PR which is felt or is not felt to be annoyance subjectively, that is, the threshold level. In this study, T-TNR or T-PR threshold levels are determined by a commercially available small axial fan noise as a reference sound source. The threshold levels for the subjective annoyance of T-TNR and T-PR are newly defined as $\langle L_{\mathrm{T}} \rangle_0$ and $\langle L_{\mathrm{P}} \rangle_0$ in this study.

4. SENSORY TEST

4.1 Test fans

In this study, seven types of small axial fans are prepared as base sound sources for sensory test and sound sources for threshold level verification. The test fans with a blade diameter of 80 mm, a rated speed of 2000 rpm and the number of blades of seven blades are adopted as a reference fan, the different blade diameter fan (Only Fan E is blade diameter of 120 mm.) and the different rated speed fans (Fan F and Fan G are rated speed of 2800 rpm.) are also targeted.

The sound sources of test fans were recorded in the hemi-anechoic room in our university. The fans were driven the approximately rated speed without flow restriction and the sound sources were measured with the precision noise level meter (RION NL-31) set at 500 mm apart from the front of the suction side of them. The sound sources were stored as WAV files to the computer via the multi-channel signal analyzer (RION SA-01). The sampling frequency at the recording was 51.2 kHz and the recording time was about 10 seconds.

The characteristics of each test fan obtained from the recorded data are shown on Table 1. In the calculation of T-TNR and T-PR, the tonal components up to the seventh order caused by rotational noise are considered.

Table 1 – Characteristics of test fans

Fan Name	$\langle L_T \rangle$, dB	$\langle L_P \rangle$, dB	Loudness, sone	Sharpness, acum	Overall level, dB
Fan A	5.4	9.5	1.1	1.5	30.7
Fan B	9.7	11.5	0.7	1.2	27.0
Fan C	3.1	9.6	0.3	1.5	22.5
Fan D	3.6	8.7	0.9	1.4	29.0
Fan E	12.0	13.9	2.9	1.5	38.9
Fan F	19.4	16.5	2.1	1.3	36.1
Fan G	6.5	12.8	1.3	1.4	31.3
Standard deviation	5.8	2.8	0.9	0.1	5.5

4.2 Test sounds

The test sounds adopt the sounds which are removed the blade passing frequency components from the sound sources of the recorded test fans as the reference sound sources. At the sensory test, it is decided to add together the tonal components up to the seventh order to these reference sound sources and adjust their levels. In addition, the change rate of every tonal component is determined based on the level at the rated speed. At the sensory test, the test sound based on the reference sound source of Fan A is named "Sound A" and the same applies to the test sounds of other fans.

4.3 Method of adjustment

The method of adjustment is used as the sensory test method in this study. The method of adjustment is a method in which the experimenter or the jury freely changes a stimulus to obtain the value of the stimulus which gives a specific sensation. This method is characterized by relatively taking little trouble, efficient measurement and less influence of subject's operation error compared to other test methods. (9, 10)

The implementation method of the sensory test by the method of adjustment is as follows. First of all, the juries hear only the reference sound source and adjust its level and then they decide the threshold level of the reference sound source at which they start feeling annoyance. Next, the juries hear the sound added together the seven tonal components to the reference sound source and adjust its level and then they decide the threshold level of the sound at which they start feeling annoyance. This test carries out for all of seven sound sources. The order of the sound sources presented to the juries are random and both ascending series and descending series are carried out in consideration of the influence of the systematic error. Although the strict time limit for judging one sound is not set, all juries are provided instructions so as not to spend too much time for one sound before the test. And the juries are 16 college students (from 20 to 25 years old) who have the normal hearing ability and were selected at random. Incidentally, this test is performed by the application that is created for the sensory test of the method of adjustment.

5. RESULT AND DISCUSSION

5.1 The threshold levels for every test sound

The threshold levels for each test sound and standard deviations are shown on Table 2. However, the numbers shown in parentheses are for the standard deviations of test sounds. Also, the correlation coefficients of indices are shown on Table 3.

