There are various cooling devices and methods, but inexpensive and effective small fans are generally used in order to cool information devices such as personal computers, projectors and the like. However, the sound generated from the small fan may be annoying components in a quiet living environment. The main factor of this annoying sound is pure tones contained in the noise which is caused by the electromagnetic force of motor, the flow interference between blades and spokes, the acoustic modes of the structure and so on. In addition, it is also known that these tonal components have very high degree of contribution to the overall sound pressure level. Although indices to evaluate the influence of tonal components on hearing have been proposed so far, it might not be said that the actual condition is able to be evaluated appropriately. Moreover, the evaluation index for small fan noise has not been developed. In this study, it is attempted to determine tonal threshold levels by investigating relationships between presented sounds and subjective annoyance by using sensory test.

Keywords: small fan, fan noise, tonal components, tone to noise ratio, prominence ratio

1. Introduction

In recent years, the information technology devices such as personal computers, projectors, and so on have become as necessities to 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 devices. The small fans are used so as to exhaust the big amount of heat because they are very efficient and low-cost. Although it is easy and efficient in comparison to other method to exhaust the heat by using them, the fan noise will have been problem instead. Especially, even in the case that the overall of A-weighted sound pressure level itself is low, the tonal components of the noise are annoying.

In the standards such as the ISO 7779 [7], ECMA-74 [9] and ANSI S1.13 [10], the judgment methods of the certain prominent discrete tone in information technology devices are presented as Tone-to-Noise Ratio (TNR) and Prominence Ratio (PR). On the other hand, the psychoacoustic approach to detect the tonal feeling has been developed and the metrics such as Tonality [2] has been used for the evaluation of the tonal feeling.

The study on Total Tone-to-Noise Ratio (T-TNR) or Total Prominence Ratio (T-PR) based on the theory of TNR or PR has been proceed as new evaluation indices of sound in which multiple tonal components coexist. The previous study [4] has suggested that these are effective as indices for quantitative evaluation of subjective annoyance. However, it is 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 be attempted to determine threshold levels for subjective annoyance of these indices by using sensory test.
2. Noise characteristics of small fan

2.1 Mechanism of fan noise generation

The noise generated from fan includes the aerodynamic noise that temporal fluctuation of flow is sound source, the mechanical noise that mechanical vibration is sound source, the electromagnetic noise that electromagnetic force fluctuation of motor is sound source and the like. 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.

The rotational noise 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 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.

On the other hand, 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.

2.2 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 \[1\]. The frequencies of tonal components are shown as the following formula:

\[
f_r = i \cdot Z_r \cdot n \text{ [Hz]} \tag{1}
\]

where,
- \( i \): number of frequency components
- \( Z_r \): number of rotor blades
- \( n \): rotational speed [rps]

2.3 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 supports 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 frequencies of tonal components are shown as the following formula:

\[
f_r = \frac{j \cdot Z_r \cdot n}{j \cdot Z_r + k \cdot Z_s} \text{ [Hz]} \tag{2}
\]

where,
- \( j, k \): integer index (\(-2, -1, 0, 1, 2\ldots\))
- \( Z_r, Z_s \): number of rotor blades and spokes
- \( n \): rotational speed [rps]
3. Evaluation methods of tonal components

3.1 Tonality

Tonality, T is widely known as the metrics that indicate the tonal feeling of the sound. This metrics is provided by Terhardt or Aures [2][3]. 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.

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

DIN 45681 “Acoustics - Determination of tonal components of noise and determination of a tone adjustment for the assessment of noise immissions” [11] defines how to determine the tonal component to the noise. However the method of this standard shows only about the excess of level and does not include the psychoacoustic consideration.

In general, the audible threshold or the prominence of a tonal component is decided by the relationships between the tonal component level and the surrounding band noise level which is masking the tonal component. The frequency bandwidth is so called the critical band that is centred at the frequency of the tone. In the standards such as the ISO 7779 [7], ECMA-74 [9] and ANSI S1.13 [10], the judgment methods of the certain prominent discrete tone in information technology devices are presented as the Tone-to-Noise Ratio (TNR) and the Prominence Ratio (PR).

