Measurement of Temporal and Spatial Factors of a Flushing Toilet Noise in a Downstairs Bedroom

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In a three-floored apartment, located in a quiet living area of Kobe, one resident was very annoyed by the flushing noise of an upstairs toilet that could be heard in the downstairs bedroom. The resident accused the construction company of improper construction, although the sound pressure level was only about 35 dBA. The purpose of this study is to clarify the characteristics of a flushing toilet noise in a bedroom on the downstairs floor in terms of the temporal and spatial factors extracted from the autocorrelation function and cross-correlation function based on the model of the human auditory-brain system [Ando, Y. (1998). Architectural Acoustics - Blending Sound Sources, Sound Fields, and Listeners: AIP Press/Springer-Verlag, New York].

The results of the measurement showed that the temporal and spatial factors for the flushing toilet noise changed dramatically as a function of time. According to the human auditory-brain system, temporal factors of sound signals are processed by the left hemisphere, and spatial factors of sound signals are processed by the right hemisphere. The flushing noise of an upstairs toilet stimulates dramatically both the left and right hemispheres, which are sensitive to change in both the temporal and spatial factors.

Keywords: flushing toilet noise, autocorrelation function, interaural cross-correlation function, auditory-brain model

1. INTRODUCTION

Environmental noises are a fact of our life. Aircraft, traffic, railway, industrial, machinery, and community noise are commonplace. These environmental noises have been evaluated according to sound pressure level (SPL) and frequency characteristics [1]. Noise criterion (NC) curves, preferred noise criterion (PNC) curves and balanced noise criterion (NCB) curves were developed to measure the SPL and its frequency characteristics [2-4]. For evaluating fluctuation noise such as traffic noise and industry noise, the equivalent sound level (Leq) has been used widely. These noise criterions are not considered sufficiently perceived acoustical properties. It has been reported that environmental noises not only disturb our sleep and conversation, but also affect the growth of unborn babies, infants, and children [5-10]. In noise measurement, it is important to clarify the relationship between physical properties and psychological affects.

We received the following investigation requests. In a three-floored apartment, located in a quiet living area of Kobe, one resident was very annoyed by the flushing noise of an upstairs toilet that spread to the downstairs bedroom. The resident accused the construction company of improper construction, although the sound pressure level was only about 35 dBA. The construction company attempted to improve noise reduction in the bedroom. As a result, the SPL for the flushing toilet noise was improved by about 5 dBA. However, the resident still found the noise annoying. This fact implies that psychological effects cannot be fully evaluated by only the measurement of the SPL.

The purpose of this study is to clarify why the resident was annoyed by a flushing noise of an upstairs toilet despite a low SPL. In the present study, we used a new system [11] that was developed for analysis of the temporal and spatial factors of sound fields based on the model of the human auditory-brain system [12]. The model consists of autocorrelators and an interaural cross-correlator for analyzing sound signals arriving in both ears and specialization of the human cerebral hemisphere. Primary sensations (loudness, pitch and timbre) and spatial sensations from a given source signal and sound field are expressed by temporal and spatial factors extracted from the autocorrelation function (ACF) and interaural cross-correlation function (IACF), respectively [13]. Binaural noise measurements were conducted in order to specify the spatial factors. According to the human auditory-brain system, temporal factors of sound signals are processed by the left hemisphere and spatial factors of sound signals are processed by the right hemisphere [12]. It has already been reported that the human auditory-brain system is effective in environmental noise measurements [14, 15].

2. METHOD

2.1 Noise Measurement

Binaural noise measurements were conducted to record the flushing noise of an upstairs toilet. The location of the noise recording was bedside (Fig. 1), because a resident was annoyed in sleeping time. The noise signals were picked up by 1/2-inch condenser microphones placed at two ear positions on a sphere representing a human head. This dummy head is made of styrene foam with a diameter of 200 mm. The thickness of the styrene foam was 20 mm. Received noise signals were recorded in DAT (digital audio tape). The measurement system is shown in Fig. 2.

In addition to recording the flushing toilet noise, background noise was recorded in order to compare it with the acoustic properties for a flushing toilet noise. The measurement system is the same as that for recording the flushing toilet noise.

The recording was conducted from nine p.m. to one a.m. on the first day, and six a.m. to eight a.m. and nine p.m. to twelve p.m. on the second day. During the measurement, all windows and the bedroom door were closed and an air conditioner was turned off.

