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THE LOUDNESS OF "COMPLEX NOISE" IN RELATION TO THE FACTORS EXTRACTED FROM THE AUTO-CORRELATION FUNCTION

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The loudness of complex signals, which include bandpass noises with different center frequencies (complex noise), is examined while changing the effective duration of the autocorrelation function (τ_e) based on a model of the human auditory–brain system for subjective response to a sound field. The center frequencies of each component of the complex noises were 2000 and 3000 Hz so that the perceived pitch was centered on 1000 Hz. The bandwidth of each component was changed by using a 2068 dB/octave sharp filter to control the τ_e of the source signal. The scale values for the loudness of the complex noises were obtained using a paired-comparison method. The results showed that the loudness increases with the τ_e of the source signal similar to that of the single-noise component centered on 1000 Hz. The loudness of complex noises having equal sound pressure levels is not constant within the critical band, 160 Hz.

1. INTRODUCTION

Previous studies on the relationship between the loudness and bandwidth of noise have concluded that the loudness of noise remains constant as the bandwidth of the noise increases until the bandwidth reaches the "critical band" then loudness increases with the bandwidth under the same sound pressure level conditions [1–4]. The spectral characteristics of the filters used in those studies were not specified, except by Greenwood [3]. Mathews and Pfafflin suggested that the loudness of bandpass noises may differ between that using an actual filter and that using an ideal (rectangular shape) filter [5].

An actual filter passes not only frequencies within the passband defined by the -3 dB attenuation at the low and high cut-off frequencies, but also at frequencies outside the passband. The outside bandwidth response of the filter affects the repetitive feature of the signal, represented by the auto-correlation function (ACF) processed in the human auditory–brain system [6, 7]. To approximate a specification for an ideal filter a sharp roll-off filter is required. Due to the sharpening effects that exist in the auditory system [8], a roll-off of more than 1000 dB/octave is required. It has been shown that the loudness of a sharply (1080 dB/octave) filtered noise with a 1000 Hz center frequency increases as the effective duration of the normalized ACF (τ_e) increases, even if the bandwidth of the signal is within the critical band [9]. A similar tendency was observed in that as the subsequent reverberation time (T_{sub}) of a sound field increases, the τ_e also increases [10]. In addition to the τ_e, the fine structure of the ACF represented by the delay time and the amplitude of the first peak of the ACF, τ_1 and ϕ_1, also affects the subjective attributes. For example, the phenomenon of the missing fundamental is well described by the τ_1 [6, 11]. The pitch of

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"complex noise" which consists of the bandpass noises whose center frequencies are the harmonics of the fundamental frequency is also perceived as being same as that of the fundamental frequency, and the strength of the pitch is correlated with the ϕ_1 [6].

The present study examines the loudness of complex noises. The complex noises consisted of the bandpass noises whose center frequencies were the harmonics of the fundamental frequency of 1000 Hz so that the perceived pitch was centered on 1000 Hz. The result was compared with those for the bandpass noises whose center frequencies are 1000 and

