Apparent Source Width (ASW) of Complex Noises in Relation to the Interaural Cross-correlation Function

Shin-ichi Sato and Yoichi Ando

Graduate School of Science and Technology, Kobe University, Rokkodai, Nada, Kobe, 657-8501, Japan

(Received 28 September 2001; accepted 23 April 2002)

This study examined the apparent source width (ASW) of complex signals, which includes bandpass noises whose center frequencies are the harmonics of the fundamental frequency (i.e., complex noises). The fundamental frequencies used in the experiment are below 800 Hz so that the perceived pitch of noises corresponds to the fundamental frequency. The lowest center frequencies of the components of the stimuli are 1600 Hz. The scale values of ASW of the complex noises were obtained by paired-comparison tests. The test results show that the ASW is judged from the frequency component of the source signal because the ASW can be calculated by the width of the interaural cross-correlation function, W_{IACC}, which is defined as the interval of delay time at a value of 10% below the IACC.

Keywords: apparent source width (ASW), interaural cross-correlation function, complex noise

1. INTRODUCTION

Apparent source width (ASW) is an important subjective attribute of the sound field in a concert hall or an opera house. ASW is the acoustical width of the sound source as perceived by a listener. Generally, it depends on the spectral component of the source signal as well as the magnitude of the interaural cross-correlation function (IACC). For example, even if the IACC is constant, the ASW increases as the center frequency of the octave band noise decreases or as the low-frequency components increase [1, 2]. The fact that wider ASW is perceived for a sound source with a predominately low frequency is reflected in the interaural cross-correlation function. The peak of the function becomes broader as the center frequency of the bandpass noise decreases. Thus, the width of the interaural cross-correlation function (W_{IACC}), which is defined as the interval of delay time at a value of 10% below the IACC, has been introduced [3, 4]. Interaural cross-correlation function represents the interdependence between the left (right) signal at the origin and the right (left) signal at a delay time within 1 ms. Thus, W_{IACC} has a unit of time. Sound pressure level, SPL, also affects ASW [5]. Based on the auditory-brain model, ASW can be described by the factors extracted from the interaural cross-correlation function [4].

Analysis of the frequency domain does not always describe subjective attributes. As for the perception of pitch, the phenomenon of the missing fundamental suggests that the frequency analysis is insufficient. Perceived pitch of the complex tone, which consists of the harmonics without fundamental frequency, cannot be detected in terms of the frequency domain [6]. The perceived pitch is strongly related to the factors extracted from the autocorrelation function (ACF), namely, delay time τ_1 and amplitude ϕ_1 of the first peak of the normalized ACF of the source signal when the fundamental frequency is below 1200 Hz.

This study examined the ASW of complex signals, which consists of the bandpass noises whose center frequencies are the harmonics of the fundamental frequency (complex noises). The scale value of ASW for complex noises was compared with that for bandpass noises. If the ASW of complex noises is judged from the frequency component, ASW of the complex noise can be described by W_{IACC} of the source signal. On the other hand, if ASW of complex noises is judged from the fundamental frequency, ASW can be described by the τ_1 value of the source signal. In latter case, ASW of the complex noise is equal to that of the bandpass noise, whose center frequency is the same as the fundamental frequency of the complex noise.

2. EXPERIMENTAL METHOD

2.1 Source Signals

Bandpass noises with center frequencies of 200, 400, and 800 Hz and complex noises with fundamental frequencies of 200, 400, and 800 Hz were used as the source signals (Table 1). The complex noises consisted of three bandpass noise

Table 1. Measured values of W_{IACC} of the stimuli used for the experiments.

	Center frequency of each component (bandwidth: 80 Hz)	W_{IACC} [ms]
Bandpass noises	200 Hz	0.74
	400 Hz	0.37
	800 Hz	0.21
Complex noises	1600, 1800, and 2000 Hz	0.08
	1600, 2000, and 2400 Hz	0.07
	1600, 2400, and 3200 Hz	0.06

components, and the center frequencies of lowest frequency components were fixed at 1600 Hz. All partial components had the same sound-pressure level by measuring the square root of the autocorrelation function at the origin of the delay time, Φ(0). The bandwidth of the bandpass noises and that of the components of the complex noise were 80 Hz with a cut-off slope of 2068 dB/octave, which was obtained by the combination of two filters.

