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PAPER

Appropriate frequency bandwidth in measuring interaural cross-correlation as a physical measure of auditory source width

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Abstract: There has been a demand for measuring the degree of interaural cross-correlation (*ICC*) as a physical measure for auditory (apparent) source width (*ASW*). Standardization of the measurement has been also discussed by ISO. One of the important problems in measurements of *ICC* is the selection of frequency bandwidth. Following ISO, *ICC* is defined with a wide frequency band and generally measured in 1/1 octave bands. This paper reports two experiments that compare *ASW* with *ICC* measured by different methods, so as to determine the best physical measure in terms of correlation with the subjective effect. The experimental results show that the use of 1/3 octave bandwidth is preferred to the use of a wide bandwidth and 1/1 octave bandwidth for measuring *ICC* as a physical measure of *ASW*.

Keywords: Interaural cross-correlation, *ASW*, ISO3382, Frequency bandwidth

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1. INTRODUCTION

It is well known that spatial impression is one of the most important characteristics of a listening space. Auditory (apparent) source width (*ASW*) is one of two characteristics that compose spatial impression perceived in a listening space [1]. It is general knowledge that the degree of interaural cross-correlation (*ICC*) has a negative correlation with *ASW*. There has been a demand for measurements of *ICC* as a physical measure for *ASW*. Standardization of the measurement has been also discussed by ISO 3382 [2].

ICC is generally defined as follows:

$$ICC = |\Phi_{lr}(\tau)|_{max} \tag{1}$$

where $|\tau| \leq$ (maximum interaural time difference). The interaural cross-correlation function $\Phi_{lr}(t)$ is generally defined as:

$$\Phi_{lr} = \lim_{T\to\infty} \frac{\dfrac{1}{2T}\displaystyle\int_{-T}^{+T} p_l(t)p_r(t-\tau)dt}{\dfrac{1}{2T}\sqrt{\displaystyle\int_{-T}^{+T} p_l^2(t)dt \int_{-T}^{+T} p_r^2(t)dt}} \tag{2}$$

where $p_l(t)$ and $p_r(t)$ are the input signals to the left and right ears, respectively, and described as follows:

$$\begin{aligned} p_l(t) &= s(t)^* r(t)^* h_l(t) \\ p_r(t) &= s(t)^* r(t)^* h_r(t) \end{aligned} \tag{3}$$

where $s(t)$ is a source signal, $r(t)$ is a room impulse response, $h(t)$ is a head-related impulse response, and an asterisk indicates convolution.

Here, $h(t)$ in Eq. (3) can be considered as acoustical characteristics of a receiving system in ordinary acoustical measurements. Therefore, the measured value of *ICC* depends on specifications of the dummy head or real head used in the measurement, even for the same source signal, $s(t)$, and the same room condition, $r(t)$. In other words, a different *ICC* is measured depending on the specifications, even though the same source signal and the same room condition convey the same *ASW* to a listener. Thus, the way $h(t)$ is treated is a key to the usefulness of the measure.

Three measurement methods of *ICC* have been proposed, considering physical factors relating to $h(t)$. ISO 3382 proposes the measurement of *ICC* using a dummy head with artificial ear simulators (B&K Type DB-100) and without A-weighting. Ando [3] proposes using a dummy head without the artificial ear simulators and with A-weighting. Morimoto and Iida [4] propose to measure it

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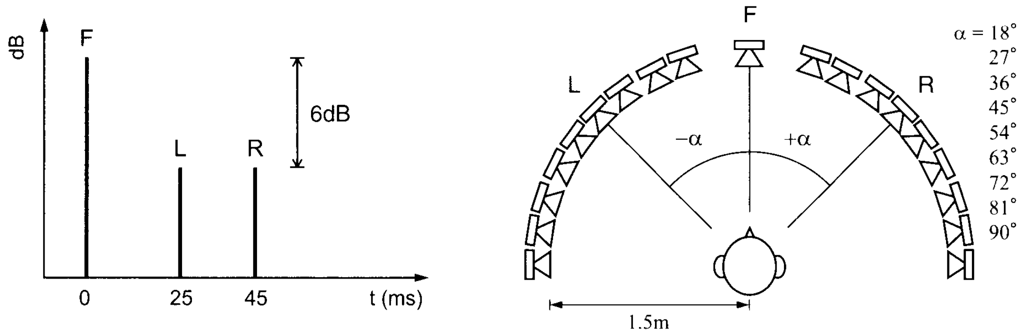

