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ACOUSTICAL PROPERTIES OF AIRCRAFT NOISE MEASURED BY TEMPORAL AND SPATIAL FACTORS

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Acoustical properties of aircraft noise were investigated by means of temporal and spatial factors in sound fields based on the model of auditory–brain system (see reference [10]). The model consists of the autocorrelation and crosscorrelation mechanisms for sound signals arriving at two ears and the specialization of human cerebral hemisphere. There are four temporal factors extracted from the autocorrelation function (ACF): (1) sound energy $\Phi(0)$; (2) effective duration of ACF, τ_e; (3) delay time of the first peak, τ_1; and (4) its amplitude ϕ_1. From the interaural crosscorrelation function (IACF), three spatial factors are extracted as (1) magnitude of the interaural crosscorrelation IACC (2) interaural delay time at IACC, τ_{IACC}, and (3) width of the maximum peak of the IACF, W_{IACC}. It is found that the acoustical properties are well represented by the factors extracted from the ACF and the IACF.

1. INTRODUCTION

This paper describes the acoustical properties of aircraft noise in terms of its temporal and spatial factors. Aircraft noise disturbs peoples' daily lives and sometimes causes serious problems such as hearing loss or has an adverse impact on the growth of unborn babies, infants, and children [1–6]. A lot of effort has been spent on noise research and noise reduction technologies [7]. Significant progress has been made on reducing noise level but a big problem remains. Noise has been evaluated only by statistical sound pressure level (SPL), but perceived acoustical properties have not been considered sufficiently [8]. In particular, the relationship between physical properties and psychological affects is not clear. For example, a sound may exist that has a SPL below standards such as EPNL or WECPNL, but that is perceived to be noisy in a given situation. Such an annoyance may be related to primary auditory sensations (pitch, loudness, and timbre) based on the mechanisms in the human auditory–brain system [9].

The most plausible mechanism in the auditory system consists of autocorrelators and a crosscorrelator for analyzing sound signals arriving at both ears [10]. Perceived pitch and its strength of complex tones or complex noises are expressed by the first peak in the autocorrelation function (ACF) of the signal [11]. Loudness is also related to a factor of the ACF, τ_e [12], not only to the SPL. In addition, spatial properties are important for noise evaluation. Noise sources are usually not fixed, but move spatially. We hear a different sound quality when the noise source is coming or going away. Information on location or direction of the sound source, subjective diffuseness, and apparent source width (ASW) can be expressed by the factors extracted from the interaural crosscorrelation function (IACF) [10, 13]. To specify such spatial characteristics, binaural measurements were conducted.

2. METHOD

2.1. MEASUREMENT PROCEDURE

Measurements were taken outdoors near the flight course of Kansai International Airport on January 12, 2000, and near Osaka International Airport on December 13, 1999. Measurement locations are illustrated in Figure 1.

For measurement of noise along the flight course of Kansai Airport, a dummy head was set near the coast. This location is 20 km southwest from the airport, and the flight course for landing is about 1·0 km from the shore. The altitude of the plane used in the measurement was about 1·0 km above the sea level, according to the flight data from the airport. It was cloudy and windless on the ground level during the measurement. The average temperature for the day was 12°C. Ambient noise level in this area was 43 ± 2 dB.

At the Osaka Airport, two locations were chosen close to a runway to measure the noise from aircraft landing and taking off. The distances between the runway and each measuring point was about 100 m. Ambient noise level in this area was higher because of road traffic (60 ± 2 dB). It was cloudy and windless on the ground level. Temperature was about 10°C during the measurement.

Noise signals were received by two 0·5 in condenser microphones set at both ear positions of a sphere representing a human head. This dummy head is made of 20-mm-thick styrofoam with a diameter of 200 mm. Microphones were set at 1·5 m above the ground.