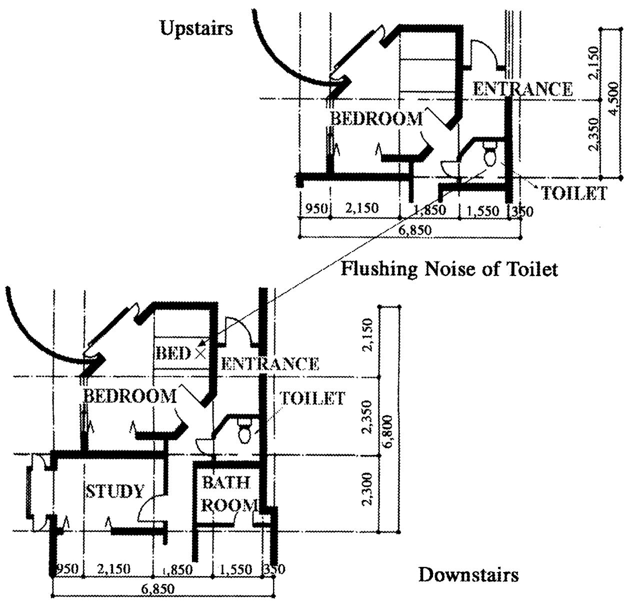

Fig. 1. Plan of the rooms in the apartment. The flushing noise of an upstairs toilet was recorded at bedside.

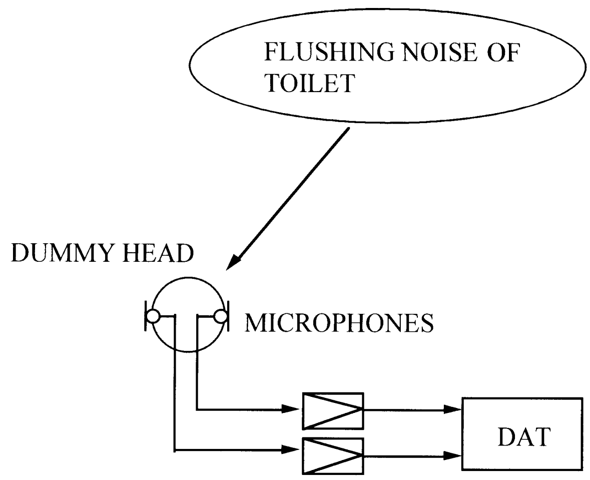

Fig. 2. The measurement system of noise recording.

2.2 Analysis of Acoustical Factors

2.2.1 Autocorrelation Function (ACF)

The autocorrelation function (ACF) is defined by

$$\Phi_p(\tau) = \frac{1}{2T}\int_{-T}^{+T} p'(t)p'(t+\tau)dt \qquad (1)$$

where $p'(t) = p(t)s(t)$, in which $p(t)$ is the sound pressure and $s(t)$ is the ear sensitivity. For convenience, $s(t)$ may be chosen as the impulse response of the A-weighted network. The value τ represents the time delay, and the value of 2T is the integration interval. There are four significant parameters from the ACF [12].

The first factor is a geometrical mean of the sound energies arriving at both ears, $\Phi(0)$, which is expressed by

$$\Phi(0) = \left[\Phi_{ll}(0)\Phi_{rr}(0)\right]^{1/2} \qquad (2)$$

where $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ are the normalized ACFs at delay time $\tau = 0$ for the left and right ears. They correspond to an equivalent sound pressure level. The second factor is the effective duration of the normalized ACF, τ_e, which is defined by a 10-percentile delay of the normalized ACF, representing repetitive features or reverberation contained within the signal itself. The definition of τ_e is shown in Fig. 3(a). Loudness is related to the effective duration of ACF, τ_e [16]. The third and fourth factors are the delay time and the amplitude of the first peak of the normalized ACF, τ_1 and ϕ_1. The definitions of τ_1 and ϕ_1 are shown in Fig. 3(b). These two factors are closely related to the pitch sensation. The perceived pitch and its strength of a sound signal are expressed by τ_1 and ϕ_1, respectively [17].

2.2.2 Interaural Cross-correlation Function (IACF)

To specify the spatial characteristics of sound signals, binaural measurements must be conducted. Three factors were extracted from the interaural cross-correlation function (IACF) [12]. The cross-correlation function between the sound signals at both ears, $f_l'(t)$ and $f_r'(t)$, is given by

$$\Phi_{lr}(\tau) = \frac{1}{2T}\int_{-T}^{+T} f_l'(t) f_r'(t+\tau)\,dt \tag{3}$$

where $f_l'(t)$ and $f_r'(t)$ are approximately obtained by signals $f_{l,r}(t)$ after passing through the A-weighting network.