Fig. 1 Schematic diagram of impulse response of the test sound field and the arrangement of loudspeakers used in the experiments.

using a dummy head without the artificial ear simulators and without A-weighting. The authors have already demonstrated that *ICC* measured by Morimoto and Iida's method is effective for evaluation of *ASW* for a music motif having the frequency characteristics of Mozart's Symphony No. 41 "Jupiter," but *ICC* measured by the ISO and Ando methods are not [4]. It is important that the same music motif be used as the source signal in the *ICC* measurements, since *ICC* depends not only on a head-related impulse response $h(t)$, but also on the source signal $s(t)$, as shown in Eqs. (1), (2) and (3).

Ueda and Morimoto [5,6] have performed basic studies on the estimation of *ASW* for a source signal with arbitrary frequency components. However, a physical measure of *ASW* for an arbitrary source signal is not yet developed. Under such circumstances, ISO3382 states, "The most general form of *IACC* (*ICC* in this paper) is defined with a wide frequency band. As in the case of monaural measurements, *IACC* is generally measured in octave bands ranging from 125 Hz to 4,000 Hz."

In this paper, an appropriate frequency bandwidth in frequency analyzing *ICC* is discussed, comparing *ICC* and *ASW* for wide band noises, 1/1 octave band noises, and 1/3 octave band noises.

Needless to say, what is important for a physical measure designed to evaluate a subjective effect is that it is well correlated with the subjective effect for the same source signal as used in measuring the physical measure. This is true of several physical measures in room acoustics, for example, the relationship between early decay time and reverberance.

2. RELATION BETWEEN *ASW* AND *ICC* FOR WIDE BAND NOISE

ISO 3382 describes the most general form of *ICC* is defined with a wide frequency band. In this experiment, it is investigated whether or not it is possible to evaluate *ASW* by a single number of *ICC* measured for a wide band noise using the three measurement methods mentioned above.

2.1. Experimental Method

Figure 1 shows the impulse response of a test sound field and the arrangement of loudspeakers used in the experiments. The experiments were carried out using a simple sound field composed of a direct sound and two discrete lateral reflections. The sound pressure level of the reflections relative to the direct sound was fixed at −6 dB. The directions of lateral reflections were changed from ±18° to ±90° in steps of 9°. The source signal used in the experiments was a pink noise generally used as a wide band signal for measurements in the field of room acoustics. The lower cut-off frequency of the pink noise was fixed at 200 Hz. The higher cut-off frequency (F_{hc}) was 8 kHz, 4 kHz, 2 kHz and 1 kHz. To reject the higher frequency components, the filter with a cut-off slope of 48 dB/oct. was used. The total sound pressure level of all stimuli was constant at 65.0 ± 1.0 dBA at the entrance of left ear of KEMAR dummy head. The frequency characteristics of all loudspeakers were flattened to within ±4 dB in the frequency range from 200 Hz to 8 kHz by a frequency equalizer.

Two kinds of paired comparison tests were performed in the experiments. In Experiment A, *ASW* generated by pairs of lateral reflections from nine different directions were compared for each F_{hc}, separately. For each F_{hc} the test had 72 pairs including reversals. The stimulus duration was 3 s and the interval between the two stimuli was 1 s. All pairs of stimuli were arranged in random order, followed by an interval of 4 s. In the experiments the 72 pairs were separated into two units of 36 pairs and presented to the subjects, separately. In Experiment B, *ASW* generated by pairs of lateral reflections from 36° and 54° for all of four F_{hc} were compared. The test had 56 pairs including reversals. The stimulus duration was 3 s and the interval between the two stimuli was 1 s. All pairs of stimuli were arranged in random order, followed by an interval of 4 s. In the experiments the 56 pairs were separated into two units of 28 pairs and presented to the subjects, separately.

Subjects were six males, 22–28 years, with normal hearing sensitivity. All were experienced in this type of test. Each subject was individually tested in a darkened anechoic chamber. The subject's head was fixed while seated. The task of the subject was simply to judge which *ASW* was wider horizontally. Each subject judged the same pair twice. The total number of subject judgements was twenty-four per pair, including reversals of stimuli.