The standard deviations of Loudness and Sharpness have been small and the standard deviations of $\langle L_{\mathrm{T}} \rangle_0$, $\langle L_{\mathrm{P}} \rangle_0$ and Overall levels have been largish. That is, since the threshold values of Loudness and Sharpness have had small dispersion, it is considered that they tend to be good as the threshold levels. However, as shown on Table 1, since the standard deviation of Sharpness in fan noise is also small, it might be difficult to use only Sharpness as an evaluation index for the annoyance. About the other indices, since the standard deviations of the threshold levels and the standard deviations of the fan noises have been secured, it is considered that there is a possibility that one or a combination of them can be used as the evaluation indices. According to Table 3, it has been confirmed that $\langle L_{\mathrm{T}} \rangle_0$ or $\langle L_{\mathrm{P}} \rangle_0$ and Sharpness had a high negative correlation. On the other hand, it has been confirmed that $\langle L_{\mathrm{T}} \rangle_0$ or $\langle L_{\mathrm{P}} \rangle_0$ and Overall levels are not as large as the correlation coefficient with Sharpness, but have positive correlation. Also, the correlation coefficient between $\langle L_{\mathrm{P}} \rangle_0$ and Loudness has been small. Thus, it has been confirmed that $\langle L_{\mathrm{T}} \rangle_0$ and $\langle L_{\mathrm{P}} \rangle_0$, which have a high correlation with Sharpness that is stable as a threshold level, are effective as an evaluation index of annoyance.

Table 2 – Threshold levels for every test sound

Test Sound	$\langle L_{\mathrm{T}} \rangle_0$, dB	$\langle L_{\mathrm{P}} \rangle_0$, dB	Loudness, sone	Sharpness, acum	Overall level, dB
Sound A	12.5 (6.8)	13.9 (5.1)	1.9 (1.4)	1.2 (0.3)	33.8 (7.5)
Sound B	17.9 (8.4)	20.3 (7.1)	2.4 (1.7)	1.0 (0.3)	37.0 (6.9)
Sound C	16.3 (6.3)	16.6 (5.3)	2.1 (1.1)	1.2 (0.3)	34.7 (5.7)
Sound D	12.5 (5.3)	14.3 (4.0)	1.5 (1.1)	1.3 (0.2)	31.8 (6.7)
Sound E	20.3 (7.1)	24.0 (6.8)	2.2 (1.8)	1.1 (0.3)	34.9 (6.9)
Sound F	19.0 (7.5)	24.5 (6.9)	1.8 (1.2)	1.1 (0.3)	35.1 (6.6)
Sound G	13.2 (6.0)	15.4 (4.3)	2.1 (1.8)	1.3 (0.3)	33.3 (8.4)
Standard deviation	3.3	4.5	0.3	0.1	1.6

Table 3– Correlation coefficients for every test sound

	$\langle L_{\mathrm{T}} \rangle_0$	$\langle L_{\mathrm{P}} \rangle_0$	Loudness	Sharpness	Overall level
$\langle L_{\mathrm{T}} \rangle_0$	---	0.96	0.51	-0.83	0.74
$\langle L_{\mathrm{P}} \rangle_0$	0.96	---	0.33	-0.81	0.64
Loudness	0.51	0.33	---	-0.55	0.80
Sharpness	-0.83	-0.81	-0.55	---	-0.89
Overall Level	0.74	0.64	0.80	-0.89	---

5.2 The threshold levels for every jury

The standard deviations of every jury are shown on Table 4 and the correlation coefficients are shown on Table 5.

The standard deviations of Loudness and Sharpness have been small, while the standard deviations of $\langle L_{\mathrm{T}} \rangle_0$ or $\langle L_{\mathrm{P}} \rangle_0$ and Overall level have been largish. The standard deviations have tended to be larger in all indices as compared with the results for every test sounds. It is considered that this is affected by the difference in individual tolerance range with respect to the presentation test sounds.