TNR is defined as the decibel value of the ratio of the power of tonal component and other noise component in the critical band. In the ECMA-74, when TNR exceeds by 8 dB at 1 kHz or higher, the tonal component is regarded as the 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 values tends to show bigger or smaller.

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

\[
\Delta L_T = 10 \log_{10} \left( \frac{W_T}{W_n} \right) \text{[dB]} \tag{3}
\]

\[
\Delta L_P = 10 \log_{10} \left[ \frac{W_M}{(W_L + W_U)/2} \right] \text{[dB]} \tag{4}
\]
where,

\[ \Delta L_T : \text{Tone-to-noise ratio [dB] (according to ECMA-74)} \]
\[ W_t : \text{Power of tone [Pa}^2\text{]} \]
\[ W_n : \text{Power of other components in critical band [Pa}^2\text{]} \]
\[ \Delta L_P : \text{Prominence ratio [dB] (according to ECMA-74)} \]
\[ W_M : \text{Power of middle critical band [Pa}^2\text{]} \]
\[ W_L : \text{Power of lower critical band [Pa}^2\text{]} \]
\[ W_U : \text{Power of upper critical band [Pa}^2\text{]} \]

![Figure 2: Schematic view of TNR and PR calculation (Left: TNR, Right: PR) [9]](image)

### 3.3 Total TNR (T-TNR) and Total PR (T-PR)

In fan noise evaluation, it is important to quantify the tonal components for the product quality control, the identification 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 are the indicators for the prominent discrete tone of one tonal component and do not consider relationship between the multiple tonal components.

The new evaluation parameters called Total Tone-to-Noise Ratio (T-TNR) and Total Prominence Ratio (T-PR) have been proceed. The individual levels (TNRs or PRs) are calculated for a plurality of tonal components in the noise based on calculation methods of TNR or PR, and the sum thereof is defined as an evaluation index T-TNR or T-PR. These evaluation parameters are given by the equations.

\[ \langle L_T \rangle = 10 \log_{10} \left( \sum_{i=1}^{n} 10^{\frac{\Delta L_{T_i}}{10}} \right) \text{ [dB]} \]  

\[ \langle L_P \rangle = 10 \log_{10} \left( \sum_{i=1}^{n} 10^{\frac{\Delta L_{P_i}}{10}} \right) \text{ [dB]} \]

where,

\[ \langle L_T \rangle : \text{Total tone-to-noise ratio [dB]} \]
\[ \Delta L_{T_i} : \text{Tone-to-noise ratio for } i\text{-th peak component [dB]} \]
\[ \langle L_P \rangle : \text{Total prominence ratio [dB]} \]
\[ \Delta L_{P_i} : \text{Prominence ratio for } i\text{-th peak component [dB]} \]
3.4 The threshold level for subjective annoyance of T-TNR or T-PR

It is necessary to determine the minimum value, that is, the threshold level, which is felt to be the subjective annoyance of T-TNR and T-PR, as is the case with TNR and PR. The threshold levels for the subjective annoyance of T-TNR and T-PR are newly defined as $\langle L_T \rangle_0$ and $\langle L_P \rangle_0$ in this study.

3.5 About 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) \cite{7}. 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.

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 study, these are also examined.

4. Sensory test

4.1 On test sound

As previously stated, the aerodynamic noise is dominant in the operating state of a normal fan and it can be classified into the rotational noise (tonal component) and the turbulent flow noise (broadband components) from its sound source characteristics. In this study, the synthesized sounds (pseudo fan noise) with white noise as broadband components and sine wave as tonal components are used, because the convenience of creating a test sound is high.

4.2 Method of adjustment

The method of adjustment is a process in which a jury (or an experimenter) freely changes a stimulus to obtain PSE (point of subjective equality) and the like. In this sensory test, it is selected the method that juries adjust the stimulus \cite{6}. The sensory 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 the paired comparison method of the previous study \cite{4}, white noise is simulating broadband components and sine wave is simulating tonal component. The sounds that is synthesized the tonal components (720, 1440, 2880, 5760 Hz) and the white noise are used as the test sounds.