The normalized IACF is defined by

$$\phi_{lr}(\tau) = \frac{\Phi_{lr}(\tau)}{\sqrt{\Phi_{ll}(0)\Phi_{rr}(0)}} \tag{4}$$

where the values of $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ represent the sound energies arriving at the left and right ears. The denominator represents the geometrical mean of the sound energies arriving at both ears.

The magnitude of the IACF is defined by

$$IACC = \left|\phi_{lr}(\tau)\right|_{\max}, \quad |\tau| \le 1 \text{ ms} \tag{5}$$

The value of the IACC, which represents the degree of similarity of sound waves arriving at each ears, corresponds to the subjective diffuseness in the sound field [12]. The factor τ_{IACC} is the interaural time delay at the maximum peak, which determines the IACC. It represents the horizontal sound localization and the balance of the sound fields. When τ_{IACC} is zero, the front-sound-source image and a well-balanced sound field are perceived. The factor W_{IACC} is defined as the time interval at the IACF within 10 % of the maximum value. It is related to the apparent source width (ASW) [18]. Three spatial factors extracted from the IACF are shown in Fig. 4.

3. RESULTS AND DISCUSSION

3.1 Temporal Factors Extracted from ACF

The measured factors extracted from the ACF are shown in Figs. 5(a)-(d). Solid lines indicate values for a typical example of the flushing toilet noise and dotted lines indicate the background noise. The measurement time was 5 s. The values of all factors were obtained every 100 ms with an integration interval of 0.5 s.

As shown in Fig. 5(a), the $\Phi_{ll}(0)$ values for the flushing toilet noise are distributed between 30 and 35 dBA, but the background noise is about 23 dBA. The signal-to-noise ratio was 12 dBA at maximum. If the difference between the background noise level and the noise signal level is greater than 10 dB, the background noise does not affect significantly the noise signal measurement [19]. Thus, we see that the resident was able to perceive easily the flushing toilet noise as a noise.

As shown in Fig. 5(b), the τ_e values for the flushing toilet noise sometimes exceed 50 ms. On the other hand, the background noise was below 0.1 ms in all measurement times.

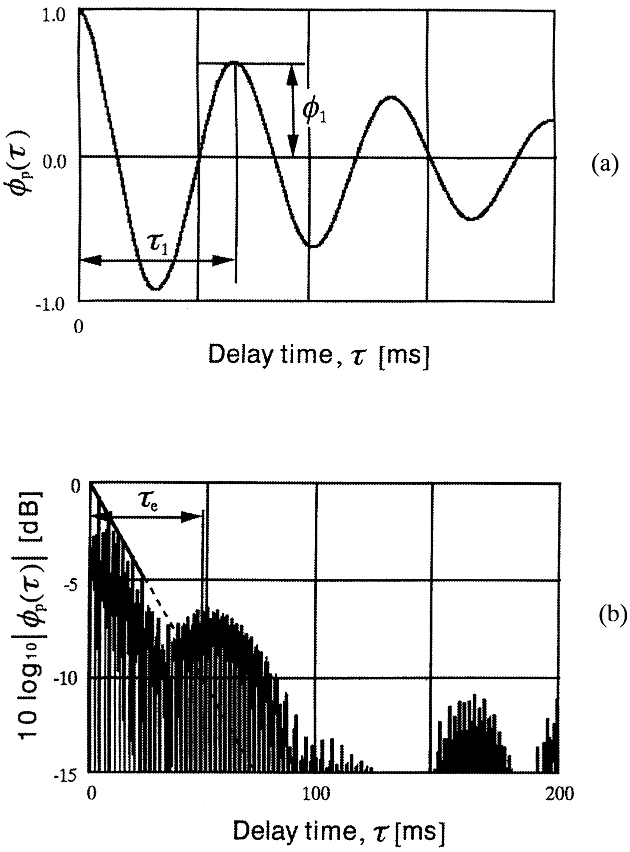

Fig. 3. Definition of independent factors extracted from the normalized ACF. (a) τ_e defined by the ten-percentile delay (at −10 dB), obtained practically from the decay rate extrapolated in the range from 0 dB to −5 dB of the normalized ACF; and, (b) τ_1 and ϕ_1 in the fine structure of the normalized ACF.

