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MEASUREMENT OF REGIONAL ENVIRONMENTAL NOISE BY USE OF A PC-BASED SYSTEM. AN APPLICATION TO THE NOISE NEAR AIRPORT "G. MARCONI" IN BOLOGNA

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Measurements of aircraft noise were made at the airport "G. Marconi" in Bologna by using a measurement system for regional environmental noise. The system is based on the model of the human auditory–brain system, which is based on the interplay of autocorrelators and an interaural cross-correlator acting on the pressure signals arriving at the ear entrances, and takes into account the specialization of left and right human cerebral hemispheres (see reference [8]). Measurements were taken through dual microphones at ear entrances of a dummy head. The aircraft noise was characterized with the following physical factors calculated from the autocorrelation function (ACF) and interaural cross-correlation function (IACF) for binaural signals. 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, τ_1, and (4) its amplitude, ϕ_1 were extracted. From the IACF analysis, (5) IACC, (6) interaural delay time at which the IACC is defined, τ_{IACC}, and (7) width of the IACF at the τ_{IACC}, W_{IACC} were extracted. The factor $\Phi(0)$ can be represented as the geometrical mean of the energies at both ears. A noise source may be identified by these factors as timbre.

1. INTRODUCTION

It has been shown that the environmental noises, such as aircraft, traffic, railway, industrial, machinery, and community noise, not only disturb conversation and sleep, but also affect the human body such as by affecting the growth of unborn babies, infants, and children [1–6]. Such serious and accumulative effects are unconscious. Environmental noise is usually evaluated statistically as a sound pressure level (SPL), measured by a sound level meter and its frequency characteristic [7]. For the evaluation of aircraft noise, WECPNL has been adopted as one of the physical factors.

For these environmental noises, binaural measurements should be conducted to reflect the human psychological or physiological activity. In the field of concert hall acoustics, binaural measurements are widely used for subjective evaluations based on the model of the human auditory–brain system [8], which is based on the interplay of autocorrelators and

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an interaural cross-correlator acting on the pressure signals arriving at the two ear entrances and takes into account the specialization of left and right human cerebral hemispheres. For example, a sound may exist that is perceived to be noisy even though the SPL of the sound is quite low in a given situation. Moreover, the phenomenon that the fundamental pitch of a complex tone, can be perceived by a person, is well known as the "phenomenon of the missing fundamental". In the phenomenon, the pitch of harmonic components without a fundamental frequency is perceived as being the same as the pitch of a pure tone of the fundamental frequency. However, this fundamental pitch cannot be obtained by the frequency analysis of the signal. The phenomenon cannot be explained from a frequency analysis when the complex tone consists of random-phase components, but it can be explained by a factor extracted from ACF analysis [9]. Moreover, loudness is related to not only SPL, but also to τ_e, which is another ACF factor [10]. Considering these facts, the use of ACF analysis for the psychological evaluation of noise is quite reasonable. The physical factors extracted from ACF and IACF analyses can be used to identify a noise source as timbre by using a multi-dimensional analysis. In addition, a short-time moving (running) ACF and IACF as described in section 3.1 can be adopted for evaluating time-variant noise.

In order to distinguish specific noises from other noises, an observer must continuously monitor a target sound during a measurement or check the whole recorded data after the measurement. Since the 1980s, environmental noises have been measured automatically with on-line data communication using a modem and a laptop computer [11]. For aircraft noise, the source of a noise can be identified by the variation in intensity of a specific electric wave from a specific aircraft (1090 MHz). It is also possible to obtain flight routes by using three microphones at two different locations.

As an example of regional environmental noise measurement using the model described above, aircraft noise was measured at the airport "G. Marconi" in Bologna in Italy. Each physical factor can be obtained as fine structures of running ACF and running IACF after passing through A-weighting network of binaural signals.

2. METHOD

2.1. MEASUREMENT LOCATIONS

Noise measurements were conducted in a residential area near the airport "G. Marconi" in Bologna on October 5 and 6, 1999 (see Figure 1). They were taken at two locations around the airport, marked A and B in Figure 1. The distances between the airstrip and the two locations were about 200 and 250 m. There is only one airstrip at the airport. At location A, some apartments or houses were situated behind the receiver. At location B, there were no buildings near the receiver, as measurement was conducted on the bank along the airport.

