Applied Acoustics 116 (2017) 164–169

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

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

ARTICLE INFO

Article history:
Received 13 October 2015
Received in revised form 1 August 2016
Accepted 11 August 2016

Keywords:
Parametric loudspeaker
Sound localization
Super-directivity
Interaural level difference

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).

http://dx.doi.org/10.1016/j.apacoust.2016.08.014
0003-682X/© 2016 Elsevier Ltd. All rights reserved.

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.

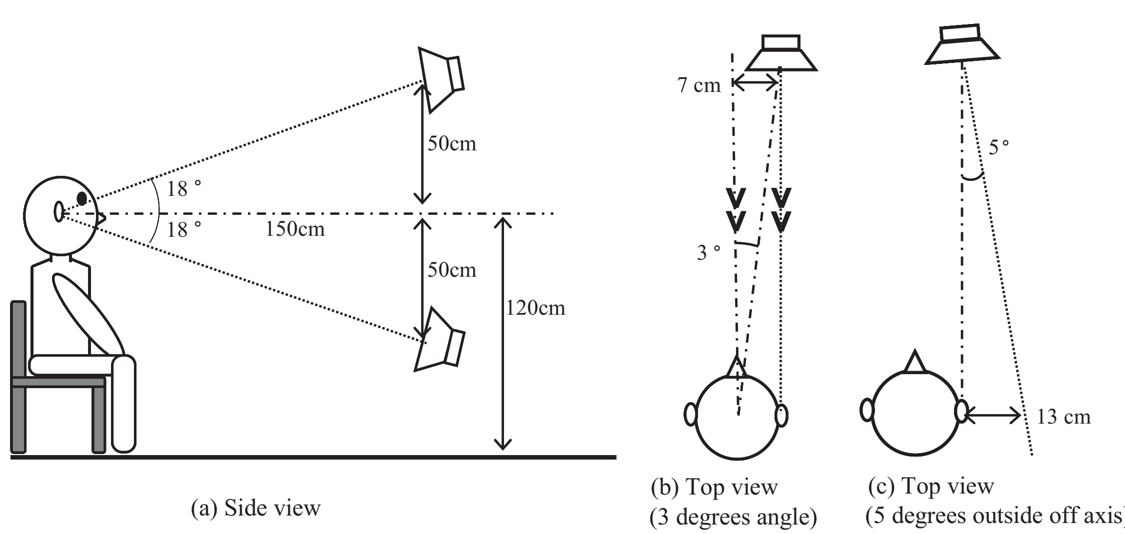
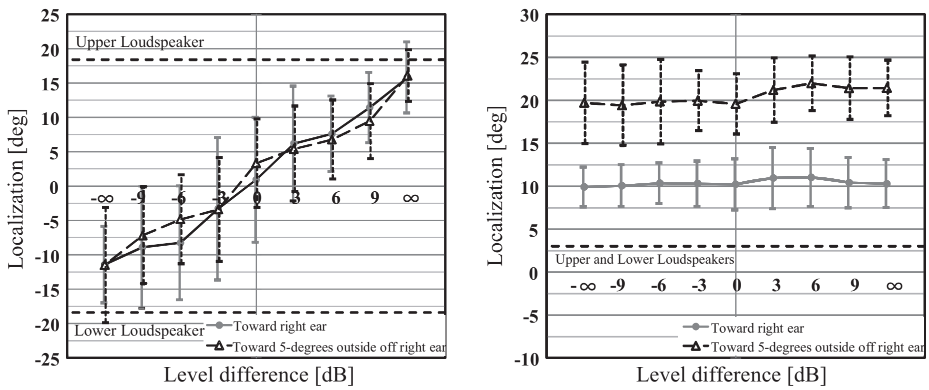


Fig. 1. Loudspeakers and listening positions. (a): Side view, (b): Top view when the acoustical axis is set toward right ear, that 3 deg angle and (c): Top view when the acoustical axis is set toward 5 deg outside off right ear.



(a) Sound localization in the vertical direction.

