Journal of Sound and Vibration (2002) 250(1), 47–52
doi:10.1006/jsvi.2001.3888, available online at http://www.idealibrary.com on IDEAL®

LOUDNESS OF SHARPLY (2068 dB/OCTAVE) FILTERED NOISES IN RELATION TO THE FACTORS EXTRACTED FROM THE AUTOCORRELATION FUNCTION

S. SATO, T. KITAMURA AND Y. ANDO

Graduate School of Science and Technology, Kobe University, Rokkodai, Nada, Kobe 657-8501, Japan.
E-mail: satos@kobe-u.ac.jp

(*Received* 5 *September* 2001)

This study examines the loudness of bandpass noises with center frequencies of 250, 500 and 1000 Hz while changing the autocorrelation function (ACF). The bandwidth of the source signal was altered with a 2068 dB/octave sharp filter to control the ACF of the source signal. The scale values of loudness were obtained using a paired-comparison method. It is shown that the loudness of the bandpass noises inside the critical band is not constant. The loudness of the pure tone is greater than that of sharply filtered noises. The loudness of the bandpass noises increases with increasing effective duration of the ACF (τ_e) of the source signal.

1. INTRODUCTION

A theory on primary sensations and spatial sensations to environmental noise has been proposed [1, 2]. Primary sensations—loudness, pitch, and timbre—can be described by temporal factors extracted from the autocorrelation function (ACF). From the ACF analysis, (1) energy represented at the origin of delay, $\Phi(0)$, (2) effective duration of the envelope of the normalized ACF, τ_e, (3) the delay time of the first peak of the normalized ACF, τ_1, and (4) its amplitude, ϕ_1 were extracted. Applying this theory to loudness, we found that not only the sound pressure level but also the repetitive feature, which is represented by the τ_e of the source signal, influence the loudness. 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 when the bandwidth of the signal is within the "critical band" [3]. A similar tendency was observed in that, as the subsequent reverberation time (T_{sub}) of a sound field increases, the τ_e also increases [4].

The ACF and the power density spectrum mathematically contain the same information. Previous studies on the relationship between loudness and the bandwidth of noises using frequency analysis have concluded that the loudness of a noise remains constant as the bandwidth of the noise increases until the bandwidth reaches the critical band. Loudness then increases with increasing bandwidth under the same sound pressure level conditions [5–8]. However, an actual bandpass filter passes not only at 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. Mathews and Pfafflin suggested that the loudness of

0022-460X/02/060047 + 06 $35.00/0

bandpass noises may differ according to filter shape, i.e., the actual filter or an ideal (rectangular) filter [9]. The recommended filter slope of the one-third octave bandpass filter is about − 50 dB/octave at most. The outside bandwidth response of the filter affects the repetitive feature of the signal, represented by the ACF processed in the human auditory–brain system [1, 10]. Such a gentle slope cannot take into consideration the repetitive feature of the source signal, which influences the loudness. To approximate the specification of an ideal filter, a sharp roll-off filter is required. Due to the sharpening effects that exist in the auditory system [11], its roll-off should be more than 1000 dB/octave.

The present study examines the loudness of bandpass noises in terms of the factors extracted from the ACF. The scale values of loudness of sharply (2068 dB/octave) filtered noises centered on 250 and 500 Hz were obtained using a paired-comparison method. The results were compared with those of the bandpass noises centered on 1000 Hz.

2. EXPERIMENT

2.1. SOURCE SIGNALS

Bandpass noises with center frequencies of 250 and 500 Hz were used as source signals. The source signals were characterized in terms of their ACF (Figure 1). To control the ACF of the bandpass noise, the filter bandwidth (Δf) was changed by using a cut-off slope of