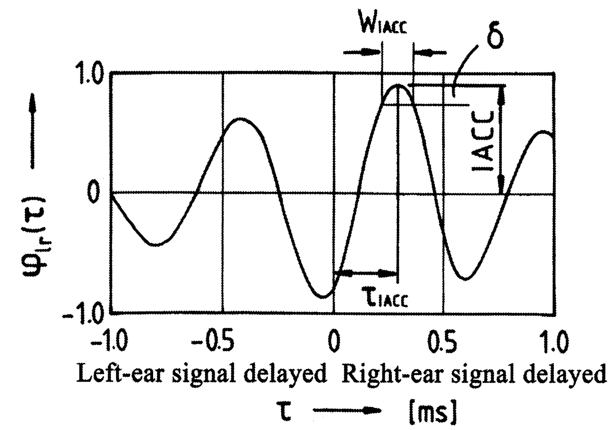

Fig. 4. Definition of independent factors extracted from the normalized IACF, IACC, τ_{IACC} and W_{IACC}.

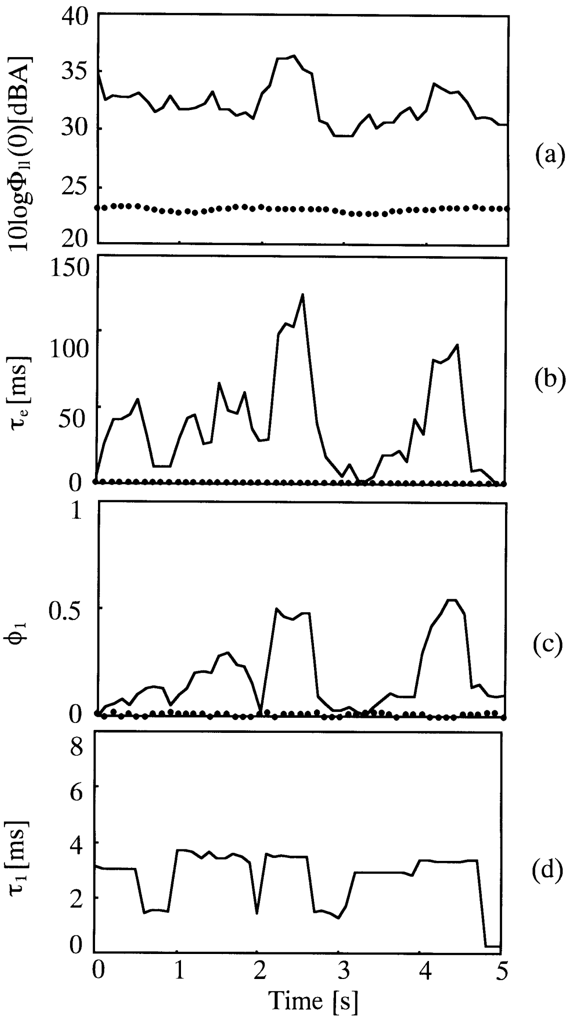

Fig. 5. Measured factors extracted from ACF. Solid line indicates values for the flushing toilet noise and dotted line indicates the background noise. (a) $\Phi_{ll}(0)$; (b) τ_e; (c) τ_1; and, (d) ϕ_1. Measurement time was 5 s. The values of all factors were obtained every 100 ms with an integration interval of 0.5 s.

