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Study of vertical sound image control with parametric loudspeakers

Shigeaki Aoki *, Kazuhiro Shimizu, Kouki Itou

Department of Electronics, Information and Communication Engineering, Kanazawa Institute of Technology, 7-1 Ohgigaoka, Nonoichi, Ishikawa 921-8501, Japan

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ABSTRACT

A parametric loudspeaker utilizes nonlinearity of a medium and is known as a super-directive loudspeaker. In this paper, the sound localization in the vertical direction using the upper and lower parametric loudspeakers is confirmed by listening tests and physical measurements. The differences in levels between the upper and lower parametric loudspeakers are varied as a parameter. The direction of sound localization in the vertical plane can be controlled not only when the acoustical axis is set to the right ear but also when it is set to at 5 deg to the right of the right ear. The effect of the level difference between the upper and lower loudspeakers is weaker than the differences observed when using ordinary loudspeakers. We obtained interesting characteristics of the left-right sound localization in the horizontal plane with the upper and lower parametric loudspeakers in the vertical plane. It is found that by setting the parametric loudspeaker at the right ear (that is, the horizontal angle of a listener to it is only 3 deg to the right), the direction of sound localization in the horizontal plane moved approximately 10 deg to the right. Moreover, by setting the parametric loudspeaker 5 deg to the right, the direction of sound localization moves approximately 20 deg to the right. The ILD (Interaural Level Difference) using a dummy head is calculated from the measured left and right sound signals. It is determined that ILDs of the parametric loudspeaker are larger than those of the ordinary loudspeaker. A simple geometrical acoustic model is introduced and analyzed. The analysis helps to explain the measured characteristics.

1. Introduction

A parametric loudspeaker utilizes nonlinearity of a medium and is known as a super- directive loudspeaker. The parametric loudspeaker is one of the prominent applications of nonlinear acoustics. In 1963, Westervelt describes a parametric acoustic array as two infinite amplitude waves generated by nonlinear interaction [1]. Super-directivity can be proved by theoretical analysis. The parametric array in the underwater has been investigated in numerous theoretical and experimental studies. In 1975, Benett and Blackstook led theoretical predictions on a perturbation solution of Burgers' equation and demonstrated the existence of the parametric array in air [2]. In 1982, Yoneyama et al. reports the principle of the parametric loudspeaker [3]. The primary wave is amplitude modulated by audio signal. By the interaction of the primary wave, that is, self-demodulation of the amplitude modulated sound wave, an audible signal is produced in the air. The principle and applications of the parametric loudspeaker are summarized in books and reports: for example, in [4,5]. The parametric loudspeaker can produce an audio spot because of the sharp directivity. The audio spot is useful to transmit information to the concerned person without the leak of information and without annoyance to the third person. To date, the applications have been limited to monaural reproduction sound system for public addresses in such locations as museums, stations and streets [6,7].

We discuss characteristics of left-right sound localization in stereo reproduction with two parametric loudspeakers by comparing with those with two ordinary dynamic loudspeakers [8]. Human perceive left-right sound localization by binaural information that is ILD (Interaural Level Difference) or/and ITD (Interaural Time Delay) [9]. In stereo reproduction, where we can perceive the correct and stable sound localization is one of the important effects. It is known that when listening to music with two ordinary dynamic loudspeakers, it is possible to reproduce correct sound localization at the only sweet spot by controlling ILD or/and ITD adequately. Moreover, the cross talks which are the sounds from the left loudspeaker to the right ear and vice versa have some effects on perception of sound localization. We conduct listening tests to compare the sound localization between with the two parametric loudspeakers and the two ordinary dynamic loudspeakers [8]. In listening tests, there are three listening positions. The first two listening positions are the sweet spots, which are at the top of equilateral triangle, the other tops of which are the left

* Corresponding author.
E-mail address: aoki_s@neptune.kanazawa-it.ac.jp (S. Aoki).

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and right loudspeakers positions. Lengths of the side are different. The last listening position is just in front of the left loudspeaker. The characteristics of stereo reproduction using the parametric loudspeakers are different from those using the ordinary dynamic loudspeakers. It is determined that the difference was caused by the effect of cross talks.

To date, we have clarified the characteristics of left-right sound localization with the left and right parametric loudspeakers. Therefore, it is necessary to investigate the characteristics of up-down sound localization with the upper and lower parametric loudspeakers. The preliminary test with the lower and upper parametric loudspeakers reports that the direction of sound localization in the vertical plane can be controlled [10]. The difference in levels between the upper and lower parametric loudspeakers are varied as a parameter. In this paper, the characteristics of the sound localization with the upper and lower parametric loudspeakers in the vertical direction are investigated by listening tests. Moreover, it is observed that the left-right sound localization can be realized only with the upper and lower parametric loudspeakers. In order to make clear the obtained new finding, the effect of the acoustic axis of the parametric loudspeaker to the direction of left-right sound localization is analyzed in detail. Next, the ILD (Interaural Level Difference) are calculated from the measured left and right sound signals with a dummy head. A simple geometrical acoustic model of a listener head is also introduced. The formulated sound pressures of the left and right ears are analyzed. The analysis leads to explanation of the obtained new characteristics of right-left sound localization with the upper and lower parametric loudspeakers.