Meanwhile, *ICC* of each stimulus was measured by three measurement methods mentioned above using the KEMAR dummy head.

2.2. Experimental Results and Discussion

Thurstone Case V model [7] was used to obtain the psychological scales of *ASW*. Gulliksen's method [8] was also used for incomplete data. First, the psychological scales of *ASW* generated by pairs of lateral reflections from nine different directions were obtained for each F_{hc} from the judgements in Experiment A. However, the scales for different F_{hc} cannot be compared directly, since paired comparison tests were performed separately for each F_{hc} in Experiment A. Then, the psychological scales of *ASW* generated by pairs of lateral reflections from 36° and 54° for four F_{hc} were obtained from the judgements in Experiment B. Next, the psychological scales of *ASW* for each F_{hc} obtained in Experiment A were corrected so that the psychological scales between 36° and 54° for each F_{hc} obtained in Experiments A and B might be equal. The corrected scales were superimposed on the scales obtained in Experiment B. Hence, the comparisons between all *ASW* for 36 stimuli (9 directions of lateral reflections × 4 F_{hc}) became possible.

Figure 2 shows the psychological scales of *ASW* obtained according to such a procedure. The closer the directions of lateral reflections get to 90°, the wider *ASW* grows for any F_{hc}. Furthermore, *ASW* has a tendency to grow wider in some directions of lateral reflections as F_{hc} becomes lower. However, the tendency cannot always be seen in all directions of lateral reflections.

Figure 3(a), (b) and (c) show measured values of *ICC* by ISO, Ando, and Morimoto and Iida, respectively. For only $F_{hc} = 1$ kHz (closed circle), all of *ICC* by three methods monotonically decrease as the directions of lateral reflections get close to 90°. Namely, they have a negative correlation with *ASW* as shown in Fig. 2. However, for

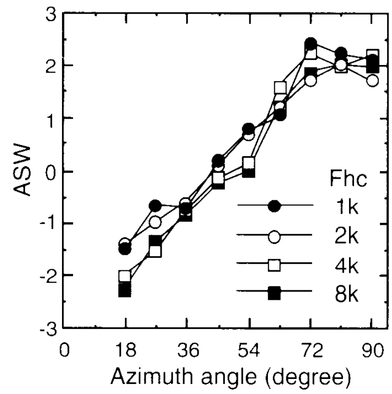

Fig. 2 Psychological scale of *ASW* for wide band noises as a function of azimuth angle of lateral reflections and as a parameter of the higher cut-off frequency, F_{hc}. Closed circle, $F_{hc} = 1$ kHz; open circle, $F_{hc} = 2$ kHz; open square, $F_{hc} = 4$ kHz; closed square, $F_{hc} = 8$ kHz.