2.2. ANALYSIS OF ACOUSTICAL FACTORS

2.2.1. *Factors from the ACF* ($\Phi(0)$, τ_e, τ_1, *and* ϕ_1)

An autocorrelation function (ACF) is defined by

$$\Phi_p(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{+T} p'(t)p'(t+\tau)\mathrm{d}t, \tag{1}$$

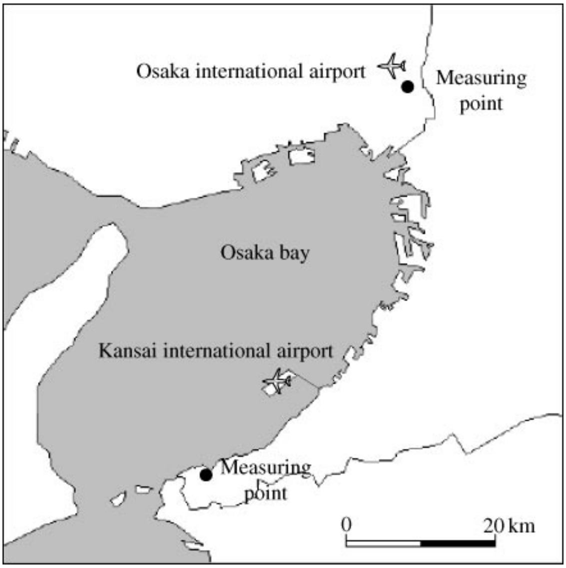

Figure 1. Location of two airports and the measurement points.

where $p'(t) = p(t)s(t)$, in which $p(t)$ is sound pressure and $s(t)$ is ear sensitivity. For practical reasons, $s(t)$ may be chosen as the impulse response of an A-weighting network. The value τ represents the time delay, and the value of $2T$ is the integration interval. There are four significant parameters extracted from the ACF [10].

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

$$\Phi(0) = [\Phi_{ll}(0)\Phi_{rr}(0)]^{1/2}, \tag{2}$$

where $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ are the normalized ACFs at delay time $\tau = 0$ for left and right ears. Sound pressure level is obtained as $\mathrm{SPL} = 10\log_{10}\Phi(0)$. The second factor is the effective duration of the normalized ACF, τ_e, which is defined by 10 percentile delay of the normalized ACF, representing repetitive features or reverberation contained within the signal itself. 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. These two factors are closely related to the pitch sensation [11].

2.2.2. *Factors from interaural crosscorrelation function* ($IACC$, τ_{IACC}, *and* W_{IACC})

For specifying the spatial characteristics of sound signals, three factors were extracted from the interaural crosscorrelation function (IACF). The crosscorrelation function between the sound signals at both ears $f_l(t)$ and $f_r(t)$ is given by

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

where $f_l'(t)$ and $f_r'(t)$ are approximately obtained by signals $f_{l,r}(t)$ after passing through the A-weighting network, as in equation (1).

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 left and right ears. The denominator represents the geometrical mean of the sound energies arriving at both ears.

The magnitude of IACF is defined by

$$IACC = |\phi_{lr}(\tau)|_{max}, \quad |\tau| \leqslant 1\ \mathrm{ms}. \tag{5}$$

The value of IACC represents the degree of similarity of sound waves arriving at each ear. This is a significant factor in determining the degree of subjective diffuseness in the sound field [10]. As IACC decreases the subjective diffuseness increases.

The interaural time delay is defined as τ_{IACC} at which the IACC is decided. It represents the horizontal sound location or direction, and the balance of the sound field. When τ_{IACC} is zero, the front-sound-source image and a well-balanced sound field are perceived. The width of the maximum peak of IACF, W_{IACC}, is defined by the delay time interval 10% below IACC. It is worth noticing that the apparent source width (ASW) could be evaluated by IACC and W_{IACC} [13].

2.2.3. *Conditions for calculating acoustical factors*

Aircraft noise lasts for a certain duration. Its duration depends on the distance between the receiver and the planes or speed of the planes. Noise was measured for 10 s for aircraft landing and 20 s for taking off. During level flying at high altitude, noise lasted about 60 s. Although the sound pressure level fluctuated throughout the flight, the mean level was constant. Therefore, the measurement time for one session was set to 10 s for level flying aircraft with center of maximum SPL.

As sound signals vary continuously, the acoustical factors described above should be calculated in every short interval with a certain duration. In the case of music sources, the integration interval ($2T$ in equation (1)) is between 2 and 5 s. This length is based on the theory of "psychological present", which states that humans perceive successive events as one thing [14]. But in calculating ACF to describe a single syllable for Japanese speech, a much shorter integration interval (30 ms) is used because the speech signal varies in very short time [15].