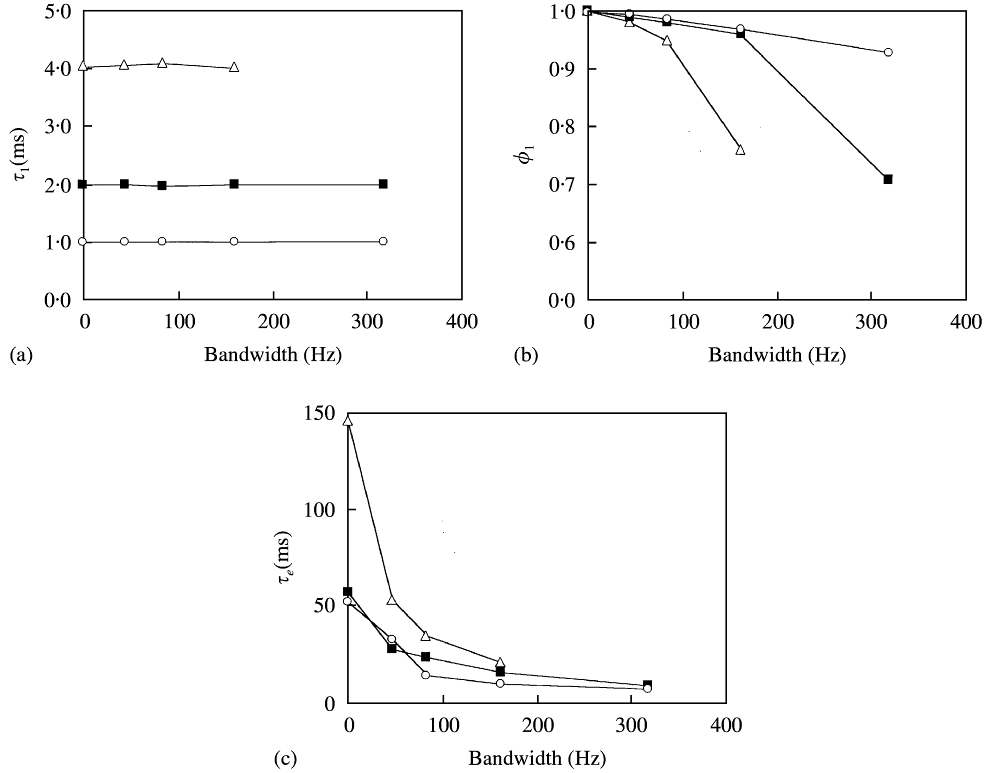

Figure 1. Measured factors extracted from the ACF of the source signal as a function of the bandwidth. Different symbols indicate different frequencies: △, 250 Hz; ■, 500 Hz; ○, 1000 Hz. (a) Delay time of the first peak of ACF (τ_1); (b) amplitude of the first peak of ACF (ϕ_1); and (c) effective duration of ACF (τ_e).

2068 dB/octave, which was obtained by a combination of two filters. In fact, the filter bandwidth of 0 Hz was the only slope component. All source signals had the same sound pressure level (74 dB(A)) by measurement of the ACF at the origin of the delay time, $\Phi(0)$. Figure 1 shows the measured τ_1, ϕ_1, and τ_e of the source signals as a function of the filter bandwidth and as a parameter of the center frequency. The τ_e is defined by the delay time at which the envelope of the normalized ACF becomes 0·1. Measured values of bandpass noises centered at 1000 Hz with a cut-off slope of 1080 dB/octave are also indicated. τ_1 corresponds to the center frequency of bandpass noises (Figure 1(a)), ϕ_1 and τ_e increase as the filter bandwidth decreases (Figures 1(b) and 1(c)), and there is a certain degree of coherence between ϕ_1 and τ_e.

2.2. PROCEDURE

Loudness judgments were made by a paired-comparison method while the ACF of the bandpass noise was changed. The reproducible source signals were presented binaurally through a pair of headphones. All stimuli were fixed at the same sound pressure level (74 dB(A)) by measurement of the ACF at the origin of the delay time, $\Phi(0)$. The duration of the sound signals was chosen to be 1·0 ms in this experiment. 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 a sampling frequency of 48 000 Hz. The magnitude of the interaural cross-correlation function (IACC) was kept constant at nearly unity because the signals fed to both ears were identical.

Paired-comparison tests were conducted for each center frequency. Five subjects with normal hearing participated in each test session. They were seated in an anechoic chamber and asked to judge which of two sound signals reproduced by a pair of headphones they perceived to be 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. Ten sessions were held for each subject.

3. RESULTS AND DISCUSSION

Fifty responses (5 subjects × 10 sessions) to each stimulus were obtained. Consistency tests indicated that all subjects had a significant ($p < 0{\cdot}05$) 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 was confirmed by goodness of fit [13].