2.2. MEASURED AIRCRAFT NOISE

The target sound sources were aircraft landing and taking off. Information on the types of aircraft and their flight schedules were available for the measurement days. The sound sources were categorized in five different states: landing ("land"), taxing just after landing ("land_stop"), taking off ("takeoff"), taxing for takeoff ("takeoff_2"), and waiting for takeoff ("waiting") (see Table 1). The category names are given in parentheses.

Noise radiated from aircraft is caused by (1) the sound of the engine (jet engine or propeller), (2) the resistance or friction between the aircraft body and the airstrip, and (3) the

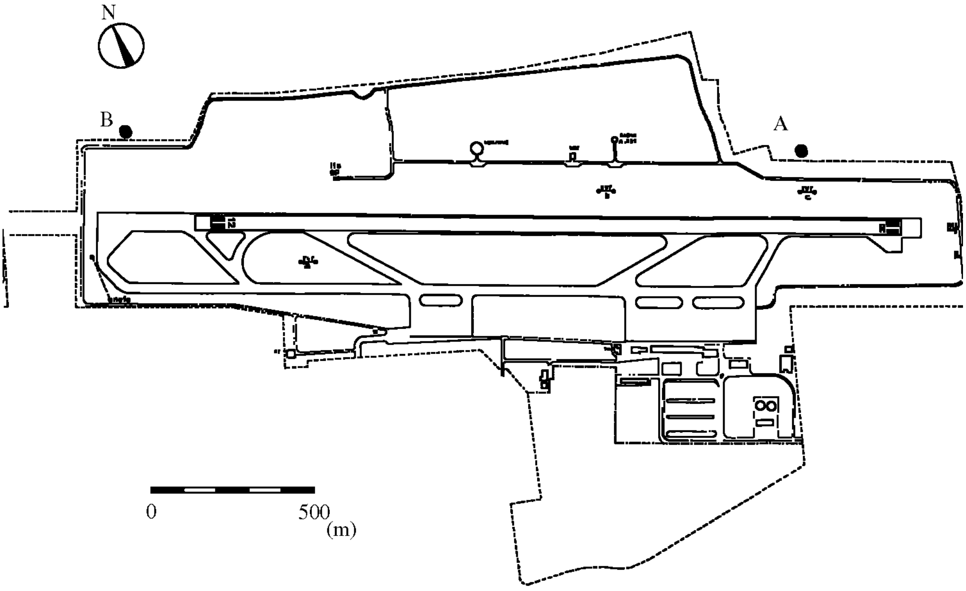


Figure 1. Map of the airport where the measurements were conducted. A and B represent the two locations for the measurements.

TABLE 1

Measurement data categories and number of sessions

	Location A	Location B
Landing	2	12
Land_stop	0	5
Takeoff	7	14
Takeoff_2	1	2
Waiting	2	3
Total	12	36

resistance or friction between the aircraft body and the atmosphere. Noise from fans or propellers has strong directivity in the direction of the shaft. Noise from a jet engine also has strong directivity diagonally behind the exhaust gas. The takeoff and landing speeds for each aircraft were not measured during the noise measurements. In general, the speed of a B747 is between 200 and 400 km/h, and aircraft land into the airstrip with about three-degree inclination.

2.3. PROCEDURES

The measurement system, illustrated in Figure 2, was controlled by a laptop computer (CPU speed: 366 MHz; Main memory: 143 MB) with the measurement software. Noise was recorded in the computer at a sampling frequency of 44·1 kHz. Half-inch dual-channel condenser microphones were attached to the opposite sides of a sphere made of styrene foam and having a diameter of 200 mm. The sphere was used as a dummy head during