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. The juries are 10 college students who have the normal hearing and are selected at random.
Table 1: Noise source patterns

<table>
<thead>
<tr>
<th>N</th>
<th>Noise source</th>
<th>Series</th>
<th>N</th>
<th>Noise source</th>
<th>Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>White Noise</td>
<td>Ascending</td>
<td>17</td>
<td>White Noise + Sine Wave 2880Hz</td>
<td>Ascending</td>
</tr>
<tr>
<td>2</td>
<td>White Noise</td>
<td>Ascending</td>
<td>18</td>
<td>White Noise + Sine Wave 2880Hz</td>
<td>Descending</td>
</tr>
<tr>
<td>3</td>
<td>Sine Wave 720Hz</td>
<td>Ascending</td>
<td>19</td>
<td>White Noise + Sine Wave 5760Hz</td>
<td>Ascending</td>
</tr>
<tr>
<td>4</td>
<td>Sine Wave 1440Hz</td>
<td>Ascending</td>
<td>20</td>
<td>White Noise + Sine Wave 5760Hz</td>
<td>Ascending</td>
</tr>
<tr>
<td>5</td>
<td>Sine Wave 2880Hz</td>
<td>Ascending</td>
<td>21</td>
<td>White Noise + Sine Waves (720/1440/2880/5760Hz)</td>
<td>Ascending</td>
</tr>
<tr>
<td>6</td>
<td>Sine Wave 1440Hz</td>
<td>Descending</td>
<td>22</td>
<td>White Noise + Sine Waves (720/1440/2880/5760Hz)</td>
<td>Descending</td>
</tr>
<tr>
<td>7</td>
<td>Sine Wave 2880Hz</td>
<td>Descending</td>
<td>23</td>
<td>White Noise + Sine Wave 720Hz</td>
<td>Descending</td>
</tr>
<tr>
<td>8</td>
<td>Sine Wave 2880Hz</td>
<td>Descending</td>
<td>24</td>
<td>White Noise + Sine Wave 720Hz</td>
<td>Ascending</td>
</tr>
<tr>
<td>9</td>
<td>Sine Wave 5760Hz</td>
<td>Ascending</td>
<td>25</td>
<td>White Noise + Sine Wave 1440Hz</td>
<td>Descending</td>
</tr>
<tr>
<td>10</td>
<td>Sine Wave 5760Hz</td>
<td>Descending</td>
<td>26</td>
<td>White Noise + Sine Wave 1440Hz</td>
<td>Ascending</td>
</tr>
<tr>
<td>11</td>
<td>White Noise + Sine Waves (720/1440/2880/5760Hz)</td>
<td>Ascending</td>
<td>27</td>
<td>White Noise + Sine Wave 2880Hz</td>
<td>Descending</td>
</tr>
<tr>
<td>12</td>
<td>White Noise + Sine Waves (720/1440/2880/5760Hz)</td>
<td>Descending</td>
<td>28</td>
<td>White Noise + Sine Wave 2880Hz</td>
<td>Ascending</td>
</tr>
<tr>
<td>13</td>
<td>White Noise + Sine Wave 720Hz</td>
<td>Ascending</td>
<td>29</td>
<td>White Noise + Sine Wave 5760Hz</td>
<td>Ascending</td>
</tr>
<tr>
<td>14</td>
<td>White Noise + Sine Wave 720Hz</td>
<td>Descending</td>
<td>30</td>
<td>White Noise + Sine Wave 5760Hz</td>
<td>Ascending</td>
</tr>
<tr>
<td>15</td>
<td>White Noise + Sine Wave 1440Hz</td>
<td>Ascending</td>
<td>31</td>
<td>White Noise + Sine Waves (720/1440/2880/5760Hz)</td>
<td>Ascending</td>
</tr>
<tr>
<td>16</td>
<td>White Noise + Sine Wave 1440Hz</td>
<td>Descending</td>
<td>32</td>
<td>White Noise + Sine Waves (720/1440/2880/5760Hz)</td>
<td>Ascending</td>
</tr>
</tbody>
</table>