The relationship between the scale value of loudness and the filter bandwidth is shown in Figure 2. The result of the loudness of the bandpass noises centered on 1000 Hz is also indicated. A minimum is indicated at a certain bandwidth and the loudness increases with increasing τ_e. The loudness of the pure tone was greater than that of sharply filtered noises under the condition of equal sound pressure levels. Results of analysis of variance for the scale values of loudness are indicated in Table 1. For all center frequencies tested, the scale value of loudness of pure tone was significantly longer than that of other bandpass noises within the critical band ($p < 0{\cdot}01$). In this study, there was a certain degree of coherence between ϕ_1 and τ_e. However, τ_e contributed to the loudness when the results of the loudness with changes in T_{sub} of a sound field [4] were taken into account.

The results of pitch perception of the missing fundamental showed that the pitch of the complex tones consisting of the second and third harmonics of the fundamental frequency

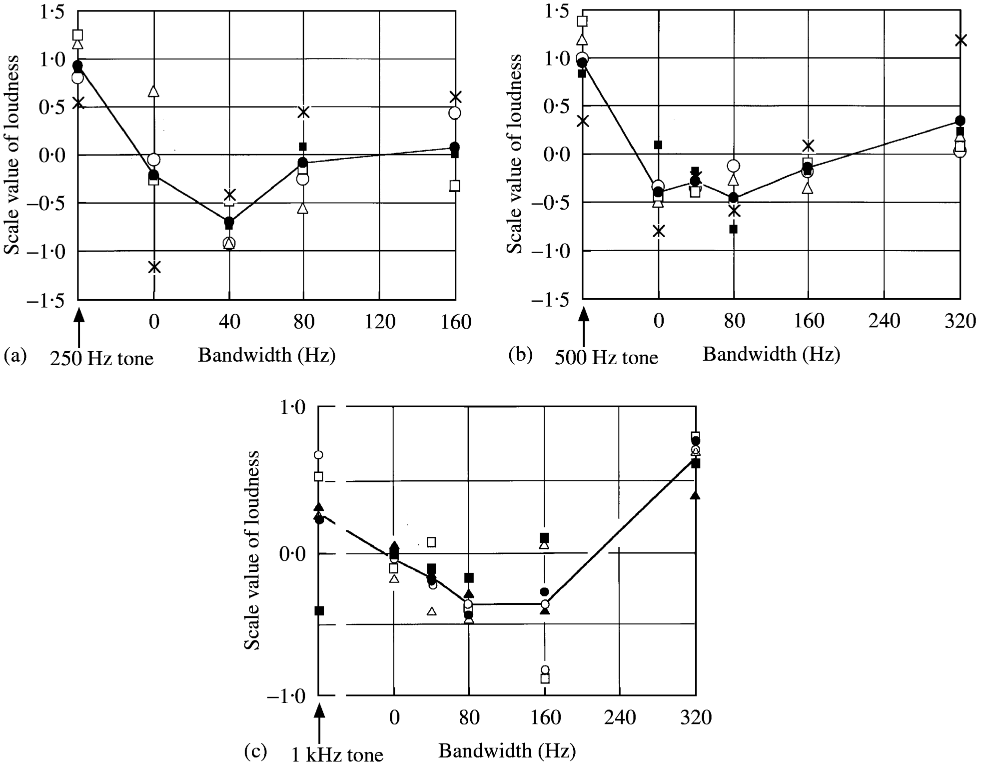

Figure 2. Scale value of loudness as a function of the bandwidth. Different symbols indicate the scale values obtained with different subjects. (a) f_c = 250 Hz; (b) f_c = 500 Hz; and (c) f_c = 1000 Hz.

corresponded to τ_1 when the fundamental frequency was below 1200 Hz. Otherwise, the probability of matching the fundamental frequency rapidly decreased [13]. In addition, the loudness of complex noises with fundamental frequencies of 1000 Hz ($\tau_1 = 1$ ms) was similar to that of the single noise component centered on 1000 Hz ($\tau_1 = 1$ ms) [14]. Thus, the repetitive feature of the source signals, which is represented by τ_e, contributed to loudness when the center frequency of the bandpass noise was below 1000 Hz. According to the critical band theory, the loudness of bandpass noises rapidly increases when the bandwidth reaches the critical band. However, such an increase in loudness under the supercritical condition was not observed when sharply filtered bandpass noises were used.

4. CONCLUSIONS

To examine the relationship between loudness and the factors extracted from the ACF of the source signal, scale values of loudness for sharply (2068 dB/octave) filtered noises were obtained by using a paired-comparison method under the condition of constant $\Phi(0)$. It was found that the loudness of bandpass noises with equal sound pressure levels was not constant within the critical band. The loudness of the pure tone was significantly larger than that of sharply filtered noises, and loudness increased with increasing τ_e. The adaptive frequency range agreed with the results of a previous study based on the ACF model of the perceived pitch of the missing fundamental.