2.2 Procedure

Two symmetrical lateral reflections (±54°) added to the frontal direct sound (0°) were simulated in an anechoic chamber. The distance between the loudspeakers and the center on the subject's head was 1.0±0.01 m. To produce incoherent conditions, the time delays Δt_1 and Δt_2 between the direct sound and the two reflections were fixed at 20 ms and 40 ms, respectively. To reconfirm the effect of SPL on ASW [5], the listening level (LL) at the listener's position was also changed from 70 to 75 dB. The values of IACC of all sound fields were adjusted to 0.90 by controlling the sound pressure ratio of the reflections relative to the level of the direct sound. Two reflections had the same amplitude. The interaural cross-correlation was measured with two 1/2-inch condenser-type microphones, each placed at the entrance of the ears of a dummy head. The analog outputs from the microphones were passed through an A-weighting network and were digitized at a sampling frequency of 44.1 kHz. The normalized interaural cross-correlation function is given by

$$\phi_{lr}(j\sigma) = \frac{\Phi_{lr}(j\sigma)}{\sqrt{\Phi_{ll}(0)\Phi_{rr}(0)}} \qquad (1)$$

where the $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ represent the autocorrelation functions ($\tau = 0$) of the signals at both ears, respectively. The denominator means the geometrical mean of the sound energies arriving at the two ears, and $\Phi_{lr}(\sigma)$ is the crosscorrelation of the signals at both ears. Independent factors extracted from the interaural cross-correlation function are shown in Fig. 1. For simplicity, the value of δ is defined by 0.1(IACC) in this study. The interaural time delay at which the IACC is defined is the τ_{IACC}. Measured τ_{IACC} of all the sound fields used in the experiment were less than 0.07 ms, thus, listeners can perceive the frontal sound localization. Measured IACC of all the sound fields used in the experiment were 0.90±0.01.

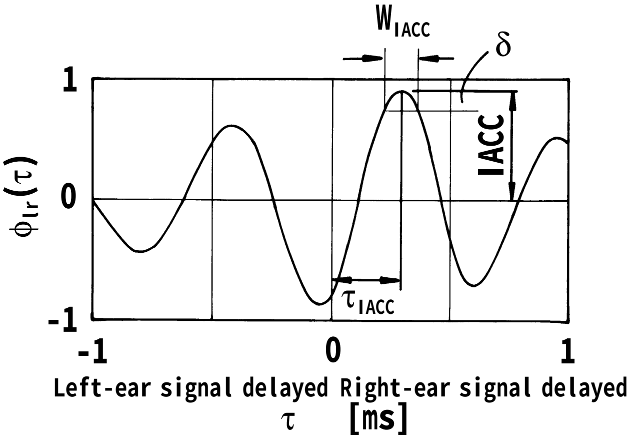

Fig. 1. Definitions of the IACC, τ_{IACC} and W_{IACC} for the interaural cross-correlation function.

2.3 Paired-comparison tests

Paired-comparison tests of twelve sound fields were performed on five subjects with normal hearing ability in order to obtain scale values of ASW. They were seated in an anechoic chamber and asked to judge which of two stimuli they perceived to be broader. The duration of each sound stimulus was 3.0 s, the rise and fall times were 50 ms, and the silent interval between stimuli was 1.0 s. Each pair of stimuli was separated by an interval of 4.0 s and the pairs were presented in random order. A single test session consisted of 66 pairs (N(N-1)/2, where N = 12) of stimuli, and each subject took part in five sessions.

3. RESULTS

Twenty-five responses (five subjects x five repeats) to each stimulus were obtained. Consistency tests indicated that all subjects had a significant ($p < 0.05$) ability to discriminate ASW. A test of agreement also indicated that there was significant ($p < 0.05$) agreement among all subjects. A scale value of ASW was obtained by applying the law of comparative judgment (Turnstone's case V) [7].

