THE RELATIONSHIP BETWEEN ARITHMETIC AVERAGE OF SOUND PRESSURE LEVELS IN 1 OR 1/3 OCTAVE BANDS AND ZWICKER'S LOUDNESS

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ABSTRACT

It has been found that the arithmetic average of the sound pressure levels in octave bands is a good estimator of loudness for various kinds of general noises in living environment, being in high correlation with the Zwicker's loudness level specified in ISO 532B (by H. Tachibana et al.). In order to investigate the reason of this fact, the relationship between these two indicators is examined by numerical study for a variety of spectra. Further, the frequency bands to be assessed in the arithmetic average are investigated based on subjective experiments using test sounds with a variety of spectrum characteristics.

INTRODUCTION

In the process of psycho-acoustical experiments on the loudness of sounds transmitted through building walls and general environmental noises, it has been found that the arithmetic average of sound pressure levels in octave bands from 63 Hz or 125 Hz to 4k Hz is highly correlated with loudness sensation and therefore in highly correlation with Zwicker's loudness level [1-4].
For this index, however, how to choose the frequency bands is an important point because the value changes according to the choice of the frequency range to be assessed. In this study, this point is examined by numerical study and subjective hearing test using artificial noises with a variety of spectrum characteristics. From these results, the frequency range which should be included in the estimation of loudness by arithmetic average of sound pressure levels in octave or 1/3 octave bands is proposed.

DEFINITION OF THE ARITHMETIC AVERAGE

The arithmetic average of sound pressure levels in $1/n$ octave bands is expressed as follows.

$$L_{m,1/n}(f_1 - f_2) = \sum_i L_i / N \qquad (1)$$

Here, f_1 and f_2 are the center frequencies of the lowest and highest bands, respectively, L_i is the sound pressure level in the i-th band, and N is the number of the $1/n$ octave bands under consideration.

THE FREQUENCY BANDS TO BE ASSESSED IN THE ARITHMETIC AVERAGE

As the first step in this study, a very simple investigation is made by assuming artificial sounds with spectrum characteristics of monotonous (straight) slopes from -12 to +12 dB/octave band as shown in Fig.1. In this figure, they are adjusted so that their loudness levels assessed by ISO 532 B (Zwicker's loudness level : LL(Z)) are the same (70 phons). Their spectrum slopes are -12, -9, -6, -3, 0 +3, +6, +9 and +12 dB/octave band.

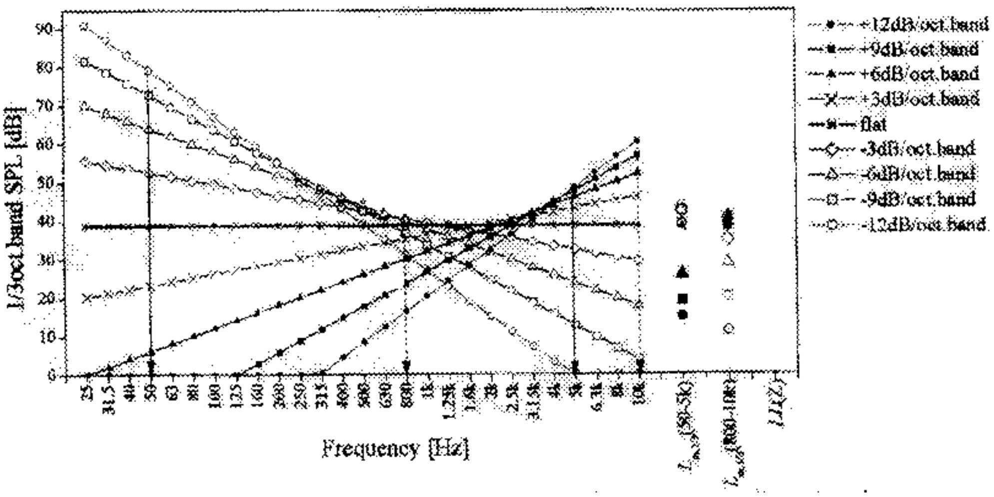

Fig.1 Straight spectrum characteristics with the same loudness level

In this figure, it can be seen that the arithmetic average values for the sounds with spectrum slopes from -12 to 0 dB/octave band are converged at around 42dB when they are assessed by $L_{m,1/3}$(50-5k), and those for the sounds with slopes from +3 to +12 dB/octave band are converged at around 40dB when assessed by $L_{m,1/3}$(800-10k). In each group, a "compensatory" relationship is seen in spectrum components. However, it is also seen that all sounds assumed here can not be assessed by the same indicator $L_{m,1/3}(f_1\text{-}f_2)$.