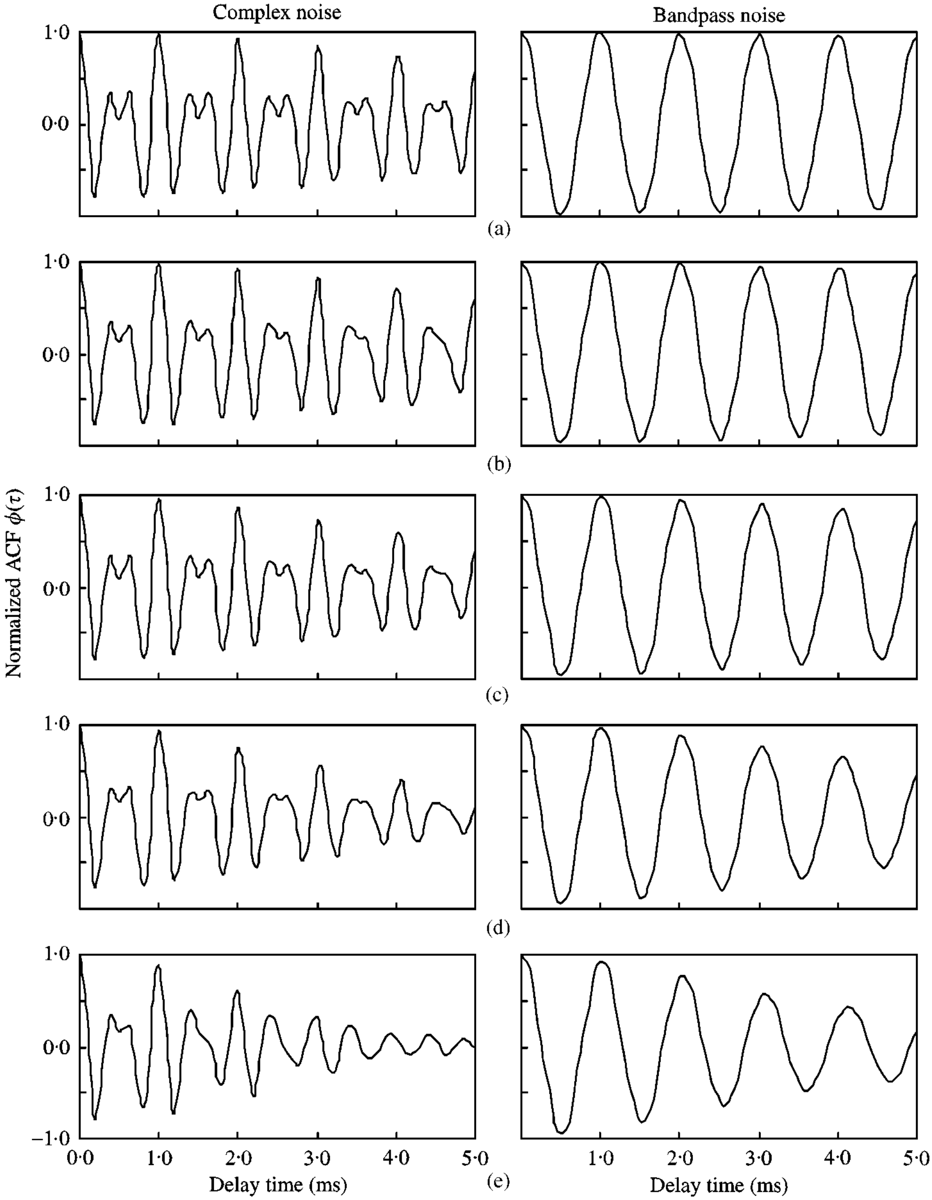

Figure 1. Normalized ACF of the complex noises whose fundamental frequencies of 1000 Hz and bandpass noises of 1000 Hz center frequency: (a) $\Delta f = 0$ Hz; (b) $\Delta f = 40$ Hz; (c) $\Delta f = 80$ Hz; (d) $\Delta f = 160$ Hz; and (e) $\Delta f = 320$ Hz.

2000 Hz in terms of the factors extracted from the ACF based on the model of the human auditory–brain system.

2. EXPERIMENT

2.1. SOURCE SIGNALS

The complex noises including bandpass noises whose center frequencies are 2000 and 3000 Hz and a complex tone with pure tone components of 2000 and 3000 Hz were used as source signals. All partial components had the same sound pressure level by measurement of the square root of the ACF at the origin of the delay time, $\Phi(0)$. The source signals were characterized in terms of their ACF. The τ_e is defined by the delay time at which the envelope of the normalized ACF becomes 0·1. To control the τ_e of the ACF of the complex noise, the bandwidth of each partial noise (Δf) was changed, respectively, to 0, 40, 80, 160, and 320 Hz with a cut-off slope of 2068 dB/octave, which is obtained by the combination of two filters. In fact, 0 Hz of the bandwidth was the only slope component. Figure 1 shows the normalized ACF of the complex noises whose fundamental frequencies of 1000 Hz and the single-noise component are centered on 1000 Hz. All signals had a maximum peak at $\tau_1 = 1·0$ ms (see Figure 2(a)). Figure 2(b) and 2(c) show the measured ϕ_1 and τ_e of the source signals as a function of the bandwidth. There is a certain degree of coherence between the ϕ_1 and τ_e for both signals.