To capture the correct properties of aircraft noise, an integration interval for ACF and IACF has been examined. Figure 2(a) and (b) show examples of measured SPL for two types of signals with different τ_e (Figure 2, top) integrated for three different intervals. It is clear

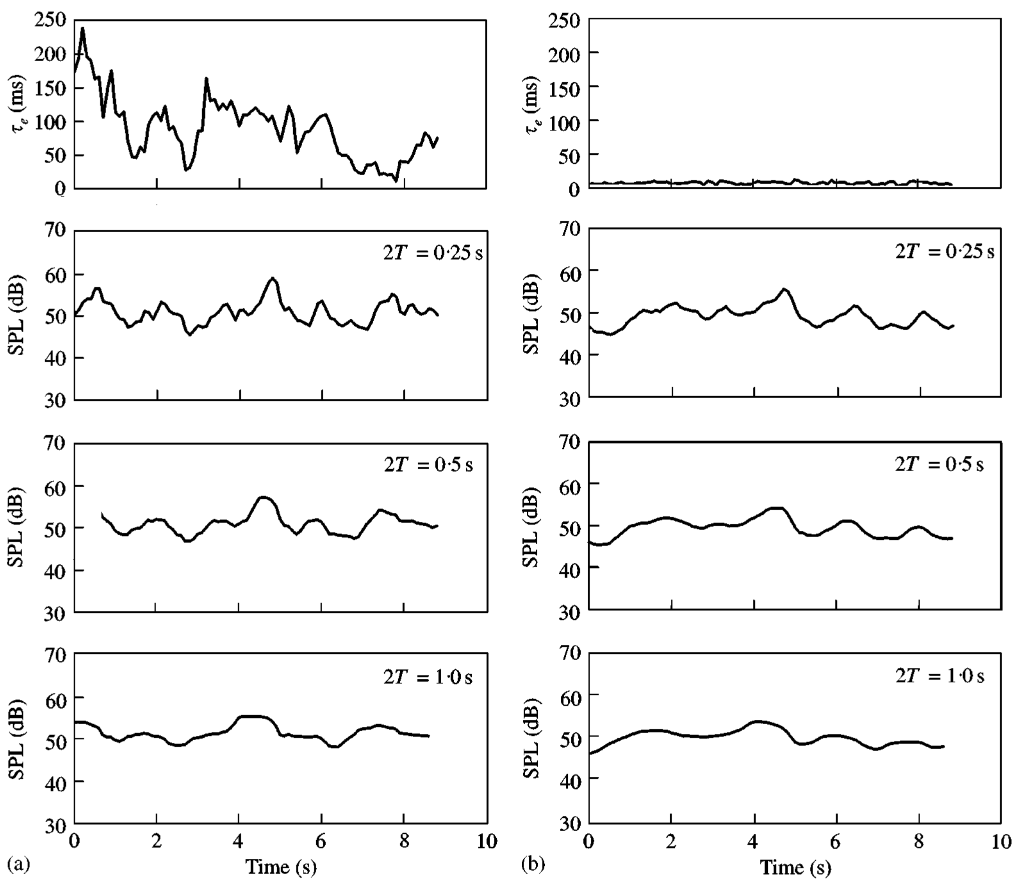

Figure 2. Examples of measured SPL for two different types of noise signals with (a) $(\tau_e)_{min} = 20$ ms and (b) $(\tau_e)_{min} = 10$ ms with three different integration intervals, from the second row, 0·25, 0·5, and 1·0 s.

that an interval of 1 s is too long to capture the fluctuation of sound properties. Such a variation could be caught by 0·25 or 0·5 s integration. The properties throughout the measuring time are the same for both intervals, but a finer variation could be measured in the case of 0·25 s. When listening to the noise with long τ_e (minimum value: 20 ms), these fine variations could not be heard. For the sound with short τ_e (minimum value: 10 ms), on the other hand, 0·25 s integration matches the actual sound fluctuation. Mouri *et al.* [16] reported that the integration interval should be set as $2T \approx 30\ (\tau_e)_{min}$. In this case, the recommended $2T$ is 0·6 and 0·3 s for signals with $(\tau_e)_{min}$ of 20 and 10 ms respectively. In the present study, the integration interval was chosen as 0·5 s for signals with $(\tau_e)_{min} = 20$ ms, and 0·25 s for signals with $(\tau_e)_{min} = 10$ ms.