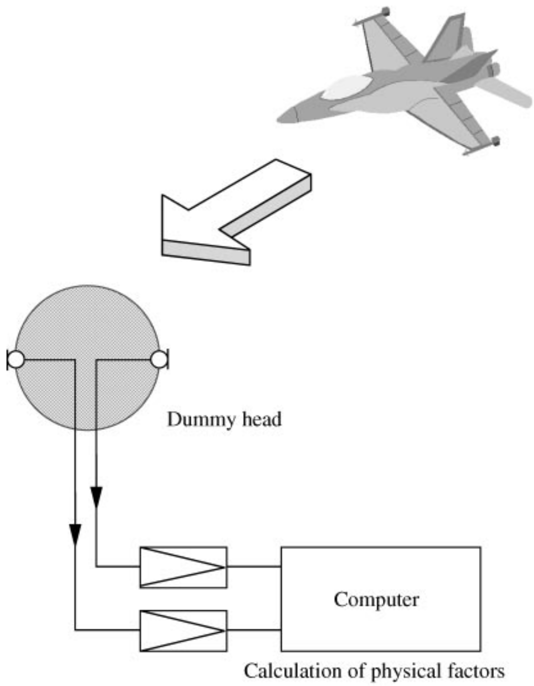


Figure 2. Block diagram of measurement system. Height of the condencer microphones was 1·5 m from the ground level.

the measurements. The thickness of the styrene foam was 20 mm. The microphones were set 1·5 m above the ground, and electrical power was supplied by the batteries of the computer. The two microphones were fixed to be parallel to the airstrip.

2.4. ATMOSPHERICAL CONDITIONS

Temperature, wind speed, and wind direction data were also available from the control tower were available for the measurement days. The average temperature was 13·8° for both days. The average wind speed was 5·0 m from the north–northwest on the first day, and 4·2 m from the west–northwest on the second day.

3. CALCULATION OF PHYSICAL FACTORS

3.1. PHYSICAL FACTORS IN NOISE FIELDS

Physical factors in noise fields, described in the following subsections, were obtained as fine structures of ACF and IACF for dual channel signals after passing through the A-weighting network, which approximates human ear sensitivity. As environmental noise varies continuously, these functions are calculated at every given interval (integration intervals). The starting time of each integration interval is delayed for a short time (say, every 100 ms). The time is called the running step. In the case of a sound source for music, the length of the integration interval may be taken to have a duration between 2 and 5 s, which a person feels the duration of time of what is considered to be "now" [12]. However, it is probably better to use a shorter integration interval, say 0·5 s, for the aircraft noise. The measurement time for one session was 10·0 s with the mid point of this duration at the center of the maximum $\Phi(0)$, which is one of the ACF factors.

3.2. FACTORS EXTRACTED FROM THE AUTOCORRELATION FUNCTION

Orthogonal factors, extracted from the running ACF, are described here [13]. The first factor is the geometrical mean of the sound energies arriving at both ears $\Phi(0)$. This factor is expressed by

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

where $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ are, respectively, the ACFs at the origin of the time delay for the left and right ears. They correspond to an equivalent sound pressure level. The second factor is the effective duration of ACF, τ_e. This factor is defined by the 10-percentile delay representing a kind of repetitive feature or reverberation within the source signal itself. The third and fourth factors are the amplitude and the delay time of the first dominant peak of NACF represented, respectively, as ϕ_1 and τ_1. As can be easily understood, the factors ϕ_2, $\phi_3, \ldots$ and τ_2, $\tau_3, \ldots$ are closely related to ϕ_1 and τ_1.

3.3. FACTORS EXTRACTED FROM THE INTERAURAL CROSS-CORRELATION FUNCTION

To specify the spatial characteristics of the sound signal, binaural measurements must be conducted. The physical factors are extracted as fine structures of the interaural cross-correlation function (IACF). The first factor is IACC, which is the maximum value of the normalized interaural cross-correlation function for the time delay, within ± 1 ms, which corresponds to subjective diffuseness. The second and third factors are interaural time delay, τ_{IACC}, and width of the IACF, W_{IACC}. The factor τ_{IACC} is interaural time delay at the maximum peak, which determines IACC. This factor corresponds to the horizontal sound localization and the balance of the sound field. In particular, directional information of the noise source can be obtained from this factor. The factor W_{IACC} is defined as the time interval at the IACF within 10% of the maximum value. This factor is related to the apparent source width [14].

Although $\Phi(0)$ is not the IACF factor, the factor $\Phi(0)$ is implied as a binaural factor. This factor is a denominator of the normalized interaural cross-correlation function.