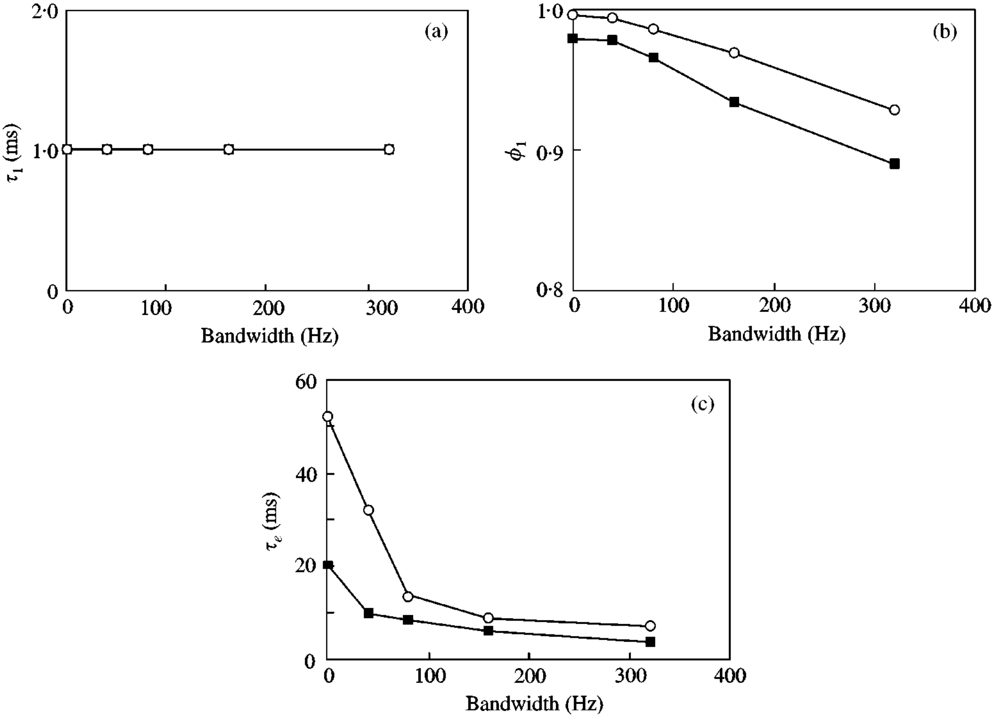

Figure 2. Measured factors extracted from the ACF of the source signal as a function of the bandwidth. ■, Complex noises whose fundamental frequencies of 1000 Hz; ○, bandpass noises of 1000 Hz center frequency: (a) Delay time of the first peak of ACF (τ_1); (b) amplitude of the first peak of ACF (ϕ_1); and (c) effective duration of ACF (τ_e).

2.2. PROCEDURE

Loudness judgments were performed by a paired-comparison method while changing the ACF of the complex noise. The reproducible source signals were presented binaurally through a pair of headphones. All stimuli were fixed at the same sound pressure level (74 dB) by measurement of the square root of the ACF at the origin of the delay time, $\Phi(0)$. The sound pressure level was calibrated by using a dummy head with $\frac{1}{2}$ in. condenser-type microphones at both ears. Input signals were digitized at 24,000 Hz of sampling frequency. Fluctuations of the measured $\Phi(0)$ for all stimuli were within $\pm 0{\cdot}06$ dB when the duration of the signals lengthened more than 0·8 s. Therefore, the duration was chosen at 1·0 s in this experiment. The magnitude of the interaural cross-correlation function (IACC) was kept constant at nearly unity because the signals fed to both ears were identical.

The paired-comparison tests were conducted for six sound signals ($\Delta f = 0$, 40, 80, 160, 320 Hz, and a complex tone). Four subjects with normal hearing ability participated. They were seated in an anechoic chamber and asked to judge which of two sound signals reproduced by a pair of headphones they perceived louder. The duration of the stimuli was 1·0 s, the rise and fall times were 50 ms, and the silent interval between the stimuli was 0·5 s. Each pair of stimuli was separated by an interval of 3·0 s and the pairs were presented in random order. A single-test session consisted of 15 pairs ($N(N-1)/2$, $N = 6$) of stimuli and lasted about 1·5 min. Ten sessions were performed for each subject.