(b) Sound localization in the horizontal direction

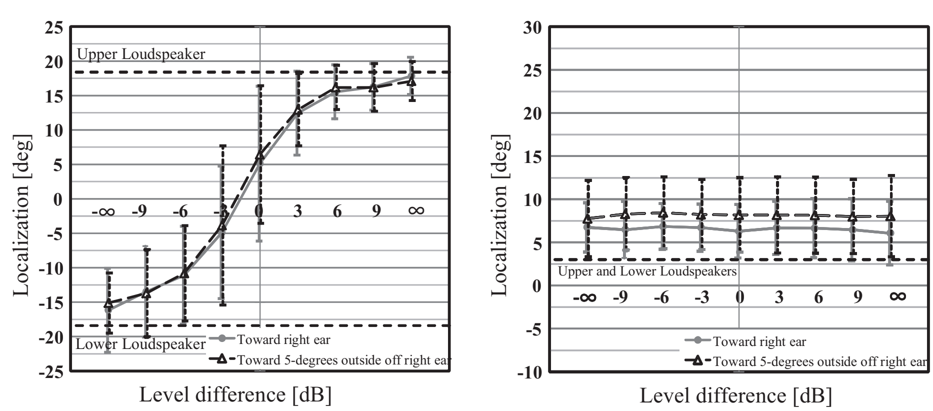
Fig. 2. Sound localization in the vertical and horizontal directions. The listening test is conducted with parametric loudspeakers.

The dashed lines show the direction of the loudspeakers. The direction of sound localization in the vertical direction can to be controlled not only when the acoustical axis was set to the right ear but also when it was set to rightward 5-degrees far from the right ear. There was a tendency which the standard deviations in the range from the lower loudspeaker to the front were a little larger.

The obtained sound localization in the horizontal direction in the listening test is shown in Fig. 2(b). The horizontal axis is the difference in level between the upper and lower loudspeakers. The vertical axis is the angle of sound localization. The front of the listener was 0 deg and the loudspeaker was set about three degrees rightward. By setting the parametric loudspeaker the right ear, that is, by setting it only 3 deg rightward, the direction of sound localization moved approximately 10 deg rightward. Moreover, by setting it 5 deg to the right, the direction of sound localization moves approximately 20 deg rightward. The results are obtained in spite of the level differences of the radiated signals between the upper and lower loudspeakers. To assess the cause of the interesting characteristics, it is necessary to analyze ILD (Interaural Level Difference) using a dummy head.

As reference, the listening test of the same scheme is conducted with two ordinary loudspeakers. The sound localization in the vertical direction is shown in Fig. 3(a). However, the dependence of the level difference is weaker in sound reproduction with the parametric loudspeakers than in sound reproduction with the ordinary loudspeakers. It is similar to the fact that the direction of sound localization can to be controlled by the level difference between the upper and lower loudspeakers. In the range of level differences between −3 dB and +3 dB, the degrees of sound image movement were 8 degs and 17 deg in the parametric loudspeaker and the ordinary loudspeaker, respectively. That is, the slope of the parametric loudspeaker and the ordinary loudspeaker are 1.3 and 2.8 deg/dB, respectively. The direction of −3 dB, 0 dB and +3 dB have main effect on the estimation of the slope. There are significant differences ($p < 0.05$ and $p < 0.001$, *T*-test) between the results for the parametric loudspeaker and the ordinary loudspeaker when the level difference is 0 dB and 3 dB, respectively. It is reported that the slope depended on the type of sounds and that the slopes of white noise and speech are similar and these were larger than that of flute [11]. The used sound in our listening test is the pink noise commonly for both the parametric loudspeaker and the ordinary loudspeaker. The slope, that is the effect of the level difference between the upper and lower loudspeakers are different. This is an interesting result of using the parametric loudspeakers. It is estimated that the different directivity of both loudspeakers has an effect on the wave front synthesis. The main cue of sound localization in the vertical plane is spectral cue. However, the details are not yet clear. The individuality is so remarkable that it is difficult to analyze simple measured spectrum with a dummy head.

The sound localization in the horizontal direction is shown in Fig. 3(b). The sound localization in setting the acoustical axis of the ordinary loudspeakers to the ear is slightly different from that in setting those to 5 deg outside off. In any case, the sound localization in the horizontal direction with the parametric loudspeaker is



(a) Sound localization in the vertical direction.