4. RESULTS

As an example, the results of all eight physical factors obtained from ACF and IACF are shown in Figure 3 (14 sessions). Each factor can be represented as a temporal function. As described in section 3.1, values for each factor were obtained every 100 ms with an integration interval of 0·5 s.

As the measurements were conducted at two different locations, the results were divided between locations because of the following reasons. First, the distances between the airstrip and the receivers at each location were different. As a result, for example, average values of $\Phi(0)$ at both locations greatly differed because of attenuation. Second, as shown in Figures 4(a) and 4(b), strong reflections from the surface of the buildings around location A reduced the IACC values, whereas location B had no reflective surface around the receiver. Third, the measurement results of the factors were closely related to the directivities of noise sources.

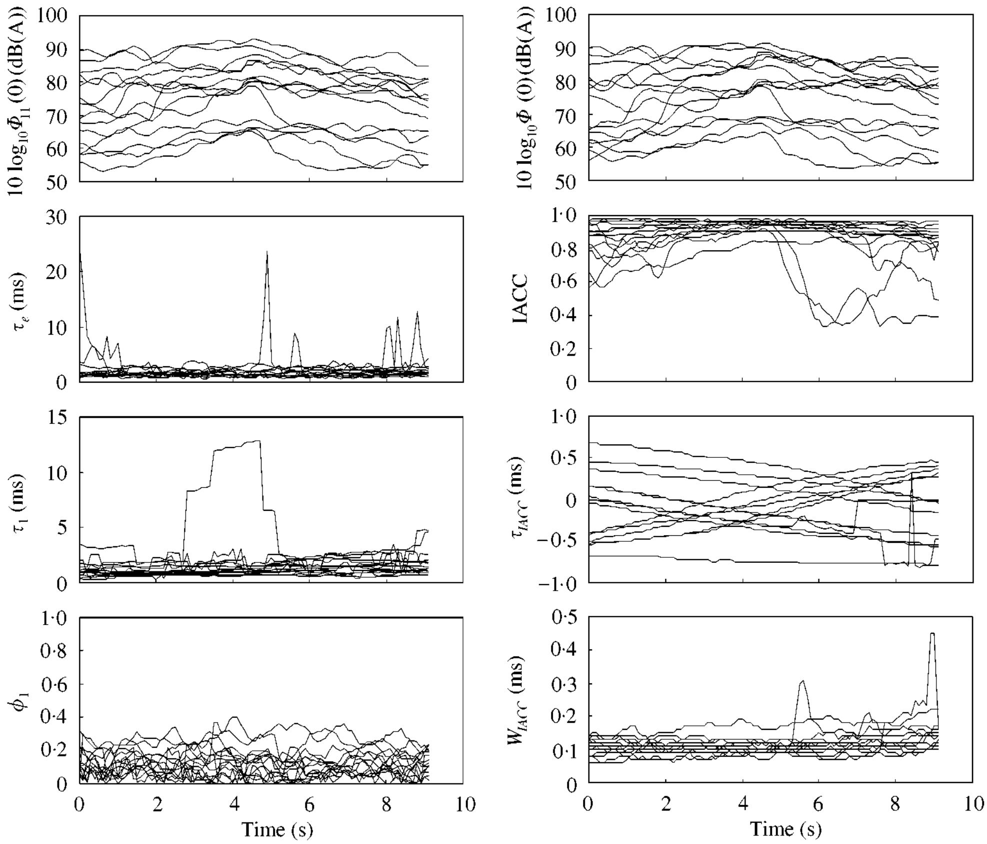


Figure 3. Examples of measurement results for all physical factors extracted from the autocorrelation function (ACF) and interaural cross-correlation function (IACF).

The direction of takeoffs was not constant during the measurements, although all landing aircraft moved in a constant direction (from west to east in Figure 1). In practice, the direction of landings or takeoffs depends on atmospherical conditions according to indications from the control tower. Because of the direction of movement, the physical characteristics of noise radiating from specific parts of aircraft vary greatly. For example, for an aircraft landing from the west, the noise around the moment when the aircraft touches the ground gives the $\Phi(0)$ peak at location B, although this peak does not appear at location A until the aircraft is running on the airstrip after landing. Considering this fact, the landing condition at location A can be regarded as having characteristics similar to those of "land_stop". These are the reasons for dividing the measurement results according to the location.