In addition, when these correlation coefficients are compared with the results for every test sounds, the sign of the correlation coefficients between $\langle L_{\mathrm{T}}\rangle_0$ or $\langle L_{\mathrm{P}}\rangle_0$ and Loudness or Sharpness have been inverted. On the other hand, it has been confirmed that the correlation coefficient with Sharpness has a high negative correlation like the result for every test sounds. Thus, as the evaluation results for every jury, the threshold levels $\langle L_{\mathrm{T}}\rangle_0$ and $\langle L_{\mathrm{P}}\rangle_0$ tend to decrease as Loudness, Sharpness and Overall level increase. It might say that this is a logical result.

Table 4 – Standard deviation for every jury

	$\langle L_{\mathrm{T}}\rangle_0$, dB	$\langle L_{\mathrm{P}}\rangle_0$, dB	Loudness, sone	Sharpness, acum	Overall level, dB
Standard deviation	4.6	4.5	1.3	0.3	6.2

Table 5 – Correlation coefficients for every jury

	$\langle L_{\mathrm{T}}\rangle_0$	$\langle L_{\mathrm{P}}\rangle_0$	Loudness	Sharpness	Overall level
$\langle L_{\mathrm{T}}\rangle_0$	---	0.97	-0.59	-0.90	-0.45
$\langle L_{\mathrm{P}}\rangle_0$	0.97	---	-0.53	-0.87	-0.35
Loudness	-0.59	-0.53	---	0.78	0.94
Sharpness	-0.90	-0.87	0.78	---	0.74
Overall Level	-0.45	-0.35	0.94	0.74	---

5.3 Threshold levels and their evaluation

The results for every test sound are adopted as the threshold levels and are shown on Table 6. The results of applying these threshold levels to the test fan noises are shown on Figure 4.

Since TNR and PR have a complementary relationship, when the test fan noise exceeding both threshold levels is regarded as NG, all the test fans have prepared this time are evaluated as OK. However, in my opinion, this evaluation results does not seem to be in line with the auditory impression. Therefore, the test fan noises have been re-evaluated with Overall level that obtained as a result of frequency analysis as an additional evaluation parameter. In this case, the calculation for Loudness is not required. The results are shown on Figure 5. If the test fan above both $\langle L_{\mathrm{T}}\rangle_0$ or $\langle L_{\mathrm{P}}\rangle_0$ and the approximate curve (linear approximation) of Overall level is regarded as NG, Fan E and Fan F of the test fans are evaluated as NG. On Figure 4, when the evaluation level is evaluated as "Threshold level − Standard deviation", it can be confirmed that the similar trend is obtained. Thus, it is considered that it is necessary to improve the accuracy of the threshold levels by increasing the number of subjects or examining a data organization method.

Table 6 – The threshold levels of T-TNR and T-PR

	$\langle L_{\mathrm{T}}\rangle_0$,dB	$\langle L_{\mathrm{P}}\rangle_0$, dB
Threshold Level	15.9	18.4