Here, when considering general environmental noises, their spectrum characteristics are in the form of decreasing slope in higher frequencies (the spectrum characteristics from -12 to 0 dB/octave band, in this case). For this kind of noises, it is suggested that $L_{m,1/3}$(50-5k) is a proper index to approximate the loudness.

NUMERICAL STUDY

The spectrum characteristics assumed in the previous study are much simplified ones, but general environmental noises have much more complicated spectrum characteristics. Therefore, by assuming sounds with various kinds of spectrum characteristics varied systematically, the following numerical study and subjective hearing test were performed to examine the validity of the arithmetic average of sound pressure levels.

Spectra Under Investigation

Fig.2 shows 45 artificially varied spectrum characteristics assumed for the examination. Here, they are classified as follows.

G1 : spectrum characteristics with -12 dB/octave band slope,

G2 : those with -9 dB/octave band slope and flat,
G3 : those with +3 and +6 dB/octave band slope, and
G4 : those with +12 dB/octave band slope.
Among them, 32 samples (lines without symbol) were varied in relative sound pressure level and 77 sounds in total were assumed for the examinations mentioned below.

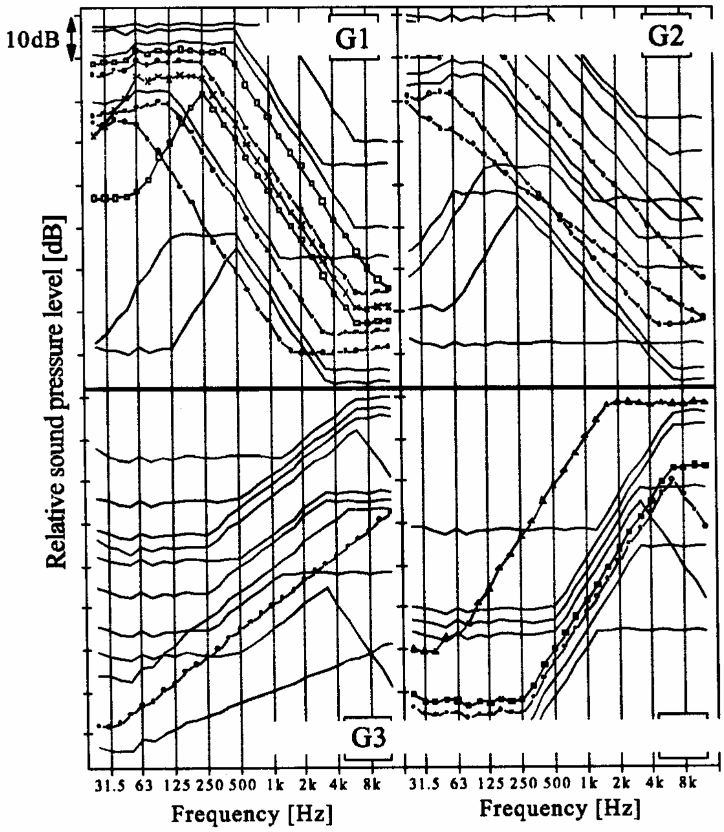

Fig.2 45 kinds of spectrum characteristics under investigation

Results
The sounds assumed in the way as mentioned above were assessed by the three kinds of indices; LL(Z), $L_{m,1/3}$(50-5k) and L_A (A-weighted sound pressure level). Fig.3 shows the correspondence between LL(Z) and $L_{m,1/3}$(50-5k) and that between LL(Z) and L_A. In the figure, R_A, $R_{1\text{-}2}$, $R_{3\text{-}4}$ indicates the correlation coefficient for all sounds, for the groups G1 and G2, for the groups G3 and G4, respectively.
When including all sounds, the correspondence LL(Z) vs. $L_{m,1/3}$(50-5k) is very poor compared with that LL(Z) vs. L_A. However, when limiting the sounds to the groups G1 and G2, the correlation between LL(Z) and $L_{m,1/3}$(50-5k) is considerably high ($R_{1\text{-}2}$ = 0.983), which is almost the same as the correlation between LL(Z) and L_A ($R_{1\text{-}2}$ =0.981). This result indicates that the loudness of general environmental noises with spectrum characteristics of decreasing slope in higher frequencies or flat like the groups G1 and G2 can be assessed by $L_{m,1/3}$(50-5k). In this case, the relationship between LL(Z) and $L_{m,1/3}$(50-5k) can be expressed as follows.

$$LL(\mathrm{Z}) = 0.914 \cdot L_{m,1/3}(50-5\mathrm{k}) + 32.8 \qquad (2)$$

$$LL(\mathrm{Z}) \approx L_{m,1/3}(50-5\mathrm{k}) + 28 \qquad (3)$$

The solid line in Fig.3 corresponds to equation (2), and the broken line corresponds to equation (3).