(b) Sound localization in the horizontal direction

Fig. 3. Sound localization in the vertical and horizontal directions. The listening test is conducted with ordinary loudspeakers.

more remarkable than those with the ordinary loudspeaker. The slight deference of acoustical axis of the parametric loudspeaker has significant effects on the sound localization in the horizontal direction. There are significant differences ($p < 0.001$, *T*-test) between the results for the parametric loudspeaker and the ordinary loudspeaker in both settings of the acoustical axes of loudspeakers. It is clear that the sound localization in the horizontal direction using the parametric loudspeakers shows its own characteristics. The main cues of sound localization in the horizontal plane are ILD (Interaural Level Difference) and ITD (Interaural Time Difference). The details of both cues have already been clear. The individuality is not sufficiently remarkable that it is easy to analyze simple measured spectrum with a dummy head. In considering this listening test scheme, the upper and lower loudspeakers were set in vertical plane, and the ITDs were estimated almost zero. Only the ILD played the main role in perception of sound localization in the horizontal direction. The measured ILD are analyzed in the next section.

4. Measurement of ILDs of parametric loudspeaker with dummy head

A listener is replaced by the dummy (B&K Type 4128C). Sound pressure levels of the right and left ears are measured in the anechoic room as shown in Fig. 1. The ILDs are calculated from the measured sound pressure levels of the right and left ears. Test signals are 500, 1 k, 2 k and 4 k Hz 1/3 oct. band noises. The ultrasonic wave is modulated by preprocessing the modulated signal SSB. The level differences of radiated signals between the upper and lower loudspeakers are $-\infty$, -9, -6, -3, 0, 3, 6, 9 and ∞ dB. The conditions are the same as those in the listening test.

The measured ILDs with dummy head when the axis of the parametric loudspeaker was toward the right ear are shown in Fig. 4. The obtained ILDs were similar in spite of the level differences of the radiated signals between the upper and lower loudspeakers when the frequency was the same. The ILDs tended to increase slightly as the frequency increased.

The measured ILDs with dummy head when the axis of the parametric loudspeaker is at 5 deg outside of the right ear are shown in Fig. 5. The obtained ILDs are similar in spite of the level differences of the radiated signals between the upper and lower loudspeakers except for 2 kHz. The ILDs increase constantly. However, the amount is little and less than approximately 2 dB. The ILDs tend to increase slightly as the frequency increases.

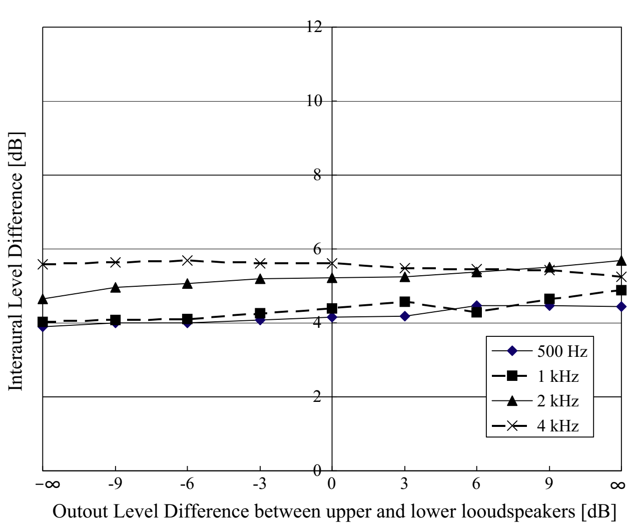


Fig. 4. Dependence of interaural level difference on frequency. The ILDs are measured with the dummy head when the acoustical axis was set toward right ear.

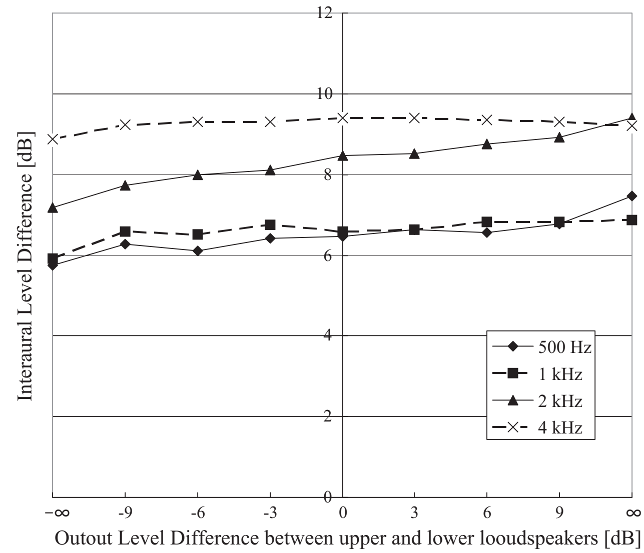


Fig. 5. Dependence of interaural level difference on frequency. These are measured with the dummy head when the acoustical axis was set toward 5 deg outside of the right ear.