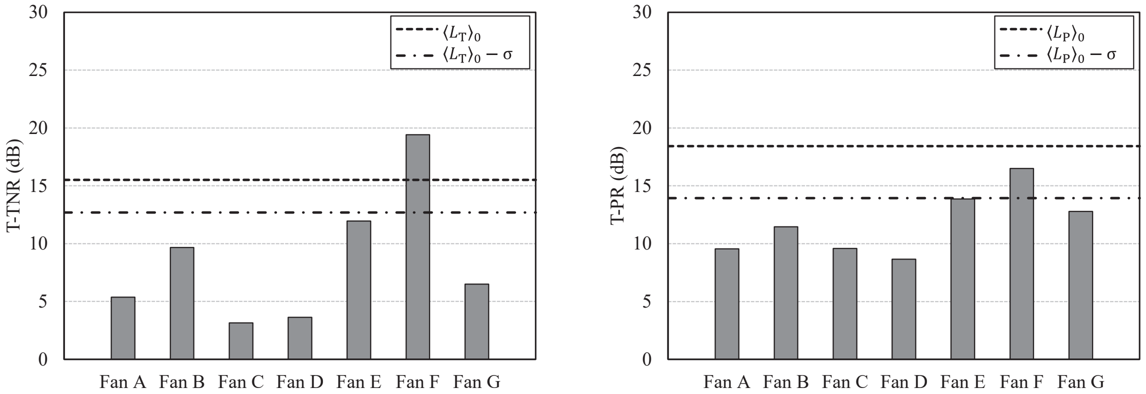

Figure 4 – Evaluation of the threshold levels

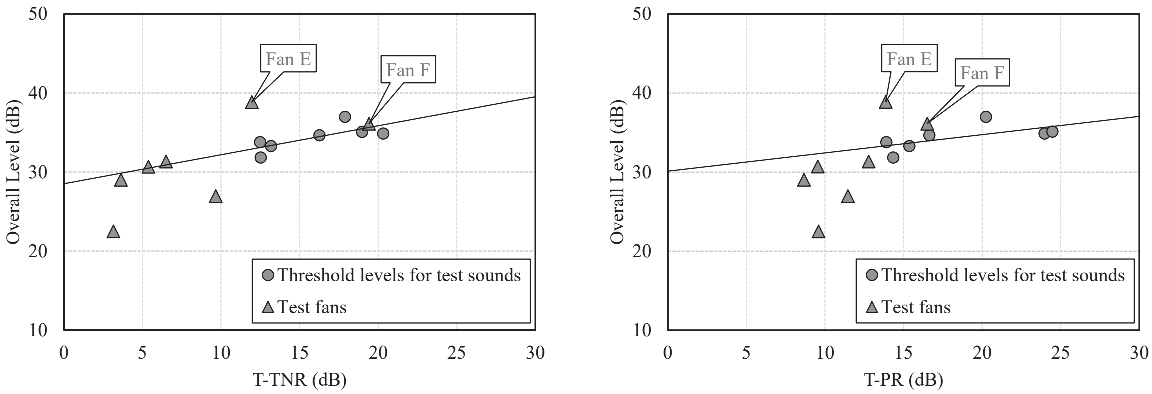

Figure 5 – Relationships between T-TNR or T-PR and Overall levels

6. SUMMARY

In this study, the threshold levels of T-TNR and T-PR which are new evaluation indices of noise including multiple tonal components have been determined with the sensory test.

1. The analysis results for every test sound have confirmed that $\langle L_{\mathrm{T}}\rangle_0$ and $\langle L_{\mathrm{P}}\rangle_0$ have a negative correlation with Sharpness. On the other hand, the correlation between $\langle L_{\mathrm{P}}\rangle_0$ and Loudness has not been not high. The threshold levels are 15.9 dB for $\langle L_{\mathrm{T}}\rangle_0$ and 18.4 dB for $\langle L_{\mathrm{P}}\rangle_0$.
2. The analysis results for every jury have confirmed that $\langle L_{\mathrm{T}}\rangle_0$ and $\langle L_{\mathrm{P}}\rangle_0$ have a negative correlation with Sharpness. On the other hand, the correlations between $\langle L_{\mathrm{T}}\rangle_0$ or $\langle L_{\mathrm{P}}\rangle_0$ and Overall level have not been high.
3. As the results of evaluating the test fan noises with the threshold levels $\langle L_{\mathrm{T}}\rangle_0$ and $\langle L_{\mathrm{P}}\rangle_0$ which are obtained, it is considered that it might be possible to evaluate the annoyance with an approximation curve (linear approximation) of $\langle L_{\mathrm{T}}\rangle_0$ or $\langle L_{\mathrm{P}}\rangle_0$ and Overall level. Also, since these trends are almost the same as the result of evaluating the threshold level as "Threshold level-Standard deviation". In future, we would like to improve the accuracies of threshold levels $\langle L_{\mathrm{T}}\rangle_0$ and $\langle L_{\mathrm{P}}\rangle_0$.

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