Table 1

F-values of the analysis of variance for the scale value of loudness between different bandwidths

	Tone	0 Hz	40 Hz	80 Hz	160 Hz	320 Hz
(a) f_c = 250 *Hz* (*five subjects*)						
Tone	—	12·92[†]	96·64[†]	24·01[†]	14·19[†]	—
0 Hz		—	2·42	0·14	0·67	—
40 Hz			—	9·38[‡]	12·36[†]	—
80 Hz				—	0·41	—
160 Hz					—	—
(b) f_c = 500 *Hz* (*five subjects*)						
Tone	—	35·28[†]	46·49[†]	44·63[†]	33·18[†]	4·75
0 Hz		—	0·60	0·08	2·46	8·17[‡]
40 Hz			—	1·90	2·66	8·08[‡]
80 Hz				—	5·07	10·55[‡]
160 Hz					—	4·60
320 Hz						—
(c) f_c = 1000 *Hz* (*six subjects*)						
Tone	—	4·39	7·97[‡]	11·52[†]	4·97[‡]	6·07[‡]
0 Hz		—	8·82[‡]	61·83[†]	4·11	59·54[†]
40 Hz			—	14·08[‡]	1·32	115·54[†]
80 Hz				—	0·08	115·81[†]
160 Hz					—	31·31[‡]
320 Hz						—

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

ACKNOWLEDGMENTS

This work was supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science. The authors thank the subjects who participated in the experimental sessions.

REFERENCES

1. Y. Ando, S. Sato and H. Sakai 1999 in *Computational Architectural Acoustics in Architecture* (J. J. Sendra, editor), Chap. 4. Southampton: WIT Press. Fundamental subjective attributes of sound fields based on the model of auditory–brain system.
2. Y. Ando 2001 *Journal of Sound and Vibration* **241**, 3–18. A theory of primary sensations and spatial sensations measuring environmental noise.
3. I Gde N. Merthayasa, H. Hemmi and Y. Ando 1994 *Memoirs of Graduate School of Science and Technology, Kobe University* **12A**, 147–156. Loudness of a 1 kHz pure tone and sharply (1080 dB/Oct.) filtered noises centered on its frequency.
4. K. Ono and Y. Ando 1996 *Reports of Architectural Institute of Japan, Kinki Chapter*, 121–124. A study on loudness of sound field in relation to the reverberation time (in Japanese).
5. E. Zwicker, G. Flottorp and S. S. Stevens 1957 *Journal of the Acoustical Society of America* **29**, 548–557. Critical bandwidth in loudness summation.
6. D. D. Greenwood 1961 *Journal of the Acoustical Society of America* **33**, 484–502. Auditory masking and critical band.
7. D. D. Greenwood 1961 *Journal of the Acoustical Society of America* **33**, 1344–1356. Critical bandwidth and the frequency of the basilar membrane.

8. B. Scharf 1962 *Journal of the Acoustical Society of America* **34**, 228–233. Loudness summation and spectrum shape.
9. M. V. Mathews and S. M. Pfafflin 1965 *Journal of the Acoustical Society of America* **38**, 1055–1056. Effect of filter type on energy-detection models for auditory signal detection.
10. Y. Ando 1998 *Architectural Acoustics, Blending Sound Sources, Sound Fields, and Listeners*, Chap. 5. New York: AIP Press/Springer-Verlag.
11. Y. Katsuki, T. Sumi, H. Uchiyama and T. Watanabe 1958 *Journal of Neurophysiology* **21**, 569–588. Electric responses of auditory neurons in cat to sound stimulation.
12. L. L. Thurstone 1927 *Psychology Review* **31**, 273–289. A law of comparative judgment.
13. F. Mosteller 1951 *Psychometrica* **16**, 207–218. Remarks on the method of paired comparisons: III. A test of significance for paired comparisons when equal standard deviations and equal correlations are assumed.
14. M. Inoue, Y. Ando and T. Taguti 2001 *Journal of Sound and Vibration* **241**, 105–116. The frequency range applicable to pitch identification based upon the autocorrelation function model.
15. S. Sato, T. Kitamura, H. Sakai and Y. Ando 2001 *Journal of Sound and Vibration* **241**, 97–103. The loudness of "complex noise" in relation to the factors extracted from the autocorrelation function.