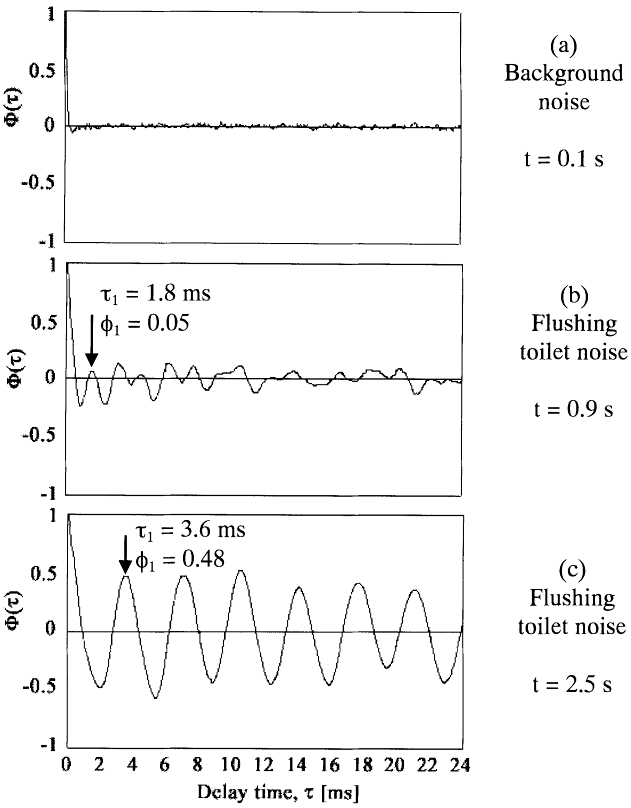

Fig. 6. Example of normalized ACF for the background noise and the flushing toilet noise. (a) Normalized ACF for the background noise measured at t = 0.1 s; (b) and (c) Normalized ACF for the flushing toilet noise measured at t = 0.9 s and 2.5 s, respectively.

Thus, the flushing toilet noise had many more repetitive features than the background noise. It has been reported that loudness increases in proportion to the value of τ_e [16]. The τ_e values for the flushing toilet noise became larger near the $\Phi_{ll}(0)$ peak, as shown in Fig. 5(a). Judging from these results, we may say that the value of τ_e increased the loudness perception of the flushing toilet noise although their SPL was low.

As shown in Fig. 5(c), the ϕ_1 values for the flushing toilet noise were much higher than those for the background noise, which ϕ_1 values were below 0.1 in all measurement times. The background noise did not have clear pitch and tonal components, as white noise components. In such cases, the τ_1 values for the background noise do not correspond to a specific pitch. This is clearly represented in Fig. 6(a), which shows the example of a measured normalized ACF for the background noise measured at t = 0.1 s. The amplitude of the first peak was very small. In addition, as shown in Fig. 7(a), which shows the power spectrum for the background noise measured at t = 0.1 s, there were no specific frequency components. Thus, the τ_1 values for the background noise are not shown in Fig. 5(d). On the contrary, the ϕ_1 values for the flushing toilet noise had strong peaks, as shown in Figs. 6(b) and 6(c), which expresses an example of the measured normalized ACF for the flushing toilet noise measured at t = 0.9 s and 2.5 s, respectively. In such cases, the tonal components increased and the perceived pitch became stronger at the dominant pitch corresponding to its τ_1 values.

As shown in Fig. 5(d), the τ_1 values for the flushing toilet noise are distributed mostly at about 1.8 ms and 3.6 ms, which means that the perceived pitches of the flushing toilet noise varied about 550 Hz and 275 Hz. This is clearly represented in Figs. 7(b) and 7(c), which shows the power spectra for the flushing toilet noise measured at t = 0.9 s and 2.5 s. The flushing toilet noise had peak frequency components at 550 Hz

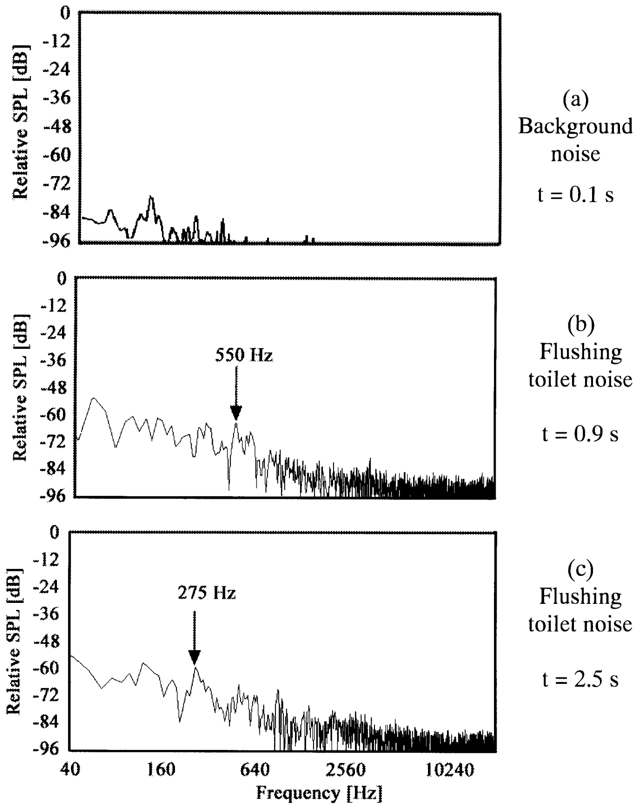

Fig. 7. Power spectra of noise sources. (a) power spectrum for the background noise measured at t = 0.1 s.; (b) and (c) power spectra for the flushing toilet noise measured at t = 0.9 s and 2.5 s, respectively.