5. Results and discussion

5.1 The threshold level obtained from the sensory test

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

According to Fig. 4, it is found that the threshold levels are higher (the response is dull) than the criterion for the discrete tones under 2 kHz and are lower (the response is high) than the criterion for the discrete tones over 2 kHz. On the other hand, it can also be considered that the permissible range of each individual threshold level 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. 3. It is defined that the threshold levels of annoyance in T-TNR or T-PR can be calculated by the sum of TNR or PR. These levels have not coincided with the sum of TNR or PR of each frequency. It is considered that the total value of TNR or PR of each frequency has not matched the threshold levels 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. Further, the standard deviations of $\langle L_T \rangle_0$ and $\langle L_P \rangle_0$ are almost the same.

Table 2: Threshold levels at each frequency

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>720</td>
<td>21.5</td>
<td>6.9</td>
<td>720</td>
<td>21.6</td>
<td>6.8</td>
</tr>
<tr>
<td>1440</td>
<td>11.5</td>
<td>4.7</td>
<td>1440</td>
<td>11.8</td>
<td>4.5</td>
</tr>
<tr>
<td>2880</td>
<td>5.0</td>
<td>3.2</td>
<td>2880</td>
<td>6.2</td>
<td>2.1</td>
</tr>
<tr>
<td>5760</td>
<td>0.5</td>
<td>2.7</td>
<td>5760</td>
<td>3.4</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Figure 4: Average threshold levels of annoyance in TNR and PR
5.2 Relationship between psychoacoustic metrics and threshold levels

The relations between the threshold levels and each psychoacoustic metrics have been investigated. These threshold levels have low correlation with the overall sound pressure level and the loudness and they have high correlation with the sharpness and the tonality. In other words, it has been confirmed that the tone pitch of a sound strongly influences the subjective annoyance rather than the loudness of a sound. More specifically, the sharpness has a negative correlation and the tonality has a positive correlation. Regarding the sharpness, the result suggests that the threshold levels become lower when the frequency balance of the tonal components included in the noise is shifted to the higher frequency side.

Table 4: Correlation coefficients between psychoacoustic metrics and threshold levels

<table>
<thead>
<tr>
<th></th>
<th>SPL</th>
<th>Loudness</th>
<th>Sharpness</th>
<th>Tonality</th>
</tr>
</thead>
<tbody>
<tr>
<td>( &lt;L_T&gt;_0 )</td>
<td>0.294</td>
<td>0.497</td>
<td>-0.913</td>
<td>0.977</td>
</tr>
<tr>
<td>( &lt;L_P&gt;_0 )</td>
<td>0.321</td>
<td>0.522</td>
<td>-0.909</td>
<td>0.979</td>
</tr>
</tbody>
</table>

Figure 5: Relating the threshold level to the sharpness

Figure 6: Relating the threshold level to the tonality

Furthermore, multiple regression analysis has been performed. The loudness and the sharpness have been selected explanatory variables in multiple regression analysis, and multiple regression equations have been generated.

\[
\langle L_T \rangle_0 = 6.43x - 8.87u + 38.32 \text{ [dB]} \quad (7)
\]

\[
\langle L_P \rangle_0 = 6.57x - 8.26u + 37.18 \text{ [dB]} \quad (8)
\]
6. Summary

In this study, the T-TNR and T-PR are presented as new psychoacoustic metrics for tonal sound, these threshold levels of annoyance have been determined and calculated the correlation coefficients between other psychoacoustic metrics. In addition, the threshold levels of pure tone have been also measured and compared those in the ECMA-74. The following results have been obtained.

1. The threshold levels of subjective annoyance have been determined by the method of adjustment. \( \langle L_T \rangle_0 \) is 17.8 dB, \( \langle L_P \rangle_0 \) is 18.2 dB.
2. The relationships between the threshold levels and psychoacoustic metrics have been obtained. It has been confirmed that the subjective annoyance depends on the tone pitch of a sound. The validity of multiple regression equations will be examined in the future.
3. It is necessary to verify the threshold levels with the actual sound generated from small fans since they are the results of sensory test using synthesized sounds in this study.
4. The method of T-TNR and T-PR might be applied to products having tonal components other than small fans for future task.

REFERENCES