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Comparison of the Sound Quality Characteristics for the Outdoor Unit of the Air-Conditioners according to the Compressors.

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ABSTRACT

As for the criteria to purchase an air conditioner, noise level has emerged as an important issue, equal to design characteristics and performance. The main feature of the noise of the outdoor unit is a complex characteristic noise due to the operation of the fan and compressor. Air-borne noise is usually caused by the vortex separation on the fan blade, and structure-borne noise is caused by compressor or vibration transmission to the chassis and components. Due to the efforts of researchers and designers who have worked on noise reduction, the sound pressure level (SPL) of outdoor units launched on the market is under 50dB (A). While the SPLs of the noises are similar, consumers can feel the noise differently according to the frequency characteristics. Therefore in this study, it was purposed to evaluate sound quality by a comparative analysis of the noise characteristics, and tests were performed on the same outdoor unit only changing the compressors. To analyze the noise characteristics of the outdoor unit of the air-conditioner, sound quality metrics such as Unbiased Annoyance (UA) and Psychoacoustic Annoyance (PA) were applied.

1. INTRODUCTION

Recently, due to the advancement and complexity of an industrial society, every system has been required to maximize its operational efficiency with reliability. Users increasingly demand more noise reduction as they have a lot of interest in the noise from various home appliances. Due to a surge in demand for higher quality products, the air-conditioner is greatly affected by this symptom. As a result, the noise level of the air-conditioner is an important criterion to decide the quality, in addition to the energy efficiency, of the products. In previous research, noise reduction for the indoor unit of air-conditioners had proceeded through the method of transfer path analysis (TPA) and contribution analysis about output noise components by quantifying a more effective solution. But in the case of outdoor units, the research for the structural durability and design of fan-flow was mainly performed, rather than noise reduction. The outdoor noise affects other people. In spite of much effort to research noise reduction, the sound pressure level of most air conditioner outdoor units on the market today is around near 50dB(A) and do not make a distinction between air-conditioners makers. Therefore, emotional indexes able to evaluate the noise characteristics are needed, not the sound pressure level alone but the definition of sound quality. In the past, most engineers only dealt with noise reduction from the product, but in recent years, to meet the needs of consumers, they have been studying to provide comfort and good sound to hear. In listening to the sound, people tend to be rather emotional and subjective. Indexes which can express people’s feelings that change along with time and place by subjective measures are required. The outdoor noise of air-conditioners can be divided into compressor radiated sound delivered according to the structure, and fluid noise caused by the air circulation in fan operation. In compressor operation, low-frequency noise appears as a single noise frequency tone and high frequency noise radiates to the characterized direction. The compressor design parameters and control methods may vary depending on the frequency characteristics and low noise is identified as a key design target for compressors manufacturers. Therefore, in this study each rotary compressor made by different manufacturers was mounted on the same outdoor unit, to determine the noise level. Sensitivity index equivalent to the difference in value that occurs in sound quality is presented.
2. Zwicker’s parameters

There are two objectives of this study of sound quality: the first one is for the consumer to use the product more comfortably when radiated noise is the sound of its own. Another is to create a new evaluation method of sound quality when the conventional methods cannot clearly represent the physical characteristics of noise in a certain situation. Therefore, this section is to describe the people evaluation of sound quality factors and how to assess them. Subjectively received by the human ear, information from the existing physical elements has very different characteristics. Having the same values of the subjective sound pressure level which noises are caused by a significant difference, representing the human auditory organ of hearing, the study of the mechanism could proceed. Physical organization and hearing ability is different, but the fact is indicated by the following. These acoustic elements, as well as in the time domain, plays an important role in the frequency domain. Thus, in terms of sound analysis and sound source identification, sound elements associated with the psychology of hearing are required in the study from Zwicker, such as loudness, sharpness, fluctuation strength, rough, etc rather than the sound pressure level.

2.1 Loudness (N)

DIN 45631 is the standard specifying a graphic procedure to calculate specific loudness, loudness and loudness level for stationary signals from third octave levels. Moreover, the Artemis program of the HEAD acoustic software is specified for simulating this procedure. This program is under ISO 532B standard. The HEAD algorithm builds excitation levels of critical band width, while the ISO method uses third octave levels, which are combined at low frequencies, since the third octaves are much narrower there than the critical band.

The lowest nine third octaves with middle frequencies from 40 to 250Hz are combined in three critical band levels. Therefore they are equalized according to a given table and then their intensities are added. The first critical band comprises third octaves with middle frequencies from 40 to 80Hz. Third octaves from 100 to 160Hz form the second critical band and the two third octaves with the middle frequencies 200 and 250Hz the third critical band. The other third octaves with middle frequencies from 315 to 1600Hz are taken as they are.

In this way 20 levels are obtained. These can be entered into a diagram using the graphic method. They appear there as main loudness. The masking curves to higher frequencies are drawn corresponding to given curves in the diagram. The area below the constructed curve indicates the loudness.