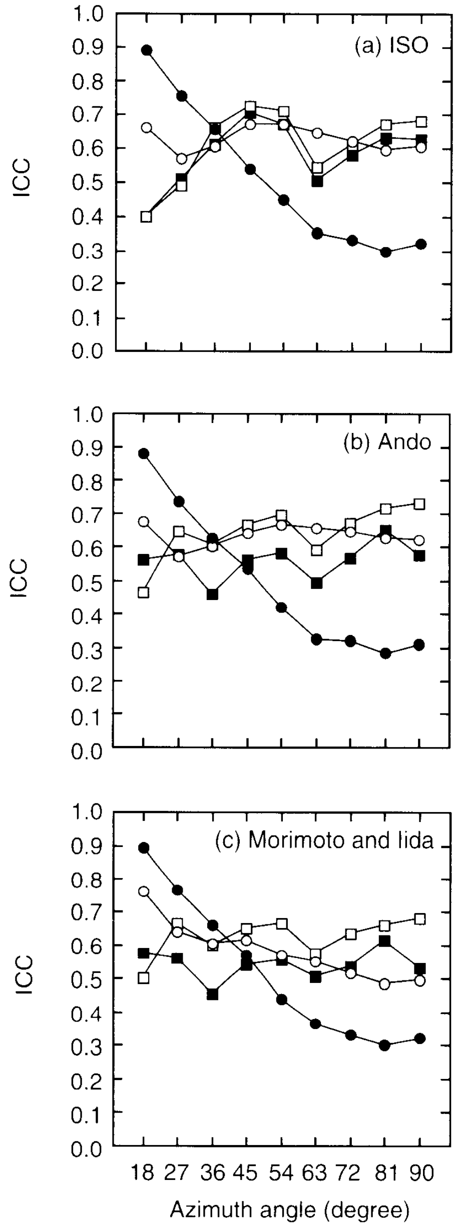

Fig. 3 Measured values of *ICC* by ISO method (a), Ando method (b), and Morimoto and Iida method (c) for wide band noises as a function of azimuth angle of lateral reflections and as a parameter of the higher cut-off frequency, F_{hc}. Closed circle, $F_{hc} = 1$ kHz; open circle, $F_{hc} = 2$ kHz; open square, $F_{hc} = 4$ kHz; closed square, $F_{hc} = 8$ kHz.

F_{hc} = 2 k, 4 k and 8 kHz, all of *ICC* almost do not depend on the direction of reflections and it is clear that they have no correlation with *ASW* shown in Fig. 2. Thus, the measured *ICC* by three kinds of measuring methods are affected by the spectrum of an input signal to the ear [4], but *ASW* is not.

In conclusion, it is impossible to evaluate *ASW* by a single number of *ICC* measured for a wide band noise including frequency components below 1 kHz using any measurement method of ISO, Ando, and Morimoto and Iida. On the other hand, it can be inferred from these results that the lateral energy fraction by Barron [9] is effective to evaluate *ASW* for all of these wide band noises, since it increases monotonically as the directions of lateral reflections get close to 90°, regardless of the spectrum of a source signal.

3. RELATION BETWEEN *ASW* AND *ICC* FOR 1/1 AND 1/3 OCTAVE BAND NOISES

As indicated in the foregoing section, it is impossible to evaluate *ASW* by a single number of *ICC* measured for a wide band noise including frequency components below 1 kHz. An alternative method to date is to state the frequency characteristics of *ICC*. ISO 3382 describes that *ICC* is generally measured in 1/1 octave bands. However, there is no evidence that *ICC* with 1/1 octave bandwidth is well correlated with *ASW*. In this experiment, it is investigated whether or not 1/1 octave is an appropriate bandwidth for evaluation of *ASW*, comparing with 1/3 octave.

3.1. Experimental Method

The impulse response of a test sound field, the arrangement of loudspeakers and loudspeakers used in this experiment were the same as those in the first experiment. The source signals used in the experiments were 1/1 and 1/3 octave noises. Their center frequencies (F_c) were 500 Hz, 1 kHz, 2 kHz and 4 kHz. The characteristics of filter accorded with IEC standard. The binaural sound pressure level [10] of all stimuli was constant at 70.0 ± 0.4 dBA.

ASW generated by pairs of reflections from different directions were compared, separately for each F_c and for each band noise. For each F_c and for each band noise, the test had 72 pairs including reversals. The stimulus duration was 3 s and the interval between the two stimuli was 1 s. All pairs of stimuli were arranged in random order, followed by an interval of 4 s. In the experiments the 72 pairs were separated into two units of 36 pairs and presented to the subjects, separately.

Subjects were eight males and four females, 21–24 years, with normal hearing sensitivity. All were experienced in this type of test. They did not serve as subjects for the first experiment. Each subject was individually tested in a darkened anechoic chamber. The subject's head was fixed while seated. The task of the subject was simply to judge which *ASW* was wider horizontally. Each subject judged the same pair four times. The total number of subject judgements was forty-eight per pair, including reversals of stimuli.

Meanwhile, *ICC* of each stimulus was measured by Morimoto and Iida method, since differences between measured values by three different methods can be neglected because of narrow bands of 1/1 and 1/3 octave.

3.2. Experimental Results and Discussion

Thurstone Case V model was used to obtain the psychological scales of *ASW*. Gulliksen's method was also used for incomplete data.

Figure 4 shows *ASW* and measured *ICC* for each 1/1 octave band noise. Roughly speaking, for all of F_c, *ASW* grows wider as the directions of the lateral reflections get close to 90°, except for F_c = 1 kHz at 90°. Then *ASW* has a highly negative correlation with *ICC* for F_c = 500 Hz and 1 kHz. However, *ASW* has a positive correlation with *ICC* for F_c = 2 kHz and *ASW* has no correlation with *ICC* for F_c = 4 kHz. This means that 1/1 octave is not an appropriate frequency bandwidth in frequency analyzing of *ICC* for evaluation of *ASW*.