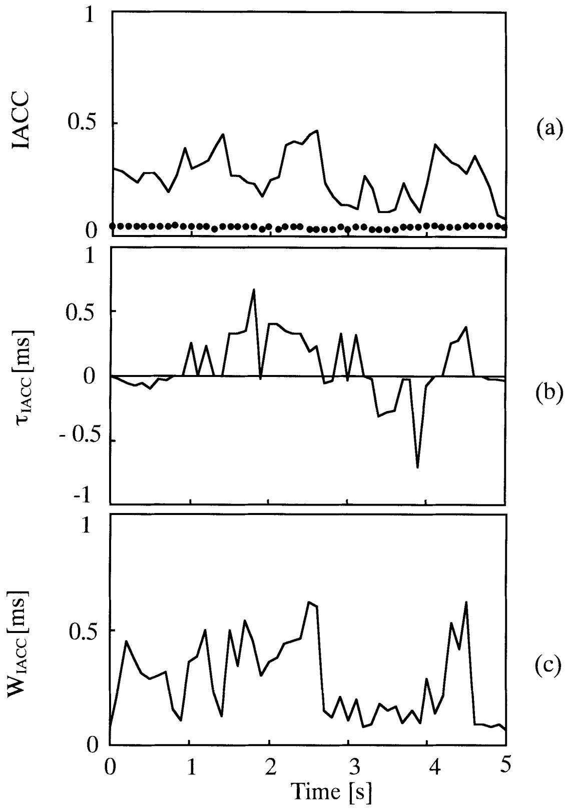

Fig. 8. Measured factors extracted from IACF. Solid line indicates values for the flushing toilet noise and dotted line indicates the background noise. (a) IACC; (b) τ_{IACC}; and, (c) W_{IACC}. Measurement time was 5 s. The values of all factors were obtained every 100 ms with an integration interval of 0.5 s.

and 275 Hz. These frequency components correspond to the values of τ_1, expressing the perceived pitch, as shown in Figs. 6(b) and 6(c). As shown in Fig. 7(b), the peak of the frequency components at 550 Hz was weak, because the amplitude of the first ACF peak, ϕ_1, was very small, as shown in Fig. 6 (b).

Both τ_1 and ϕ_1 values for the flushing toilet noise changed extremely as a function of time, as shown in Figs. 5(c) and 5(d). This is also represented in Figs. 6(b) and 6(c). The delay time and the amplitude of the first ACF peak, which correspond to τ_1 and ϕ_1, change extremely as a function of time. This indicates that the perceived pitch and its strength were changing extremely as a function of time.

As shown in Figs. 6(b) and 6(c), the normalized ACF for the flushing noise of toilet had much clearer peaks than that for the background noise, as compared with Fig. 6(a). This means that the flushing noise of toilet had more tonal components than the background noise, which included characteristics as white noise components.

3.2 Spatial Factors Extracted from IACF

The measured factors extracted from the IACF are shown in Figs. 8(a)-(c). As shown in Fig. 8(a), the IACC values for the flushing toilet noise was much higher than that for the background noise. The IACC values for the background noise was below 0.05 in all measurement times. This is clearly represented in Fig. 9, which shows an example of the normalized IACF for the background noise. As shown in Fig. 9, the normalized IACF for the background noise had little peak. The background noise was considered to be

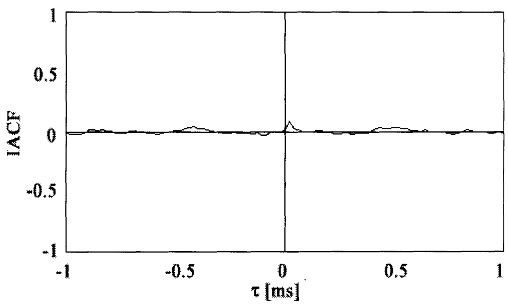

Fig.9. The example of normalized IACF for the background noise.