2.2 Sharpness (S)

There is no standardization for the calculation of sharpness. All algorithms in the sound quality analyzer use the same equation of W. Aures to determine sharpness from specific loudness:

\[
S = 0.11 \int_0^{24 \text{ Bark}} N'(z)g(z)zdz
\]

with

\[
g(z) = e^{0.171z}
\]

This term causes the higher weighting of high-frequency components, which produce the sensation of sharpness. Zwicker uses the overall loudness instead of the logarithmic term as denominator in his equation. In the above equation it is taken into account that the sensation of sharpness increases slightly at constant distribution of specific loudness but where loudness is increasing slightly.

2.3 Roughness

There is also no standardization for roughness. A preliminary implemented algorithm in the Artemis program calculated partial roughness from degrees of modulations of band signals and adds them to get a total roughness value. Firstly the signal is divided into 24 sub-bands by phase linear filters, which have a width of 2 Bark and overlap neighboring bands by 1 Bark. The bandwidth has to be wider than those used for loudness calculations in order to detect sufficiently large modulation frequencies inside one sub-bands. The overlap is necessary to prevent
signals at the limits of the sub-bands resulting in different total values than in the middle. The dependency of roughness on signal level is taken into account by doubling the partial roughness for an increase in the sub-band signal power of 20dB. Total roughness is calculated as the sum of all partial roughness as below.

$$\int_0^{24\text{Bark}} 0.0003f_{\text{mod}}(z)\Delta L(z)\Delta z$$ (2)

2.4 Fluctuation strength

The calculation of fluctuation strength takes place in a similar way to the calculation of roughness. But now the signal is divided in 1 Bark wide, non-overlapping bands. This is because at the low modulation frequencies which are to be detected here, the side lines of a tone modulated in amplitude lie very close beside the main line. The envelopes of the band signals are calculated and filtered with a bandpass with a center frequency of 4Hz. The quotient of the filtered and the unfiltered envelopes is taken as a measure for the partial fluctuation strengths. An increment of the sound pressure level by 20dB causes the fluctuation strength to rise by a factor of two, as occurs with roughness. The sum of the partial fluctuation strengths gives the fluctuation strength as below.

$$\sum_0^{24\text{Bark}} \frac{0.032\Delta L\Delta z}{f_{\text{mod}}(z)^2 + 4/f_{\text{mod}}(z)}$$ (3)

with

$$\Delta L = 20\log \left( \frac{N'(1)}{N'(99)} \right)$$

2.5 Annoyance

Another approach, that allows us to neglect the noise sensitivity problem, was proposed for the first time by Zwicker and was called unbiased annoyance (UB). It means that “noise annoyance does not depend on the relationship of the listener to the sources of the noise”. In the original model published in the book, the value of UA is calculated from $N_{10}$ loudness (the loudness value reached or exceeded in 10% of the measurement time), averaged sharpness, and fluctuation strength, together with a day-night correction. In this formula, noise annoyance is defined as a multicomponent concept depending on more than one acoustical variable. In literature there are more similar multicomponent approaches to noise annoyance.

In the second (Zwicker and Fastl, 1999) and third edition (Fastl and Zwicker, 2007) of their book, a corrected formula for the UA, now called psychoacoustic annoyance (PA) is published. Compared to the UA, in the new formula $N_{10}$ values are changed to $N_S$ and roughness is added as a component of psychoacoustic annoyance. How to calculate UA and PA is presented as follows.

$$UA = d(N_{10})^{1.3} \left[ 1 + 0.25(S - 1)\log(N_{10} + 10) + 0.3\left( F \frac{1 + N_{10}}{N_{10} + 0.3} \right) \right]$$ (4)

where $N_{10}$ stands for percentile loudness in sone, $S$ for sharpness, $F$ for fluctuation strength, and $d$ for day/night factor.

$$PA = N_S \left( 1 + \sqrt{\omega_S^2 + \omega_{FR}^2} \right)$$ (5)

with $N_S$ percentile loudness in sone, $\omega_S$ describing the effect of sharpness $S$,

$$\omega_S = (S - 1.75)0.25\log(N_S + 10) \quad \text{for} \quad S > 1.75 \text{acum}$$ (6)

$\omega_{FR}$ describing the influence of fluctuation strength $F$ and roughness $R$.
\[
\omega_{FR} = \frac{2.18}{(N_s)^{0.4}} (0.4F + 0.6R)
\]

(7)

### 3. Experiment and Result

#### 3.1 Experimental set up

The outdoor unit of a room air conditioner was chosen to illustrate the practical application of the sound quality evaluation approach for noise characteristic analysis. An outdoor unit of an air conditioner is mainly composed of a compressor, a condenser, a heat exchanger, a fan, a fan motor and a chassis. The compressor is mounted at three points on the base panel of the chassis and the suction/discharge pipes from the compressor pass through the side panel of the chassis to the indoor unit. It is known that the main sources of the noise from the outdoor unit are the structure-borne noise radiated from the chassis structure and airflow noise from the fan. The fan, with an important role in providing heat exchanger and condenser with the airflow, produces the noise mostly at the blade passing frequency and its harmonics, which are relatively in the low frequency range. Vibration generated in the compressor is transmitted to the chassis structure through several paths and then gives rise to the noise radiation. The characteristic of the radiated sound is distinguishable from the compressor made by other companies.