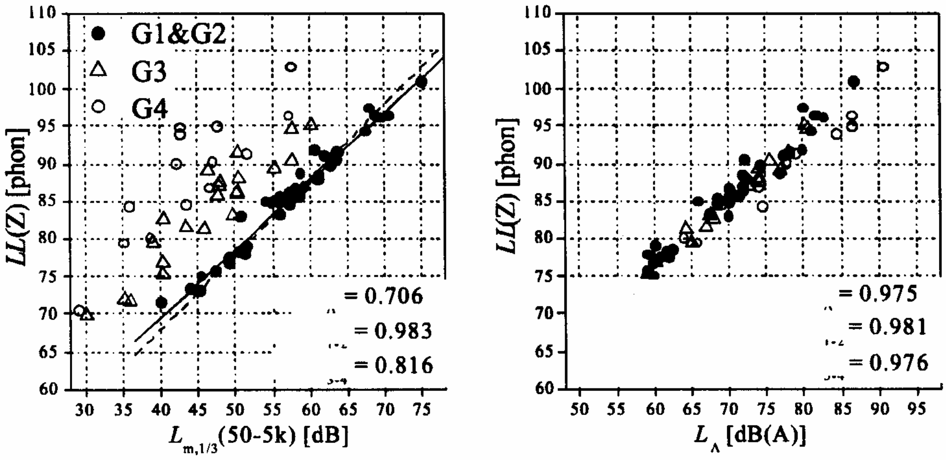

Fig.3 Correlations of LL(Z) vs. $L_{m,1/3}$(50-5k) and LL(Z) vs. L_A

SUBJECTIVE EXPERIMENT

Following the numerical examination, a psycho-acoustical study on loudness was performed as follows.

Experimental Set Up

The experiment was performed in an anechoic room as shown in Fig.4. The 77 test sounds were synthesized in a computer and recorded onto a digital tape recorder, and they were reproduced from a loudspeaker for middle-high frequency range and a woofer for low frequency range. The subject sat at a point 2 m apart from the loudspeaker system. The spectrum characteristics of loudspeaker system including the transfer function from it to the listening position was compensated by an equalizer so that the whole reproduction system was a flat response over the frequency range from 25Hz to 12.5kHz in 1/3 octave bands.

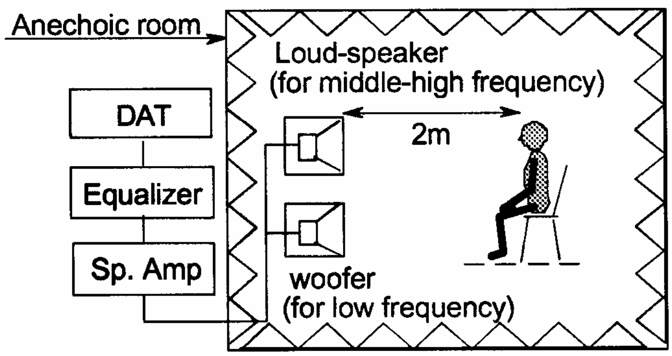

Fig.4 Experimental set up

Test Procedure

The loudness test was performed by the magnitude estimation (ME) method. Subjects judged the representative number of the loudness for the test sounds. Each duration time of the test sound was 5 seconds. To confirm the repeatability of the responses by subjects, the test was repeated three times for each subject by changing the order of the test sounds. Nine graduate and under graduate students (2 male and 7 female) with normal hearing ability participated in this experiment.

Experimental Results

For all of the experimental results by all subjects, geometric mean values were calculated and the results were arranged by the three indices, $LL(Z)$, $L_{m,1/3}(50\text{-}5k)$ and L_A as shown in Fig.5. In this figure, the followings are seen:

When including all test sounds (G1 to G4), the convergence of the experimental results arranged by $LL(Z)$ is the best and that arranged by L_A is the second, whereas the plots are much scattered in the results arranged by $L_{m,1/3}(50\text{-}5k)$. However, when limiting the sounds to the groups G1 and G2, the plots (black circles) are much converged ($R_{1\text{-}2}$=0.931).