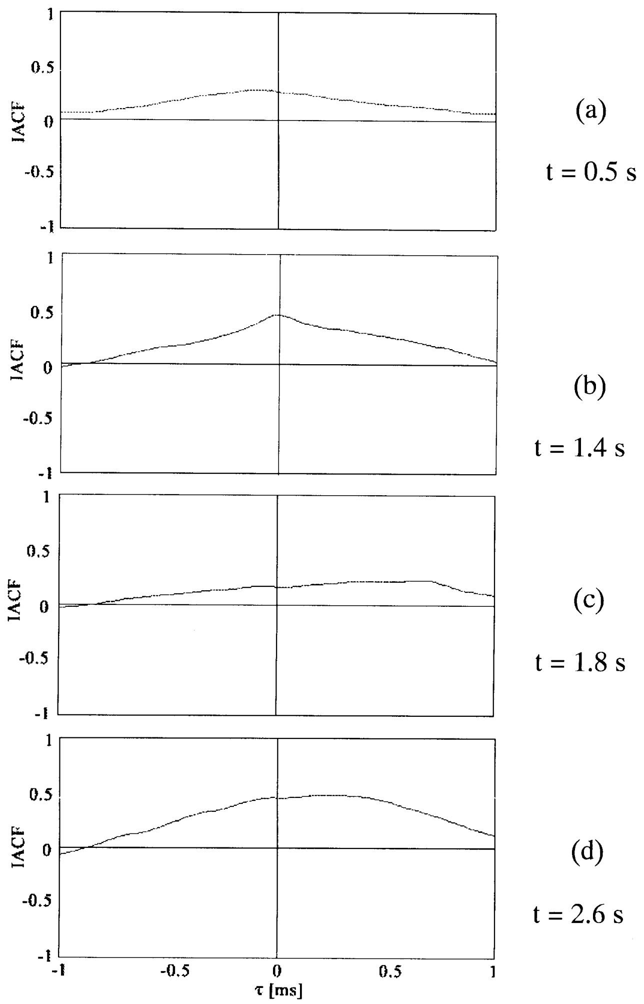

Fig. 10. The examples of normalized IACF for the flushing toilet noise. (a)-(d) measured time at t = 0.5 s, 1.4 s, 1.8 s, and 2.6 s, respectively.

perceived no specific directions and had little spatial information. In this case, the effects of the τ_{IACC} and W_{IACC} values for the background noise are minor. Thus, the τ_{IACC} and W_{IACC} values for the background noise are not shown in Figs. 8(b) and 8(c).

The example of the normalized IACF for the flushing toilet noise, measured at 0.5, 1.4, 1.8, and 2.6 s, is shown in Figs. 10(a)-(d). As shown in Fig. 8(a) and Fig. 10, the IACC was changed dramatically as a function of time. This means that subjective diffuseness for the flushing toilet noise changed dramatically as a function of time.

As shown in Fig. 10(b), the IACF had a strong peak at $\tau = 0$, meaning that the frontal direction of the flushing toilet noise was perceived clearly. The IACF peak changed dramatically as a function of time, corresponding to the behavior of the τ_{IACC} values for the flushing toilet noise, as shown in Fig. 8(b). In such cases, the receiver perceives the noise sources from various directions. This fact corresponds to the resident's comments. Further investigation must focus on the relationship between the characteristics of the room shape and the directional information of the flushing noise of an upstairs toilet.

The values of the W_{IACC} also changed dramatically as a function of time, as shown in Fig. 8(c) and Fig. 10. As a result, the receiver felt various apparent source widths (ASW) [18].

4. CONCLUDING REMARKS

It was found that the temporal and spatial factors extracted from the ACF and IACF for the flushing toilet noise had specific characteristics. This fact indicates that the resident perceived significantly primary sensations (loudness, pitch and timbre) and spatial sensations of the flushing toilet noise. In addition, temporal and spatial factors for the flushing toilet noise changed dramatically as a function of time. According to the human auditory-brain system, temporal information is mainly processed in the left hemisphere and spatial information is mainly processed in the right hemisphere [12]. Judging from the above results, the flushing noise of an upstairs toilet stimulated dramatically both the left and right hemispheres of the resident. This is why the resident felt that the flushing noise of an upstairs toilet was annoying despite its low SPL.

In noise measurements, it is insufficient to evaluate only its SPL and frequency characteristics. Primary sensations and spatial sensations of the noise source must be taken into consideration. Thus, it is highly recommended that not only the SPL and frequency characteristics be measured, but also other temporal and spatial factors, even if their SPL is low.

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