Average values for the factors $\Phi(0)$, τ_e, τ_1, ϕ_1, and IACC are shown in Figure 5. The upper four categories indicate the results for location A, and the lower ones for location B. The open circles indicate the average values over 10 s for each session. The closed circles indicate the average values for all sessions for each category.

As shown in Figures 6(a) and 6(b), the $\Phi(0)$ values for landing were distributed over a smaller range (standard deviation = 4·90 in dB(A) at location B when the one exception with the largest $\Phi(0)$ is eliminated) than those for takeoff (SD = 10·3 at location B).

As shown in Figure 6(c), for "land_stop" at location B, the factor $\Phi(0)$ rapidly increased before its peak, although the variation in $\Phi(0)$ was smaller after the peak. For just after

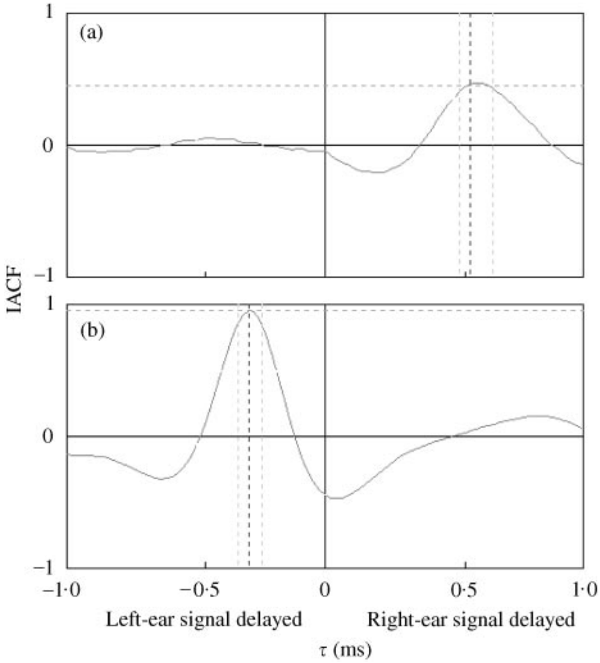


Figure 4. Examples for IACF. (a) IACF with IACC reduced by reflective surface of the buildings at location A (landing); (b) IACF with larger IACC at location B (landing).

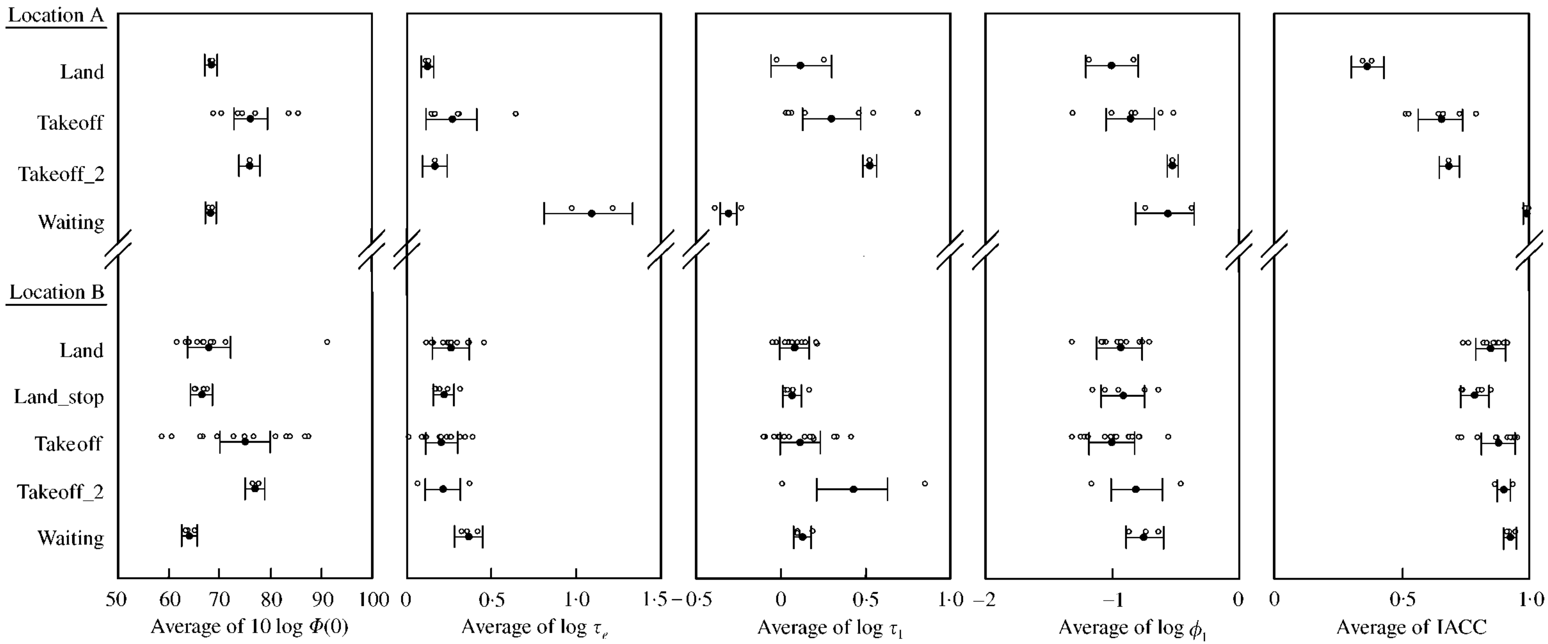
landing at location B, values of $\Phi(0)$ remained near the $\Phi(0)$ peak because of the strong directionality of the noise of the jet engine.