3. RESULTS AND DISCUSSION

3.1. TEMPORAL FACTORS EXTRACTED FROM ACF

An aircraft flying overhead produces a noise on the ground, which rises above the ambient level, reaches a maximum when the aircraft is approximately overhead, and then decreases again below the ambient level. The properties of the aircraft noise vary throughout the flight. The typical case is one in which the noise is predominantly of high frequency while the aircraft is approaching and is predominantly of low frequency after the aircraft has passed over and is receding. Such characteristics are clearly represented by the factors from the ACF as shown in Figure 3(a)–(c) for the landing condition.

Measured SPL is shown as a function of time; at $t = 5{\cdot}0$ s the aircraft was directly overhead. The duration above the ambient level was about 10 s. The delay time and the amplitude of the first peak in ACF, τ_1 and ϕ_1, represent the perceived pitch and its strength. The reciprocal of τ_1 corresponds to the perceived pitch. Results indicate that the perceived pitch varied throughout the flight. As the aircraft approached, τ_1 was about 1 ms with the value of ϕ_1 increasing. The strongest pitch of 3300 Hz was perceived when the aircraft passed overhead, at which the value of τ_1 was 0·3 ms. Such a strong tonal component is emitted from fan exhaust. After the aircraft passed over, the τ_1 value increased and the ϕ_1 value decreased simultaneously, indicating that the noise was dominated by the lower frequency components produced by the jet exhaust.

Power spectra and the ACF measured at $t = 1{\cdot}0$, 5·0, and 7·0 s are illustrated in Figure 3(b) and (c). They show that τ_1 and ϕ_1 represent the properties of aircraft noise clearly; at $t = 1{\cdot}0$ s there is a small peak around 1000 Hz, which is perceived as a noise with a weak pitch; at $t = 5{\cdot}0$ s there is a high-frequency component at 3300 Hz perceived as a tonal sound; and at $t = 7{\cdot}0$ s the strong peak disappears and the lower frequency components increases below 500 Hz, which is perceived like white noise.

For the same type of aircraft during taking off, the duration above the ambient level was approximately 20 s, longer than that of the landing condition. The acoustical properties of taking-off aircraft were somewhat different from those of the landing aircraft. The ϕ_1 value was always below 0·2, which means the high-frequency tonal components were lessened and low-frequency components were pronounced. This is possibly because the engine power is higher and the aircrafts is rising rapidly. Thus, high-frequency components are attenuated and more jet noise is produced.

Figure 4(a) show the measured factors for the aircraft during level flying overhead at an altitude of about 1 km, and measured power spectra and normalized ACF are shown in Figure 4(b) and (c). The noise for level flying aircraft was classified into two typical cases. The SPL throughout the flight fluctuated in the same manner, but the values of τ_1 and ϕ_1 were extremely different for each case. The value of τ_1 for the two cases was almost the