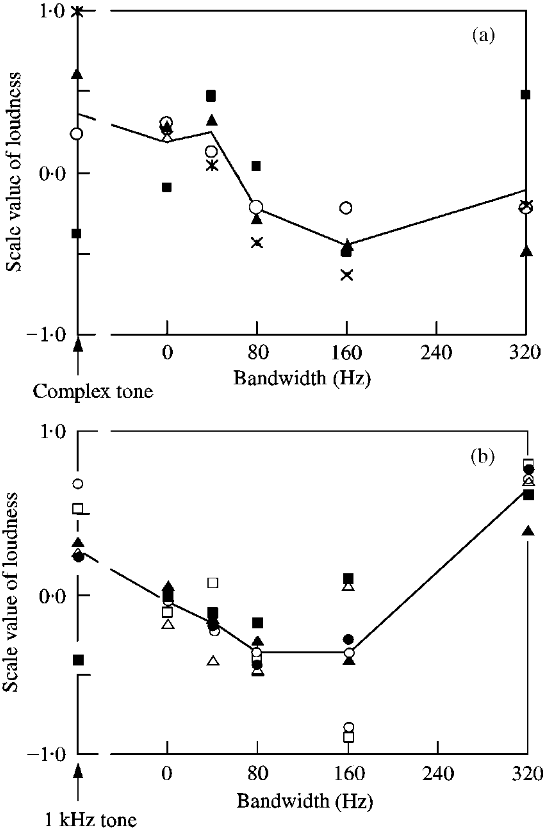

Figure 3. Scale value of loudness as a function of the bandwidth. Different symbols indicate the scale values obtained with different subjects: (a) Complex noises whose fundamental frequencies of 1000 Hz; and (b) bandpass noises of 1000 Hz center frequency.

3. RESULTS AND DISCUSSION

Forty responses (4 subjects × 10 sessions) to each stimulus were obtained. Consistency tests indicated that all subjects had a significant ($p < 0{\cdot}01$) ability to discriminate loudness. The test of agreement also indicated that there was significant ($p < 0{\cdot}05$) agreement among all subjects. A scale value of loudness was obtained by applying the law of comparative judgment (Thurstone’s case V) [12] and confirmed by goodness of fit [13]. The relationship between the scale value of loudness and the bandwidth of each partial component of complex noises is shown in Figure 3(a). The loudness of the complex noises under the condition of a constant $\Phi(0)$ was not constant. A minimum was indicated at a certain bandwidth, and the loudness increased as the τ_e of the source signal increased up to 160 Hz. Analysis of the variance for the scale values of loudness showed that there were significant differences between the pairings of a complex tone and 160 Hz, 0 and 80 Hz, 0 and 160 Hz, 40 and 80 Hz, and 40 and 160 Hz, as indicated in Table 1.

As shown in Figure 3(b), it is remarkable that the result of this experiment is similar to the one that measured loudness of the bandpass noises of a 1000 Hz center frequency [9]. All of the source signals used in this experiment had a fundamental frequency of 1000 Hz, and the measured τ_1 was 1·0 ms (see Figure 2(a)). In our preliminary experiment, subjects, who were different from those in this experiment and had pitch-matching test experience, were able to match the perceived pitch of complex noises to a 1000 Hz tone. The pitch of the complex tones consisting of the second and third harmonics of the fundamental frequency correspond to the τ_1 under the condition of the fundamental frequency below 1200 Hz; otherwise, the probability of matching the fundamental frequency rapidly decreases [11]. In addition, the loudness of sharply (2068 dB/octave) filtered bandpass noises of 2000 Hz center frequency obtained by the constant method is flat up to 160 Hz in accordance with the critical band theory (see Figure 4), although the τ_e increases with a decrease in bandwidth as shown in Figure 5. This result is not at variance with the data of Fastl [14], who investigated the masking pattern when changing the filter slope of the bandpass noises of 2000 Hz center frequency. It seems that the subjects judge the loudness in relation to the τ_e for the fundamental frequency below 1200 Hz. The larger loudness at 320 Hz may be related to the supercritical condition for the frequency centered on 1000 Hz.

A method to calculate loudness from the spectrum shape [15] and the $\frac{1}{3}$ octave band level [16] has been proposed; however, the results of our experiment cannot be explained by the spectrum in the frequency domain. In the human auditory–brain system, the sound signals may be processed by the ACF in the time domain. Considering the fact that there exist

TABLE 1

F-values of the analysis of variance for scale value of loudness between different bandwidths (4 subjects)

	Complex tone	0 Hz	40 Hz	80 Hz	160 Hz	320 Hz
Complex tone	—	0·37	0·16	3·69	7·19†	1·79
0 Hz	—	—	0·24	9·03†	24·58‡	1·65
40 Hz	—	—	—	12·05†	29·59‡	2·47
80 Hz	—	—	—	—	0·26	3·08
160 Hz	—	—	—	—	—	2·38
320 Hz	—	—	—	—	—	—

† 5% significant level.
‡ 1% significant level.