To investigate the influence of the frequency, in considering that the level differences did not effect on the ILDs, the averaged ILDs can be calculated. The relationship between the calculated ILD and the frequency is shown in Fig. 6. The obtained ILDs are larger than those of an ordinary loudspeaker [10] and different in the frequency of 1/3 oct. band. The difference of the ILDs between when the acoustical axis was set to the right ear of a listener and when the acoustic axis is set rightward 5 deg from the right ear were from 2 to 4 dB. In both axis conditions, there was a tendency for the ILDs to become large as the frequency increased. Because the higher frequency sound was harder to diffract, a cross talk level from the loudspeaker to the left ear became larger. For reference, the ILDs of an ordinary loudspeaker were measured [12,13]. The calculated ILDs from these papers are 0.44, 0.66, 0.5 and 0.94 dB in 500, 1 k, 2 k and 4 k Hz. The ILDs tend to increase slightly as the frequencies increase. However, these values are small in comparison to those of the parametric loudspeaker.

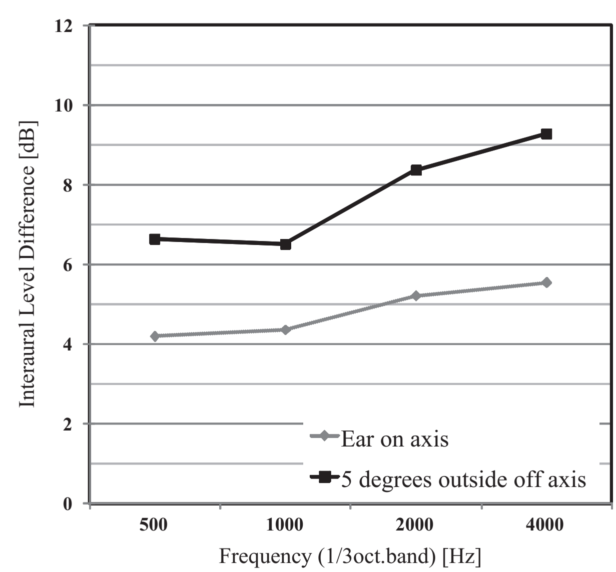


Fig. 6. Frequency characteristics of the averaged interaural level difference (ILD). The ILDs are calculated using the values of Figs. 5 and 6.

The characteristics of the parametric loudspeaker can be explained in considering directivities of both loudspeakers. To simplify, the number of loudspeaker is one. Fig. 7(a) and (b) show the cases when the axis of the loudspeaker is toward right ear and when it is toward 5 deg outside off right ear. The radiated sound signal from the loudspeaker is s. The sound signals of left and right eras ear $s_{LR,0}$, $s_{RR,0}$, $s_{LR,5}$ and $s_{RR,5}$, respectively. The subscripts 0 and 5 mean when the axis of the loudspeaker is toward right ear and when it is toward 5 deg outside off right ear. The distance between the loudspeaker and left and right ears are r_{LR} and r_{RR}. These correspond to the crosstalk and direct passes. The directivities are $D(\theta_{R,0})$, $D(\theta_{L,0})$, $D(\theta_{R,5})$ and $D(\theta_{L,5})$. The $s_{LR,0}$ and $s_{LR,5}$ is attenuated by the head and the effect is expressed by α. The α is less than 1. The r_{LR} and r_{RR} are can be assumed as mentioned below.

$$r_o = r_{RR} \simeq r_{LR} \tag{1}$$

The sound signals of left and right ears $s_{LR,0}$, $s_{RR,0}$, $s_{LR,5}$ and $s_{RR,5}$ are from the directivity $D(\theta_{R,0})$, $D(\theta_{L,0})$, $D(\theta_{R,5})$ and $D(\theta_{L,5})$ and the attenuated factor α using (1)

$$\begin{aligned} s_{RR,0} &= \{D(\theta_{R,0})/r_o\} \cdot s, \\ s_{LR,0} &= \{\alpha D(\theta_{L,0})/r_o\} \cdot s, \\ s_{RR,5} &= \{D(\theta_{R,5})/r_o\} \cdot s, \\ s_{LR,5} &= \{\alpha D(\theta_{L,5})/r_0\} \cdot s \end{aligned} \tag{2}$$