The relationship between the scale value of ASW and W_{IACC} of the source signal is shown in Fig. 2. There is a significant difference between the scale value of the ASW of the bandpass noises and that of the complex noises ($p < 0.01$). The results of the analysis of variance for scale values of ASW are listed in Table 2. It is clear that the explanatory factors W_{IACC} and LL are significant ($p < 0.01$). The interaction between W_{IACC} and LL is not significant; thus, W_{IACC} and LL must contribute to the scale value of ASW independently. Their contributions are expressed by

$$s(\mathrm{ASW}) \approx f(W_{IACC}) + f(\mathrm{LL}) \tag{2}$$

The scale value of ASW is formed by interpolation from a nonlinear equation such as

$$s(\mathrm{ASW}) \approx a(W_{IACC})^{1/2} + b(\mathrm{LL})^{3/2} \tag{3}$$

where a and b are the coefficients to be evaluated. The values of the powers, 1/2 and 3/2 for the terms of W_{IACC} and LL in Eq. (3) were determined to give the best correlation between the scale values obtained by paired comparison tests and the scale values calculated by Eq. (3). The curves in Fig. 2 confirm the calculated scale values of Eq. (3), $a \approx 2.40$ and $b \approx 0.003$. These coefficients were obtained by multiple regression. It is noteworthy that the scale value of ASW for 1/3-octave bandpass noises is also expressed in terms of the 1/2 power of W_{IACC} and that the coefficient for W_{IACC} (2.44) is close to that of this study [4].

4. DISCUSSION

A significant difference between the scale values of the ASW of bandpass noises and the complex noises ($p < 0.01$) was found. Thus, the ASW of the complex noises is judged by the frequency component of the source signal, i.e., not the fundamental frequency. The range of the delay time in the interaural cross-correlation function is within ±1 ms. On the other hand, the effect of the fundamental frequency, which is represented by the delay time of the first peak of the autocorrelation function, appears out of this ranges. Resolution of the time domain of the interaural cross-correlation seems to be different from that of the autocorrelation function. The results of analysis of variance (ANOVA) for scale values of ASW indicated that the explanatory factor LL is significant ($p < 0.01$). The scale values of ASW increase with increasing in LL. This results agrees with the data of Keet [5].

Figure 3 shows the relationship between the measured scale value of ASW and the scale value of ASW calculated by Eq. (3) with the coefficients $a \approx 2.40$, and $b \approx 0.003$. The correlation coefficient between the measured and calculated scale values is 0.97 ($p < 0.01$). Coefficients a and b in Eq. (3) for each individual are calculated by a multiple regression analysis and are listed in Table 3. Figure 4 shows the relationship between the measured scale value of ASW and the scale value of ASW calculated from Eq. (3) with the coefficients for each individual. The different symbols correspond to the different subjects. The correlation coefficient between the measured and calculated scale values is 0.90 ($p < 0.01$). The ASW for each individual can be obtained by using the same equation used in calculating the global ASW simply by changing the weighting coefficients a and b.

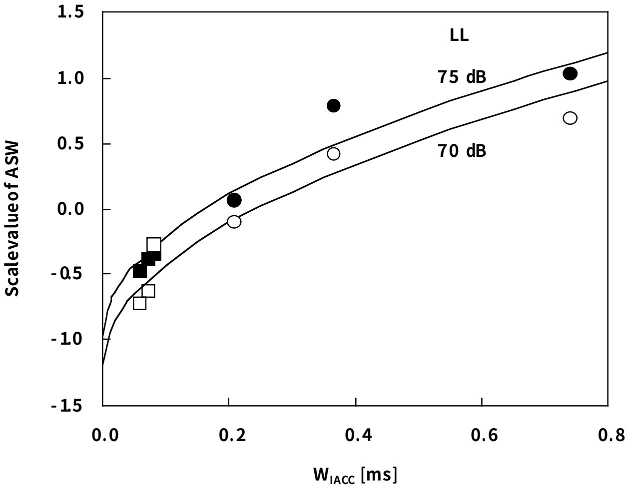

Fig. 2. Average scale values of ASW as a function of W_{IACC} and as a parameter of LL. ● : bandpass noise; LL = 75 dB; ○ : bandpass noise; LL = 70 dB; ■ : complex noise; LL = 75 dB; □ : complex noise; LL = 70 dB. The regression curve is expressed by Eq. (3) with $a \approx 2.40$ and $b \approx 0.003$.