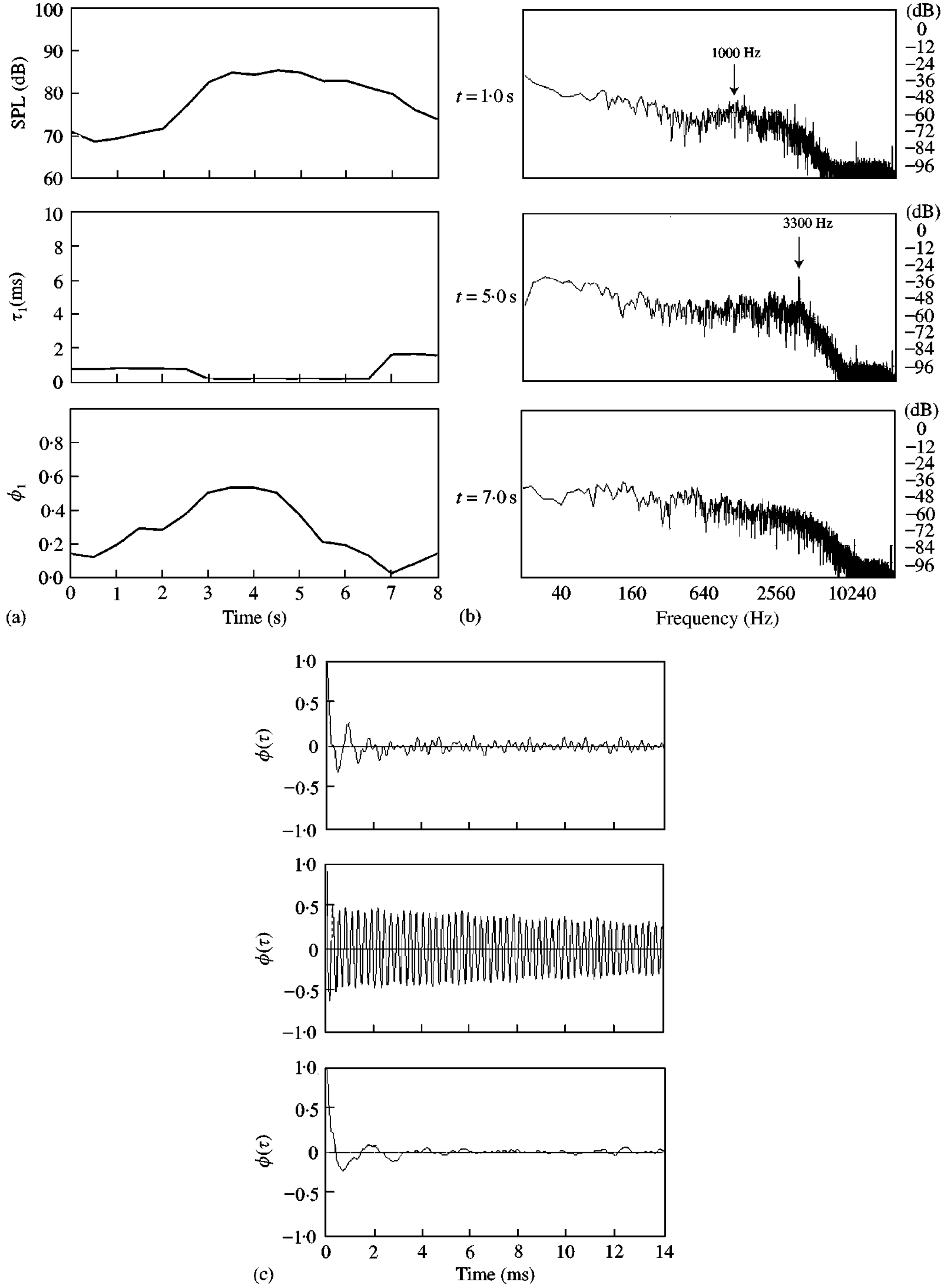

Figure 3. Results for (a) measured SPL (top), τ_1 (middle), and ϕ_1 (bottom) for landing aircraft as a function of time, (b) power spectra and (c) normalized autocorrelation functions at t = 1·0, 5·0, and 7·0 s.