On the other hand, it is easy to infer that the lateral energy fraction analyzed with 1/1 octave bandwidth has a positive correlation with *ASW*, except for F_c = 1 kHz at 90°.

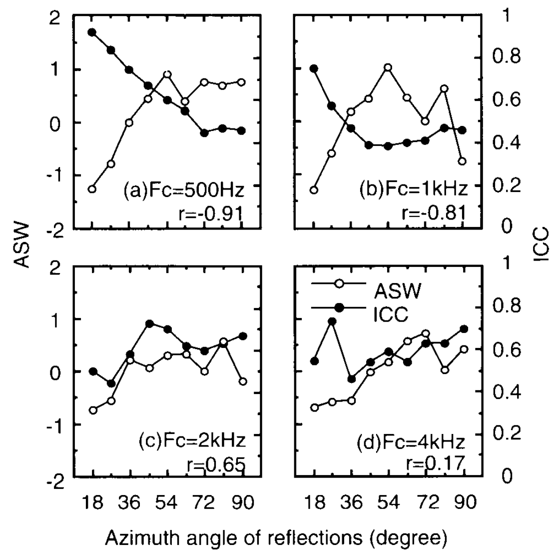

Fig. 4 Psychological scale of *ASW* (open circle) and measured *ICC* (closed circle) for 1/1 octave band noises as a function of azimuth angle of lateral reflections and as a parameter of the higher cut-off frequency, F_c. Panel (a), F_c = 500 Hz; panel (b), F_c = 1 kHz; panel (c), F_c = 2 kHz; panel (d), F_c = 4 kHz.

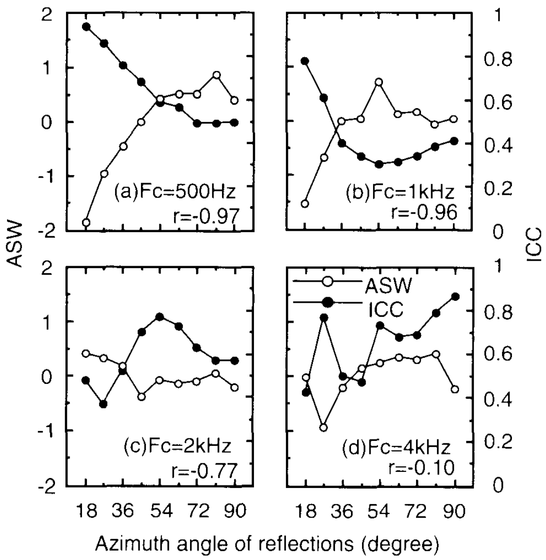

Fig. 5 Psychological scale of *ASW* (open circle) and measured *ICC* (closed circle) for 1/3 octave band noises as a function of azimuth angle of lateral reflections and as a parameter of the higher cut-off frequency, F_c. Panel (a), $F_c = 500$ Hz; panel (b), $F_c =$ 1 kHz; panel (c), $F_c = 2$ kHz; panel (d), $F_c = 4$ kHz.

Figure 5 shows *ASW* and measured *ICC* for each 1/3 octave band noise. Roughly speaking, for $F_c = 500$ Hz and 1 kHz, *ASW* grows wider as the directions of the lateral reflections get close to 90°. However, for $F_c = 2$ kHz and 4 kHz, *ASW* changes in a complicated manner. Then *ASW* has a highly negative correlation with *ICC* except for $F_c = 4$ kHz. For $F_c = 4$ kHz, though measured *ICC* are well correlated with the distinct behavior of *ASW* for the directions of lateral reflections from 18° to 45°, the overall correlation coefficient is low. However, if examined individually in the case of $F_c = 4$ kHz, *ASW* perceived by six of twelve subjects shows a negative correlation with *ICC* as shown in Fig. 6. This result suggests that the critical band [11] works also in the perception of *ASW*, and that there are differences between individuals in the width of the band. These results indicate that 1/3 octave is a more appropriate bandwidth than 1/1 octave in frequency analyzing of *ICC* for evaluation of *ASW*, though individual differences in perception of *ASW* for the 1/3 octave band noise of $F_c = 4$ kHz were observed.