Table 2. Results of the analysis of variance (ANOVA) for scale values of ASW with the factors of W_{IACC} and LL.

Factor	Sum of square	DF	Mean square	F-value
W_{IACC}	18.08	5	3.62	44.26**
LL	0.69	1	0.69	8.49**
W_{IACC}*LL	0.30	5	0.06	0.74
Residual	3.92	48		

** 1% significant level.

5. SUMMARY

To examine whether the apparent source width (ASW) of complex noises depends on the fundamental frequency or the frequency component, the scale value of ASW of bandpass noises and that of complex noises were obtained by using a paired-comparison method. The results show that ASW

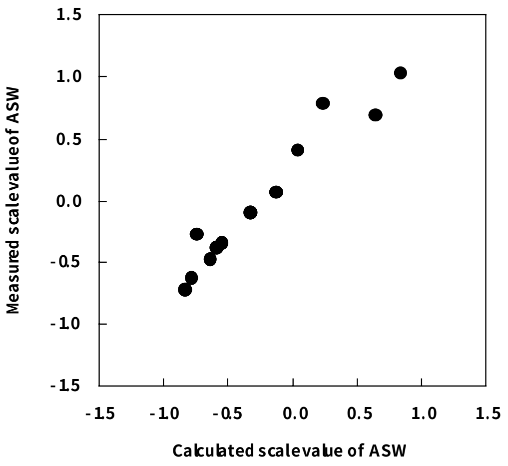

Fig. 3. Relationship between the measured scale values of ASW and scale values of ASW calculated from Eq. (3) with $a \approx 2.40$ and $b \approx 0.003$. Correlation coefficient r = 0.97 ($p < 0.01$).

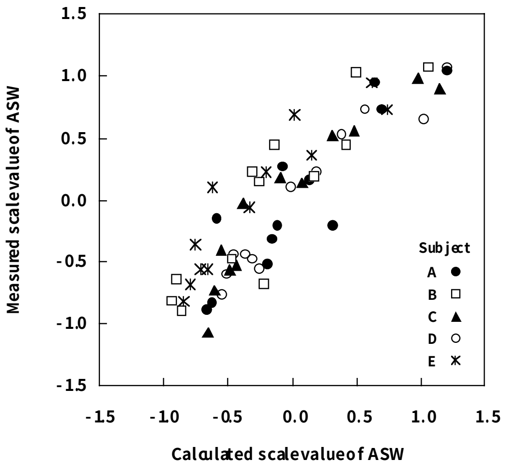

Fig. 4. Relationship between the measured individual scale values of ASW and scale values of ASW calculated from Eq. (3) for each individual. Correlation coefficient r = 0.90 ($p < 0.01$).

Table 3. Coefficients *a* and *b* in Eq. (3) for each individual, together with the correlation coefficients between the measured scale values of ASW and the calculated scale values of ASW from Eq. (3).

Subject	a	b	Correlation coefficient
A	2.21	0.008	0.90
B	2.23	0.010	0.90
C	2.66	0.003	0.94
D	2.60	0.003	0.96
E	2.37	0.002	0.92
Averaged (Global)	2.40	0.003	0.97

depends of the frequency component because the scale value of ASW of the complex noise can be calculated by using the width of the interaural cross-correlation function (W_{IACC}) of the source signal. Listening level (LL) also contributes to the scale value of ASW. These two results mean that ASW can be calculated from the physical factors extracted from the interaural cross-correlation function based on the auditory-brain model.

ACKNOWLEDGMENTS

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

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