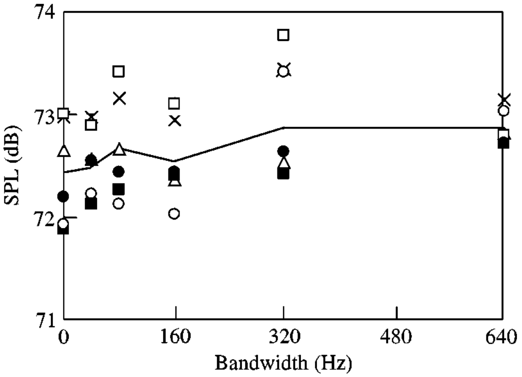

Figure 4. Loudness of the bandpass noises of 2000 Hz center frequency obtained by the constant method comparing the 2000 Hz tone as a function of the bandwidth. Different symbols indicate the loudness obtained with different subjects (six subjects).

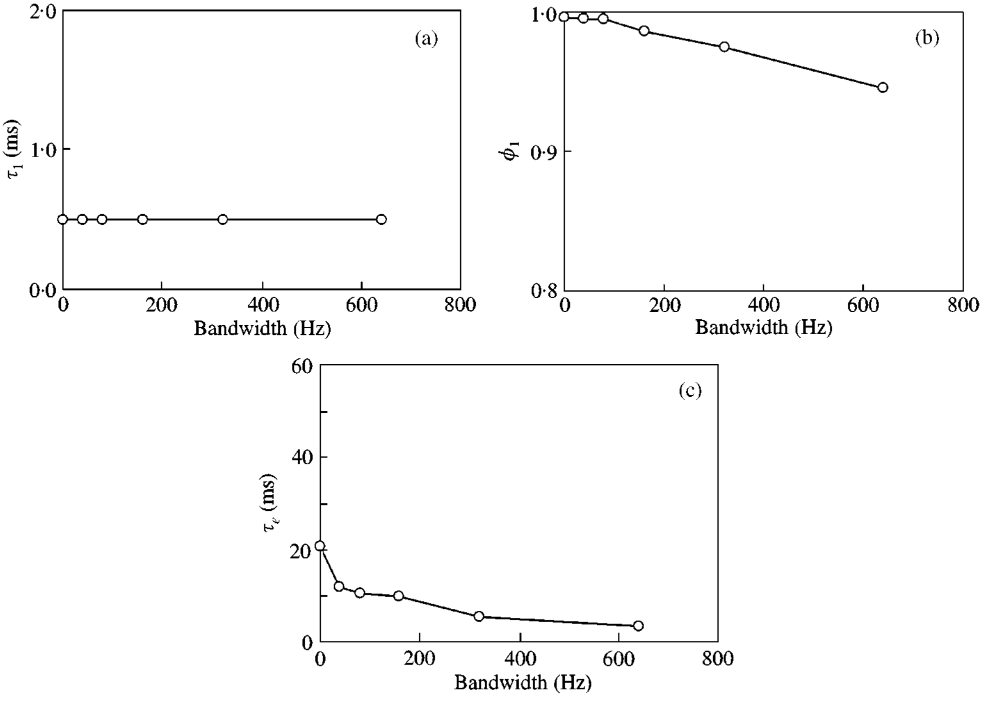

Figure 5. Measured factors extracted from the ACF of the bandpass noises of 2000 Hz center frequency as a function of the bandwidth: (a) delay time of the first peak of ACF (τ_1); (b) amplitude of the first peak of ACF (ϕ_1); and (c) effective duration of ACF (τ_e).

environmental noises which have relatively large τ_e values (near 100 ms) [17, 18], the factors extracted from the ACF should be taken into consideration in the subjective evaluation of the noise.

4. CONCLUSIONS

To examine the relationship between the loudness and the factors extracted from the ACF of the source signal based on the human auditory–brain system, the scale values of loudness for the complex noises, whose partial components were sharply (2068 dB/octave) filtered bandnoise, were obtained by using a paired-comparison method under the condition of a constant $\Phi(0)$. It is found that loudness for the complex noises whose fundamental frequencies of 1000 Hz is similar to that of the single-noise component centered on 1000 Hz. This is because both the signals have the same τ_1. Also, loudness increases with the increasing value of τ_e, even if the bandwidth of the signal is within the critical band of 1000 Hz. Loudness for the bandpass noises of 2000 Hz center frequency, which is beyond the applicable range based on the ACF model, is not affected by the value of τ_e. This result apparently agrees with the data of Fastl [14].

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