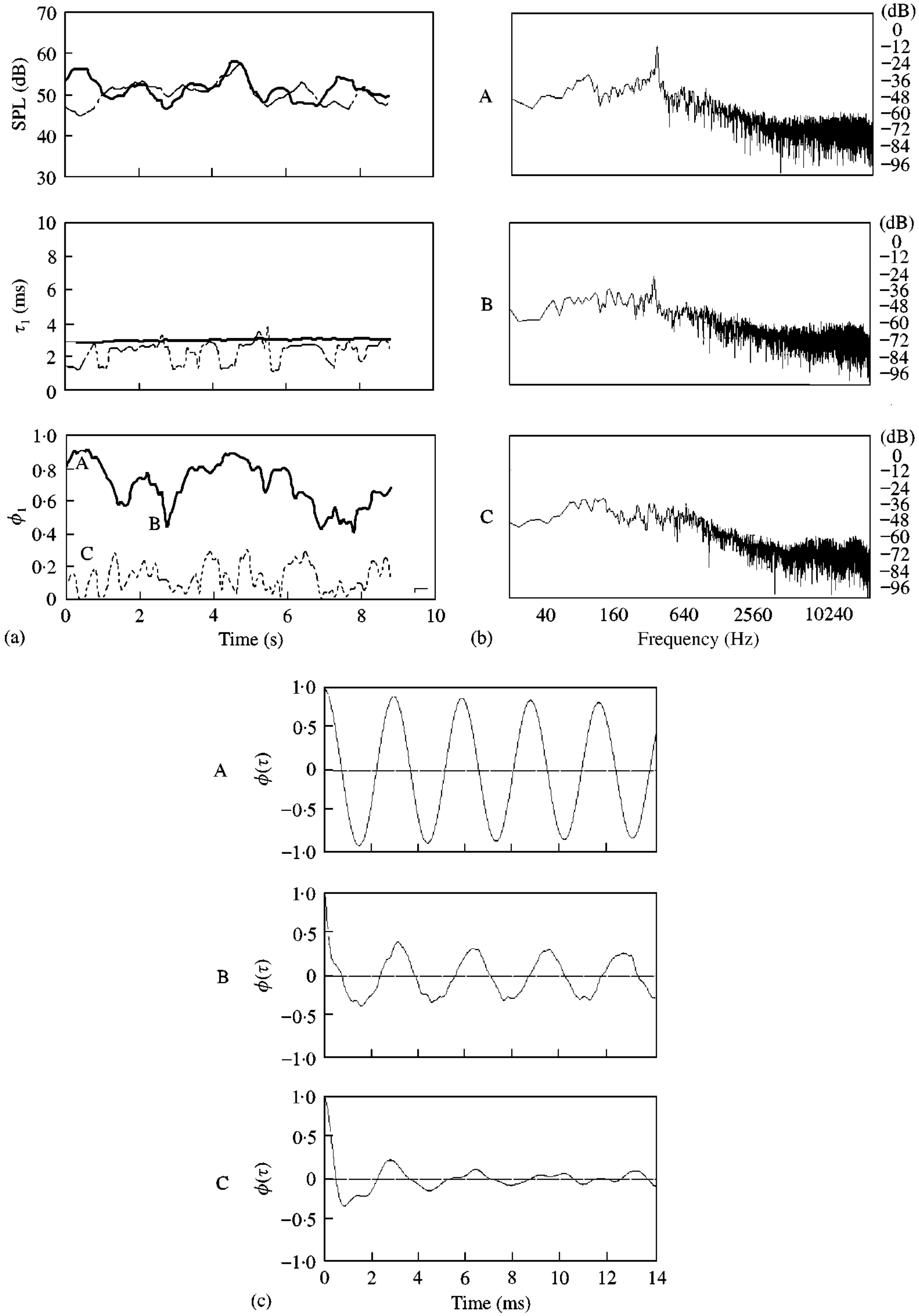

Figure 4. (a) Measured SPL, τ_1, and ϕ_1 for level flying aircraft: ——, tonal noise, – – –, un-tonal noise. (b) Examples of spectrum and (c) normalized ACF, measured at A, B, and C shown in Figure 4(a).

same (mean value: 3·06 and 2·45 ms), but the ϕ_1 value for one case varied dramatically throughout the flight. At times with high ϕ_1, a tonal sound was heard and its pitch strength fluctuated in relation to SPL. In other words, when the noise contained a strong tonal component, the total SPL increased. This phenomenon may be related to diffusion, air absorption, or the scattering reflection of sound caused by air conditions such as wind or clouds.

3.2. SPATIAL FACTORS EXTRACTED FROM IACF

The normalized interaural crosscorrelation function (IACF) is shown in Figure 5(a) for landing, taking off, and level flying conditions. The values of IACC, τ_{IACC}, and W_{IACC} were found from them. Measured IACC is shown in Figure 6(b) as a function of time. For the landing and taking-off conditions, the IACF had a strong peak at $\tau \approx 0$, meaning that the direction of the noise source is perceived clearly. The value of IACC decreased when the aircraft passed overhead for landing, possibly because the noise was dominated by the

