ACOUSTICAL LETTER

Audibility evaluation of triangle-wave tones presented against domestic sounds: Comparison with the audibility of pure tones

Kenji Kurakata* and Tazu Mizunami

National Institute of Advanced Industrial Science and Technology (AIST), AIST Tsukuba Central 6, 1–1–1 Higashi, Tsukuba, 305–8566 Japan

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1. Introduction

In an earlier study [1], the authors investigated the audibility of pure tones presented with a variety of domestic sounds in order to design auditory signals of consumer products. Using the results, they determined a range of sound levels, as a function of tone frequency, at which the tone was detectable and comfortably loud, under noisy conditions, for product users including older people with age-related hearing loss.

However, many of the auditory signals emitted from a piezo sounder are not a pure tone but a complex tone consisting of several frequency components. The authors noted that, although the number of salient components was not large and their levels were lower than that of the main component, they might have some effect on the detectability and loudness of the tone.

In this study, we examined the effect of multiplicity of frequency components on the audibility of tone presented against interfering noise. The measurement method was essentially identical to that of the previous study, but triangle-wave tones were used instead as a typical example of complex tones. The results of these two studies are mutually compared and their implication in auditory signal design is discussed.

2. Measurement method

The measurement method is summarized below. Further details are described in [1].

Stimuli Background noises were typical sounds generated by the following electric appliances or by a person doing housework, which were adopted from a sound library [2]: (1) washing dishes at a sink and (2) a ventilation fan in the kitchen, (3) a washing machine, (4) a hair dryer, (5) running water from a shower in the bathroom, (6) a television set, and (7) a vacuum cleaner in the living room.

The target tone consisted of a triangle-wave tone that had only odd harmonics and the n-th harmonic had amplitude at the ratio of $1/n^2$ to the fundamental. The tone was repeated three times with a 1 s silent interval (Fig. 1). The duration of each tone was 1 s with a rise/fall time of 10 ms. The tone frequency was 0.25, 0.5, 1, or 2 kHz. The 4 kHz tones used in the previous study were not employed because the frequencies of their harmonics were too high for older listeners' ears and, therefore, no auditory effect of the harmonics could be expected. The sound pressure level of fundamental frequency was adjusted to five different values from -10 to 30 dB in 10 dB steps, relative to the one-third-octave-band level of each background noise at the same center frequency as the fundamental frequency of the target tone.

For the dish-washing noise, combinations with pure tone targets were also made, as was done in the previous study, so that the equivalency of listeners' ratings in both studies could be examined. Consequently, the number of stimulus conditions amounted to 160 in total (triangle-wave tones, four frequencies $\times$ five levels $\times$ seven backgrounds; pure tones, four frequencies $\times$ five levels $\times$ one background).

The background noise and the target tones were reproduced by a personal computer. They were amplified using a power amplifier and presented to the listener through a loudspeaker (NS-10MC; Yamaha Corp.) in a soundproof room. The listener's chair was set at a distance of 2.5 m from the loudspeaker. The frequency characteristic of the sound reproduction system was corrected to be substantially flat at the listener's position using an equalizer. The A-weighted continuous equivalent sound pressure level, L_{Aeq}, of each background noise was adjusted as designated in the library to reproduce its original level at recording. The L_{Aeq} of a TV program, which is variable, was set to be 50 dB.

Procedure The stimulus sounds were presented to the listener in random order. After each presentation, the listener rated the audibility of the target tone against the background noise on a five-point scale and replied orally. The scale was 5. "too loud"; 4. "loud"; 3. "audible"; 2. "barely audible"; and 1. "not audible at all." Every listener made one judgment for each stimulus. When the listener was uncertain about the judgment, the stimulus sound was presented again on request.

Listeners Young listeners were university students and older listeners were those introduced by a local employment agency. Before participating in the experiment, all the listeners performed pure-tone audiometry and tympanometry, and completed a questionnaire concerning hearing difficulties to confirm that they had normal hearing for their age. As a consequence of the screening, the young listener group consisted of 15 males and 13 females aged from 18 to 25 years (median, 21) and the older listener group had 12 males and 14 females aged from 60 to 73 years (median, 65).

*e-mail: kurakata-k@aist.go.jp

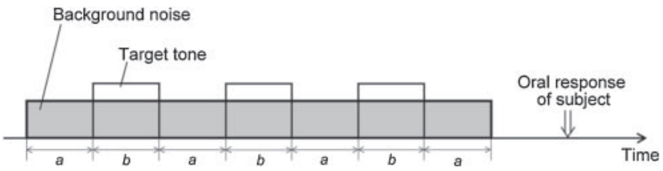

Fig. 1 Schematic illustration of stimulus presentation: $a = b = 1$ s.

3. Results and discussion

The ratings of listeners were analyzed in the same way as was done in the previous study [1]. That is, the psychometric function that relates the five tone levels to the listeners' ratings for each combination of target tone and background noise was obtained for the two age groups separately. First, the 90th-percentile rating of the listeners was calculated for each of 160 stimulus sounds. The 90th-percentile was chosen to embrace 90% of the ratings of listeners, leaving out 10% of those with poor hearing. Second, assuming linearity of the five-point scale, a sigmoidal curve was fitted to the psychometric function R, which is expressed as $R = 5/[1 + e^{-(L-\alpha)/\beta}] + 0.5$, where L is the sound pressure level of the target pure tone in decibels, and α and β are parameters that determine the form of the curve. Finally, L values that corresponded to $R = 2$ "barely audible" and $R = 4$ "loud" were calculated using the inverse function of the above equation.