2. Test method

The listening test is conducted in an anechoic room. Four young males with normal hearing ability attend. The placement of the listener and the parametric loudspeakers is illustrated in Fig. 1. The parametric loudspeaker is shaped as an equilateral hexagon. The inner and outer diameters are 99 mm and 112 mm, respectively. Two loudspeakers are used as shown in Fig. 1(a). The interval between the upper and lower loudspeakers is 1.0 m. The distance between the loudspeaker and a listener is 1.50 m. The height of the listener's pinna is 1.2 m and is immediately to the center of both loudspeakers.

In order to confirm the degree of movement of the sound localization in not only the vertical plane but also the horizontal direction, two settings of the upper and lower parametric loudspeakers are employed. One is the case that the acoustical axis was set to the right ear of a listener as shown in Fig. 1(b). The other is the case that the acoustic axis is set rightward 5-degrees far from the right ear as shown in Fig. 1(c).

The test signal is pink noise. In many sound localization studies, a pure tone has been used as a typical signal. However, it is known that a certain frequency band of pure tone is generally difficult to perceive direction of sound localization. The broad band signal is the synthesis of many pure tones. Therefore, the pink noise is used as a typical broad band signal. The ultrasonic wave is modulated by preprocessing the modulated signal. SSB (Single-sideband modulation) with the lower sideband is used in consideration of less distortion. The level differences of radiated signals between the upper and lower loudspeakers are $-\infty$, -9, -6, -3, 0, 3, 6, 9 and ∞ dB. The direction of sound localization can be controlled between the lower and the upper loudspeakers.

The listening tests are conducted in the following steps:

(1). Before a listening test, a listener listens to the three types of reproduced signal once respectively in order to experience the sound localization preliminarily.
(2). A listener listens to a set of test signal. A set consisted of 45 trials with randomly edited test signals, five times for each of type reproductions. The duration of test signal is 3 s.
(3). After a listener listens to a test signal, he points a position of sound localization on an estimate paper by a laser pointer. An angle of sound localization is calculated by the pointed position.

Three sets are conducted per listener.

3. Test results

The obtained sound localization in the vertical direction in the listening test is shown in Fig. 2(a). The horizontal axis is the difference in levels between the upper and lower loudspeakers. The vertical axis is the angle of sound localization. Symbols are the mean value and vertical lines indicate the degree of dispersion of data because positive and negative standard deviations are connected.

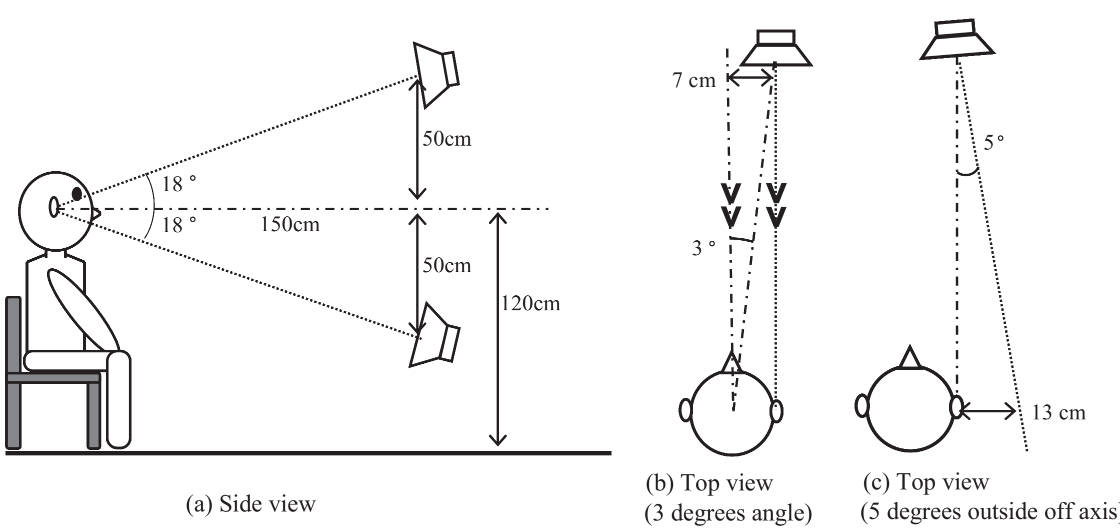

Fig. 1. Loudspeakers and listening positions. (a): Side view, (b): Top view when the acoustical axis is set toward right ear, that 3 deg angle and (c): Top view when the acoustical axis is set toward 5 deg outside off right ear.