For both locations, in some cases, the τ_e values temporarily became larger near the $\Phi(0)$ peak, especially in the case of takeoff ($\tau_e = 88{\cdot}7$ ms), as shown in Figure 7.

The τ_1 values were distributed between 1 and 2 ms for most sessions, indicating the dominance of the noise component for such cases. When the tonal components from an aircraft increased, the τ_1 value became larger, as shown in the example of the ACF waveform in Figure 8(a). The ϕ_1 values were usually distributed below 0·2, and increased to be above 0·5 in some cases. In such cases, the tonal components, including the noise, increased. Thus, the pitch became stronger at the dominant pitch corresponding to its τ_1 value. An example of the ACF waveform is shown in Figure 8(b). The corresponding τ_e values in the same category are shown in Figure 8(c). In only one case, the τ_e value increased according to the increase of the ϕ_1 value, although each physical factor was orthogonal. But considering that almost all τ_e values were distributed near 1 ms, the noise components of aircraft were dominant compared to the tonal components.

The IACC values at location A were smaller than those at location B. The average value of IACC for landing at location A was 0·34, while it was 0·85 at location B. The average values for takeoff were, respectively, 0·66 and 0·88. Relatively strong reflections from the surface of the building wall caused the lower IACC at location A.

The values for τ_{IACC}, which is the factor that gives the directional information of the source, clearly represent the directions of aircraft in landing or takeoff as shown in the example in Figure 9. When the τ_{IACC} is zero, the target source should be located in front of the receiver. If the distance between the airstrip and the receiver is already known, information on the source speed may be obtained from the τ_{IACC} activity.


Location A
Land
Takeoff
Takeoff_2
Waiting
Location B
Land
Land_stop
Takeoff
Takeoff_2
Waiting
50 60 70 80 90 100
Average of 10 log Φ(0)
0 0·5 1·0 1·5
Average of log τe
−0·5 0 0·5 1·0
Average of log τ1
−2 −1 0
Average of log φ1
0 0·5 1·0
Average of IACC