The noise data for sound quality evaluation were recorded at the rear position of the outdoor unit based on KS C 9306 using a 1/2 inch microphone in hemi-anechoic rooms. The measurement systems are shown in Table 1. Temperature condition was 20°C (indoor) and 7°C (outdoor) for heating operation. Operational loads on air conditioner compressors may vary significantly depending on the ambient temperature, humidity, operating time, and so on and, therefore, lead to inconsistent noise signals making the steady state analysis inadequate. The system was exchanged only compressors with the same chassis for air-conditioner. So, the noise data was obtained through a decrease of the rotational speed of compressor per 3 revolution per second (rps).

#### 3.2 Results and discussion

An objective analysis of all data was performed with the help of the HEAD acoustics software called Artemis Analyzer. The A-weighted sound pressure level (SPL), loudness, sharpness, fluctuation strength and roughness were calculated. For each mentioned sound characteristic, the averaged as well as the percentile (5%, 10%) loudness values were calculated. Finally unbiased annoyance (UA) and psychoacoustic annoyance (PA) were calculated through the equation (4) and (5). The results of all calculations according to the installed compressors are presented in Figure 1 and Figure 2. The installed compressors had some of the same specifications. The compressor type was a hermetic motor compressor and its application was for cooling and heating applications with BLDC inverter system. Also, the compressor type was rotary. But the dimension of the cylinder and number of motor poles were different. “A” compressor had six poles, while “B” compressor had four poles.

Figure 1 shows the results of SPL, UA and PA according to the installed A compressor. And figure 2 shows the results of the installed B compressor. The tendency of UA was similar with SPL. It showed that N10 was a more effective factor than N5 by presenting SPL value. In the case of G compressor, according to the increasing operated speed, the UA value increased much higher than B compressor. In other words, both of their differences of SPL value were shown to be about 5dB from minimum to maximum SPL. The difference of B compressor’s UA was shown as fewer than 10, but the UA value of B compressor was over 10.

B compressor internal structure had a resonance frequency of around 244Hz. So the maximum value of sound metrics (SPL, UA, PA) was shown at 59rps such as figure 2. The solution to prevent the resonance phenomenon was to avoid its rotating speed.

### Table 1: Specification of measurement equipment

<table>
<thead>
<tr>
<th>Measurement devices</th>
<th>Maker/Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT analyzer</td>
<td>LMS Test lab.</td>
</tr>
<tr>
<td>Microphone</td>
<td>GRAS MICROPHONE TYPE 46AE</td>
</tr>
</tbody>
</table>
Figure 1: Comparison of sound quality values according to installed “A compressor”

Figure 2: Comparison of sound quality values according to installed “B compressor”

Table 2 shows the annoyance results by the similar SPL between A and B compressor. The value range of the overall sound pressure level was described around one decibel place, but the values of UA and PA were shown over one value. This meant it was difficult to distinguish with just the SPL factor, but it could be explained in more detail for sound quality analysis using UA and PA factors.

Figure 3 shows an SPL of 1/3 octave band frequency at the point of noise data of table 2. The frequency characteristics of A compressor presented a much higher level than B compressor’s, around 2kHz–6kHz range. It
meant that it had a greater effect on a human’s hearing sensitivities. Its ingredient could be guessed to be generated by the electronic noise of the motor signal.

Table 3 shows the comparison results of the objective sound quality analysis. It means that the most important factor to decide the values of UA and PA was sharpness. In the case of fluctuation strength it was concerned with only PA as shown in equation (7). So fluctuation strength was not an important factor.

<table>
<thead>
<tr>
<th>Table 2: The comparison of annoyance values for similar SPL point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound Pressure Level (dBA)</td>
</tr>
<tr>
<td>Unbiased Annoyance</td>
</tr>
<tr>
<td>Psychoacoustic Annoyance</td>
</tr>
</tbody>
</table>

Figure 3: Comparison of the third octave band at similar SPL

<table>
<thead>
<tr>
<th>Table 3: The comparison of objective sound quality metrics for similar SPL point</th>
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</thead>
<tbody>
<tr>
<td>Percentile difference</td>
</tr>
<tr>
<td>Loudness (sone)</td>
</tr>
<tr>
<td>( N_5 )</td>
</tr>
<tr>
<td>( N_{10} )</td>
</tr>
<tr>
<td>Sharpness (acum)</td>
</tr>
<tr>
<td>Roughness (asper)</td>
</tr>
<tr>
<td>Fluctuation Strength (vacil)</td>
</tr>
</tbody>
</table>
6. CONCLUSIONS

This study shows that the outdoor noise of the air-conditioner received in the rear position can influence annoyance judgments. However, the phenomenon is not very sensitive to subtle changes in the spectrum pattern and the effect becomes significant only for a broad difference in the spectrum characteristic. This study found that the sharpness value was better correlated with the annoyance ratings.

REFERENCES

KS C 9306, Air-conditioners, 2007