Figure 2 presents $R = 2$ and $R = 4$ values of triangle-wave tones expressed as the signal-to-noise ratio (SNR) of the overall A-weighted sound pressure level and the SNR in the one-third-octave band that embraces the fundamental frequency of tones, respectively. Each mark indicates the median of L values under seven background noise conditions with an interquartile range.

The ratings obtained in the previous study using pure tone targets are also shown for comparison; they were recalculated using the ratings that had been obtained for the seven noise conditions employed in the present study. The listeners in those two studies were regarded as samples from an identical population and their ratings can be compared mutually, according to the results of the four-way analysis of variance (listener group, in the previous study or the present study × age group × tone frequency × tone level) applied to the ratings of individual listeners for pure tones and triangle-wave tones combined with dish-washing noise; the main effect of the listener group was not statistically significant [$F(1{,}130) = 3.07, p > 0.05$].

Both panels in Fig. 2 indicate that the ratings in the present study were generally lower than those in the previous study. Although the difference varied depending on tone frequencies and listener groups from around zero to 10 dB or more, it amounted to a SNR(A) of 2.5 dB and a $SNR_{1/3}$ of 5 dB on average. This suggests that triangle-wave tones are audible and loud enough at a lower level in the background than pure tones are. The higher frequency components, which were absent in pure tones, increased the loudness of the triangle-wave tones and made the signal more distinct among the noise.

In the previous study, the authors proposed a sound level range of auditory signals suitable for consumer products. The range is applicable to pure-tone-like auditory signals or signals with some minor frequency components other than the fundamental one. However, when a triangle-wave tone or other tones with strong multiple components are used for signaling, their level range may be shifted down by 2.5 dB in SNR(A) and 5 dB in $SNR_{1/3}$. For example, the sound level range suitable for a 2,000 Hz pure-tone-like signal was 5–30 dB when one-third-octave-band level analysis was used. This range could be changed to 0–25 dB for a triangle-wave tone with the same fundamental frequency.

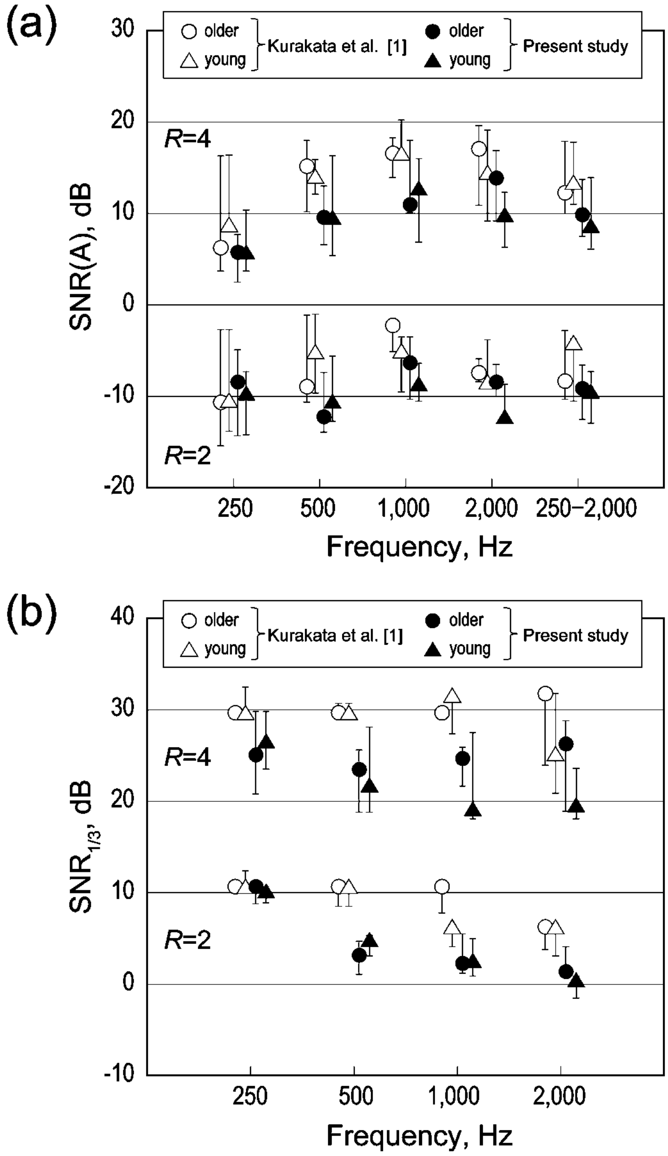

Fig. 2 Median audibility ratings of target tones, pure tones in [1], and triangle-wave tones in the present study. The signal-to-noise ratio (SNR) was measured in terms of (a) A-weighted sound pressure level and (b) the level in the 1/3 octave band of fundamental frequency of target tone. Error bars represent interquartile ranges of ratings for seven types of background noise. The 250–2,000 values in panel (a) are medians of the average ratings for the signal frequencies from 250 to 2,000 Hz. See text for the calculation of R.

4. Concluding remarks

A method for determining the sound pressure level of auditory signals for consumer products, which was based on the authors' study [1], has been established as an ISO standard [3]. The results of the present study revealed that the level of auditory signals could be made lower than that described in the standard. However, it should be noted that complex tones with many strong harmonics are not desirable for auditory signals of everyday products in the home because, as the number of strong higher frequency components is increased, the perceptual quality is degraded. The advantage of auditory signals with moderate harmonics that have often been used must be less than 5 dB on average; the international standard also provides a fairly good estimate of suitable sound level ranges for those auditory signals.

References

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