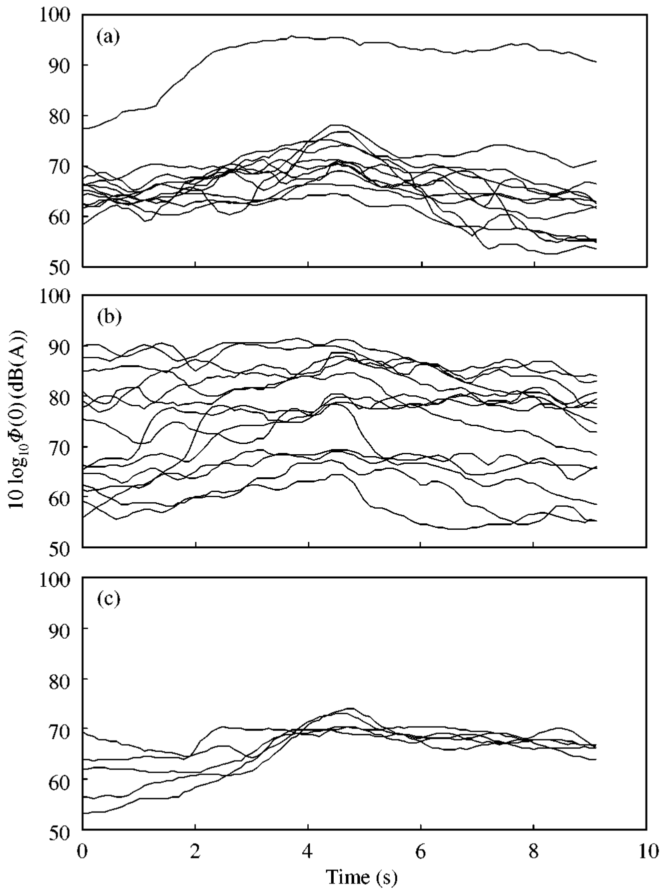


Figure 6. Measurement data of $\Phi(0)$. (a) Data from landing at location B (12 sessions); (b) data from takeoff at location B (14 sessions); (c) data from "land_stop" at location B (4 sessions).

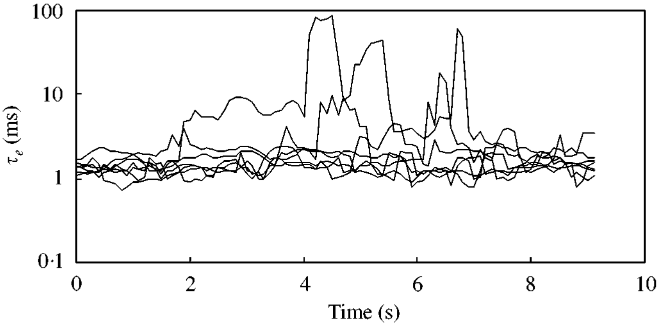


Figure 7. Measurement data of τ_e from takeoff data at location A ($\tau_e = 88{\cdot}7$ ms).

Figure 5. Average values for factors $\Phi(0)$, τ_e, τ_1, ϕ_1, and IACC. Upper four categories for each figure indicate results for the location A and lower five categories for location B. Open circles indicate the average values over 10 s for each session and closed circles indicate average values for all sessions for each category. Error bars represent the standard deviation from running data in all sessions.