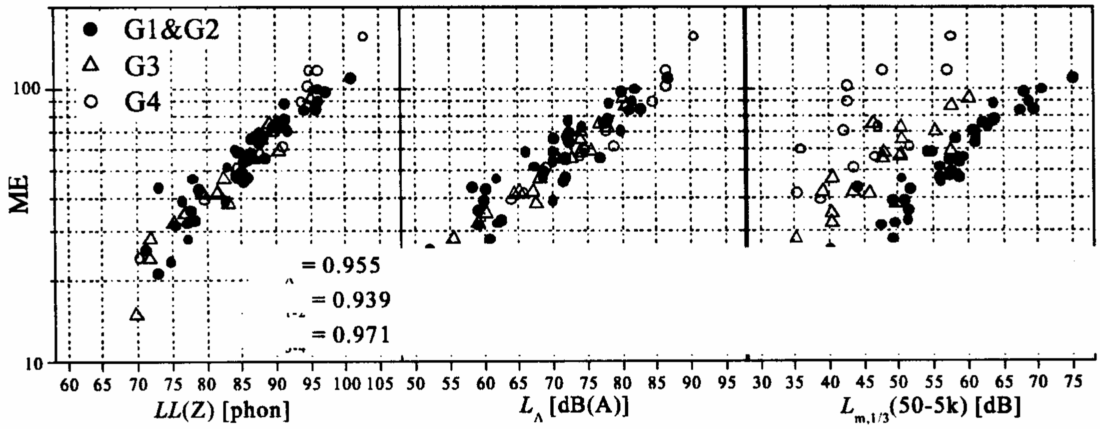

Fig.5 Experimental results arranged by $LL(Z)$, L_A and $L_{m,1/3}(50\text{-}5k)$

In the studies mentioned above, arithmetic average in 1/3 octave bands has been examined, whereas octave band analysis is also often performed in practical noise measurements. Here, the relationship between $L_{m,1/3}(50\text{-}5k)$ and $L_{m,1/1}(63\text{-}4k)$ which cover the same frequency range was examined for the 77 sounds used in this study. In the result shown in Fig.6, it can be seen that there exist a very high correlation between them and it can be expressed as follows.

$$L_{m,1/1}(63-4k) = L_{m,1/3}(50-5k) + 4.8 \qquad (4)$$

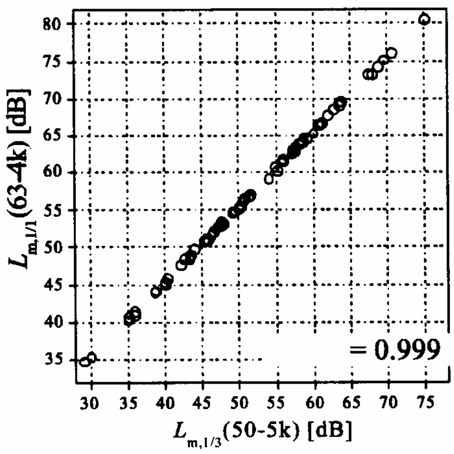

Fig.6 The correspondence between $L_{m,1/3}(50\text{-}5k)$ and $L_{m,1/1}(63\text{-}4k)$

CONCLUSIONS

The applicability of the arithmetic average of sound pressure levels in octave or 1/3 octave bands has been examined by numerical study and psycho-acoustical experiment by assuming a variety of spectrum characteristics.

In the numerical study, the frequency bands to be assessed in the calculation of the arithmetic average was examined and it has been found that the value for the 1/3 octave bands from 50 Hz to 5k Hz, $L_{m,1/3}$(50-5k), is highly correlated with LL(Z) for the sounds with dominant spectrum components in low frequencies including almost flat spectrum characteristic.
Next, in the psycho-acoustical experiment on loudness, it has been found that $L_{m,1/3}$(50-5k) is a good estimator of loudness when assessing the sounds as mentioned above.
From the additional examination, it has been confirmed that $L_{m,1/3}$(50-5k) and $L_{m,1/1}$(63-4k) are in remarkably high correlation.
The problem why such a simple indicator as arithmetic mean value of sound pressure levels in octave or 1/3 octave bands is a good indicator for loudness and therefore highly correlated with LL(Z) has not yet been well explained [5,6], but this fact has been again confirmed phenomenally in this paper. As a result, it can be concluded that $L_{m,1/3}$(50-5k) or $L_{m,1/1}$(63-4k) is a good estimator for the loudness assessment of general environmental sounds.

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