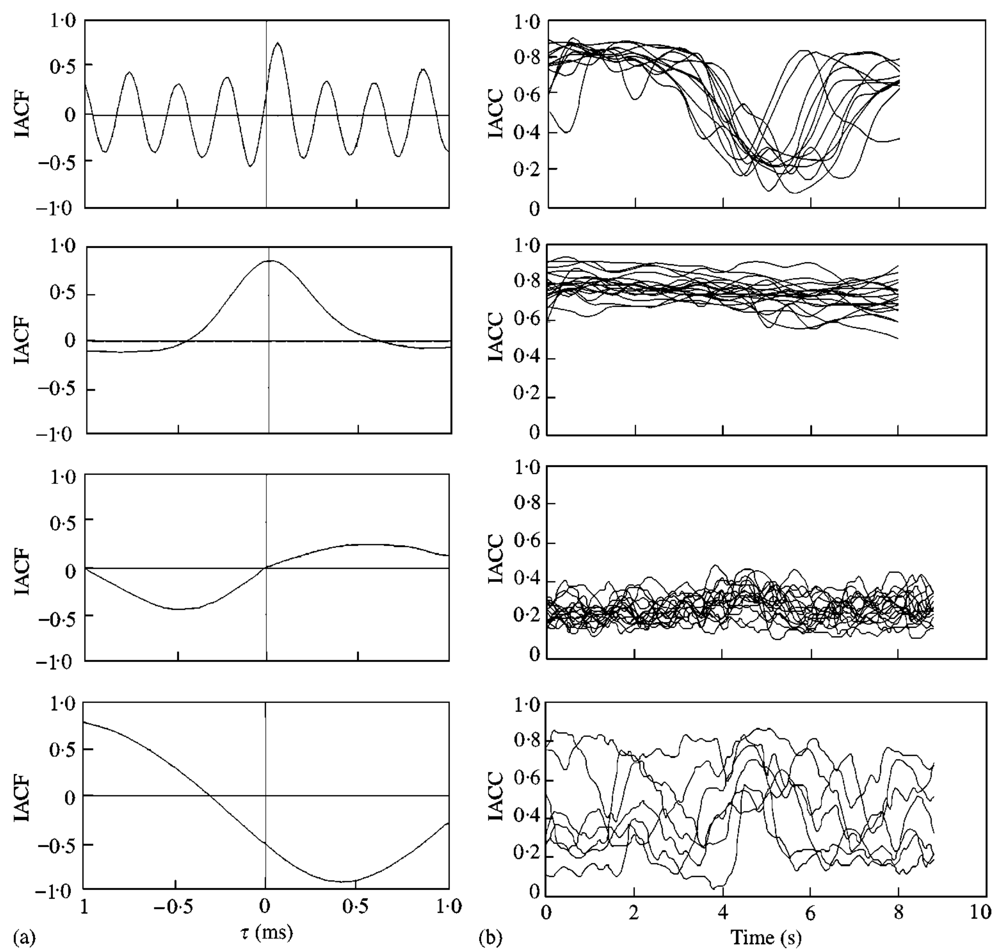

Figure 5. (a) Normalized interaural crosscorrelation function and (b) measured IACC as a function of time for the conditions of landing (top), takeoff (second row), level flying 1 (third row), and level flying 2 (bottom).

high-frequency component produced by fan exhaust. The value of W_{IACC} is dependent on the dominant frequency of the sound. For the taking-off condition, W_{IACC} was large because of the low-frequency components.

The value of IACC was generally small for the level flying condition. In this case, subjective diffuseness became high or no spatial impression was perceived. For flying aircraft at high altitude, the sound signals may come from various directions because of diffusion or the scattering reflections by clouds. It was also found that the value of IACC increased when the noise was dominated by tonal components. It is possible that such a tonal component reached the ground from the aircraft directly.

The value of τ_{IACC} for landing and taking-off aircraft was always close to zero, which means that the sound source is perceived for a frontal direction. On the contrary, for level flying condition the value of τ_{IACC} could not be calculated in many cases because the peak of the IACF shifted over 1 ms. The value of W_{IACC} was also larger for level flying than for landing or takeoff conditions. As a result, information about sound source direction may be lost and apparent source width (ASW) may become wider.

4. GENERAL DISCUSSION

It was found that the measured temporal and spatial factors represent the acoustical properties of aircraft noise well. Although the results has already been reported such that the dominant frequency component varies throughout the flight for landing aircraft [17], the present ACF analysis represents these properties simply and clearly.

For the level flying condition, aircraft noise was classified as either tonal noise or un-tonal noise with low-frequency components. For the tonal noise, the value of τ_e becomes longer because of the repetitive component of the signal. It has been reported that loudness increases in proportion to the value of τ_e [12]. It is possible that the aircraft noise including tonal component is perceived louder than the un-tonal noise. Psychological experiments should be performed to examine the relationship between loudness and the value of τ_e for aircraft noise.

The spatial properties of aircraft noise are also interesting. It was found that the value of IACC decreases and W_{IACC} increases for the level flying condition. This phenomenon may be related to the scattering reflection by clouds in the sky. The aircraft noise for level flying condition may cause higher subjective diffuseness and wider ASW. Psychological tests on spatial impressions also need to be performed to examine the correspondence between the measured physical properties and psychological perceptions or evaluations for the aircraft noise.

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