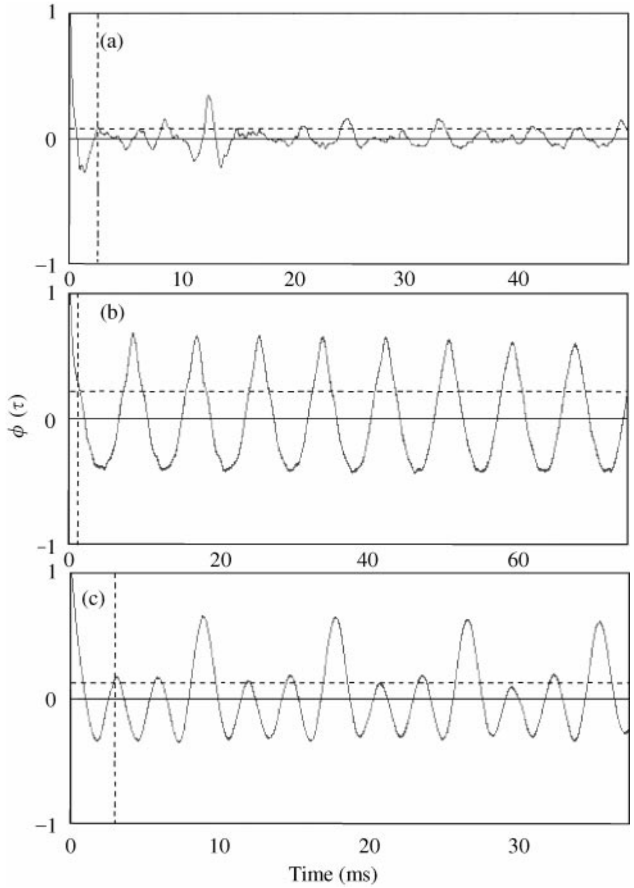


Figure 8. Examples for ACF. (a) ACF waveform with longer τ_1 value; (b) ACF waveform with longer ϕ_1 value; (c) τ_e values corresponding to longer ϕ_1 value.

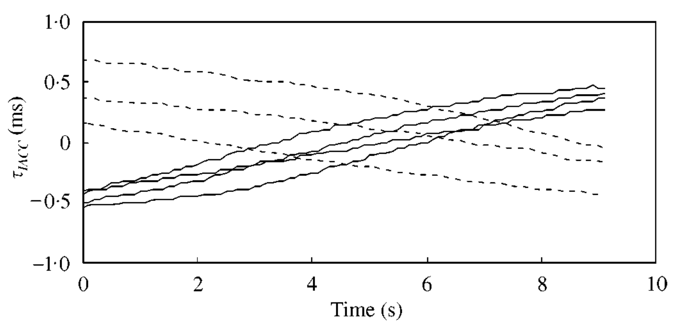


Figure 9. Examples for τ_{IACC}. The values of τ_{IACC} clearly represent the directions of aircraft in landing or takeoff.

5. DISCUSSION

The variety of $\Phi(0)$ values for "land_stop" at location B is larger before the $\Phi(0)$ peak than after the peak. The corresponding τ_1 did not indicate the perceived pitch in this case, although lower frequency components from the jet engine increased in actual listening condition during the measurement. This fact indicates that the first ACF peak does not always correspond to the dominant pitch for such a complicated ACF waveform as aircraft noise. There are some cases in which clear ACF peaks with regular time intervals appear after the first ACF peak, as shown in Figure 8(c). Psychological experiments on pitch perception with different τ_1 and ϕ_1 values must be conducted in order to determine the dominant pitch.

According to the measurements for the flying aircraft [15], the integration interval should be less than 0·5 s. In the present measurements, the integration interval was 0·5 s. However, there is a possibility that the integration interval may vary according to the τ_e value of a target sound source [16]. This means that a longer integration interval is necessary for noise with a strong tonal component. In the noise from a jet engine in landing or takeoff, tonal components were included in some sessions, optimum integration interval may be longer than 0·5 s. The length of time for each session was 10 s, and its center was the $\Phi(0)$ peak. Considering flying aircraft in the sky, time duration becomes longer than in landing and takeoff, say, about 20 s or more. In the present measurement, 10 s may be an appropriate length of time for landing or takeoff.

Noise from fans, propellers, or jet engines has strong directivities, as already described in section 2.2. The τ_{IACC} values vary greatly in both landing and takeoff according to the motion of the source. In waiting for takeoff, the τ_{IACC} value should be almost constant. Thus, the directional information of landing and takeoff by use of the τ_{IACC} factor can be obtained to characterize the noise source, including the directivity of noise from the specific parts of the aircraft.

These four ACF factors have been used to describe the speech intelligibility of Japanese single syllables by using a multi-dimensional analysis [17]. For sound fields which consist of the direct sound and a single reflection, the speech intelligibility can be well described in terms of the distance between the template source signal and a sound field signal by using ACF factors. If the method is applicable to regional environmental noises, the identification of a noise source may be achieved.

6. CONCLUDING REMARKS

Binaural measurements of aircraft noise in landing and takeoff conditions were conducted based on a model of the human auditory–brain system. The physical factors extracted from running ACF and IACF analyses of the noise sources well characterize the landing and takeoff activities of aircraft. Especially, the binaural effects, including IACC and τ_{IACC}, are effective for the characterization of noise sources. These results will become the basis for subjective evaluations including annoyance and spatial perception as well as primary sensations (loudness, pitch, and timbre), and identification of aircraft noises or other kinds of noise.

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