On the other hand, it is easy to infer that the lateral energy fraction analyzed with 1/3 octave bandwidth has no correlation with *ASW*.

In conclusion, measurements of *ICC* with 1/3 octave bandwidth are preferred for evaluating *ASW*, whereas the use of 1/1 octave bandwidth is not. However, it remains to be solved how the frequency characteristics of *ICC* measured with 1/3 octave bandwidth is useful to evaluate *ASW* for arbitrary source signals perceived in listening spaces.

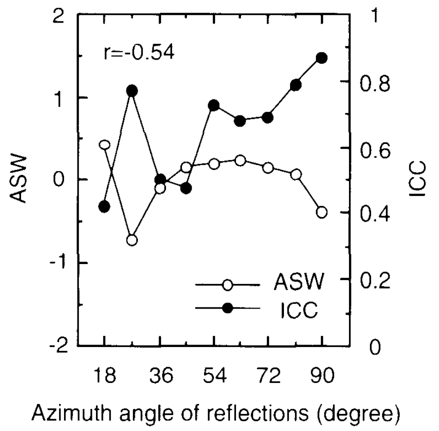

Fig. 6 Psychological scale of *ASW* (open circle) perceived by six of twelve subjects and measured *ICC* (closed circle) for 1/3 octave band noises with $F_c = 4$ kHz as a function of azimuth angle of lateral reflections.

4. CONCLUSIONS

The comparison of measured values of *ICC* with *ASW* indicates that: (1) It is impossible to evaluate *ASW* by a single number of *ICC* measured for a wide band noise including frequency components below 1 kHz using any measurement method proposed by ISO 3382, Ando, and Morimoto and Iida. (2) Measurements of *ICC* with 1/3 octave bandwidth are preferred for evaluating *ASW*, whereas the use of 1/1 octave bandwidth is not. Meanwhile, (3) Lateral energy fraction proposed by Barron is effective to evaluate *ASW* for a wide band noise including frequency components below 1 kHz. (4) Lateral energy fractions measured with 1/1 octave bandwidth have a correlation with *ASW*, but those measured with 1/3 octave bandwidth do not.

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REFERENCES

[1] M. Morimoto and Z. Maekawa, "Auditory spaciousness and envelopment," *Proc. 13th Int. Congr. Acoustics*, pp. 215–218 (1989) and M. Morimoto, H. Fujimori and Z. Maekawa, "Discrimination between auditory source width and envelopment," *J. Acoust. Soc. Jpn. (J)*, **46**, 449–457 (1990).

[2] ISO 3382:1997, "Acoustics — Measurement of the reverberation time of rooms with reference to other acoustical

parameters" (1997).

[3] Y. Ando, *Concert Hall Acoustics* (Springer-Verlag, Berlin, 1985).

[4] M. Morimoto and K. Iida, "A practical evaluation method of auditory source width in concert halls," *J. Acoust. Soc. Jpn. (E)*, **16**, 59–69 (1995).

[5] K. Ueda and M. Morimoto, "Estimation of auditory source width (*ASW*): I. *ASW* for adjacent 1/3 octave band noises with equal band level," *J. Acoust. Soc. Jpn. (E)*, **16**, 77–83 (1995).

[6] K. Ueda and M. Morimoto, "Estimation of auditory source width (*ASW*): II. *ASW* for adjacent 1/3 octave band noises with different band level," *J. Acoust. Soc. Jpn. (E)*, **18**, 121–128 (1997).

[7] L. Thurstone, "A law of comparative judgment," *Psychol. Rev.*, **34**, 273–286 (1927).

[8] H. Gulliksen, "A least squares solution for paired comparison with incomplete data," *Psychometrika*, **21**, 125–134 (1956).

[9] M. Barron and A. H. Marshall, "Spatial impression due to the early reflections in concert halls: The derivation of a physical measure," *J. Sound. Vib.*, **77**, 211–232 (1981).

[10] D. W. Robinson and L. S. Whittle, "The loudness of directional sound field," *Acustica*, **10**, 74–80 (1960).

[11] B. C. J. Moore, *An Introduction to the Psychology of Hearing* (Academic Press, London, 1982), pp. 75–97.