The ratios of sound signal of right to left ears are from (2),

$$\frac{s_{RR,0}}{s_{LR,0}} = \frac{D(\theta_{R,0})}{\alpha D(\theta_{L,0})}, \frac{s_{RR,5}}{s_{LR,5}} = \frac{D(\theta_{R,5})}{\alpha D(\theta_{L,5})} \tag{3}$$

In the case of the ordinary loudspeaker, the directivity is very dull. The ratios of $s_{RR,5}$ to $s_{LR,5}$ and $s_{RR,0}$ to $s_{LR,0}$ are from (3)

$$\therefore \left(\frac{D(\theta_{R,5})}{D(\theta_{L,5})}\right)_{ordinary} \simeq \left(\frac{D(\theta_{R,0})}{D(\theta_{L,0})}\right)_{ordinary} \simeq 1$$

$$\frac{\left(\frac{s_{RR,5}}{s_{LR,5}}\right)_{ordinary}}{\left(\frac{s_{RR,0}}{s_{LR,0}}\right)_{ordinary}} \simeq 1 \tag{4}$$

In the case of the parametric loudspeaker, the directivity is very sharp. The ratios of $s_{RR,5}$ to $s_{LR,5}$ and $s_{RR,0}$ to $s_{LR,0}$ are from (3)

$$\therefore \left(\frac{D(\theta_{R,5})}{D(\theta_{L,5})}\right)_{parametric} > \left(\frac{D(\theta_{R,0})}{D(\theta_{L,0})}\right)_{parametric} > 1$$

$$\frac{\left(\frac{s_{RR,5}}{s_{LR,5}}\right)_{parametric}}{\left(\frac{s_{RR,0}}{s_{LR,0}}\right)_{parametric}} > 1 \tag{5}$$

Totally, the relationship of the ratios of $s_{RR,5}$ to $s_{LR,5}$ and $s_{RR,0}$ to $s_{LR,0}$ for the parametric loudspeaker and ordinary loudspeaker are from (4) and (5),

$$\frac{\left(\frac{s_{RR,5}}{s_{LR,5}}\right)_{parametric}}{\left(\frac{s_{RR,0}}{s_{LR,0}}\right)_{parametric}} > \frac{\left(\frac{s_{RR,5}}{s_{LR,5}}\right)_{ordinary}}{\left(\frac{s_{RR,0}}{s_{LR,0}}\right)_{ordinary}} \simeq 1 \tag{6}$$

The relationship of the ratios in decibels, that is, ILDs for the parametric loudspeaker and ordinary loudspeaker are from (6).

$$20\log\left(\frac{\left(\frac{s_{RR,5}}{s_{LR,5}}\right)_{parametric}}{\left(\frac{s_{RR,0}}{s_{LR,0}}\right)_{parametric}}\right) > 20\log\left(\frac{\left(\frac{s_{RR,5}}{s_{LR,5}}\right)_{ordinary}}{\left(\frac{s_{RR,0}}{s_{LR,0}}\right)_{ordinary}}\right) \simeq 0[\mathrm{dB}] \tag{7}$$

For example, by using the data of 1 kHz 1/3 oct., a numerical analysis is considered. Eqs. (8) and (9) are derived from Fig. 6. Eq. (10) is estimated from the HRTFs database provided by MIT [14].

$$20\log\left(\frac{s_{RR,5}}{s_{LR,5}}\right)_{parametric} \simeq 6[\mathrm{dB}] \tag{8}$$

$$20\log\left(\frac{s_{RR,0}}{s_{LR,0}}\right)_{parametric} \simeq 4[\mathrm{dB}] \tag{9}$$

$$20\log\left(\frac{s_{RR,0}}{s_{LR,0}}\right)_{ordinary} \simeq 1[\mathrm{dB}] \tag{10}$$

Eqs. (6) and (7) are confirmed and Eq. (11) is transformed into more convenient form by Eqs. (6)–(10).

$$\begin{aligned} &20\log\left(\frac{s_{RR,5}}{s_{LR,5}}\right)_{parametric} > 20\log\left(\frac{s_{RR,0}}{s_{LR,0}}\right)_{parametric} > 20\log\left(\frac{s_{RR,5}}{s_{LR,5}}\right)_{ordinary} \\ &\simeq 20\log\left(\frac{s_{RR,0}}{s_{LR,0}}\right)_{ordinary} > 0[\mathrm{dB}] \end{aligned} \tag{11}$$

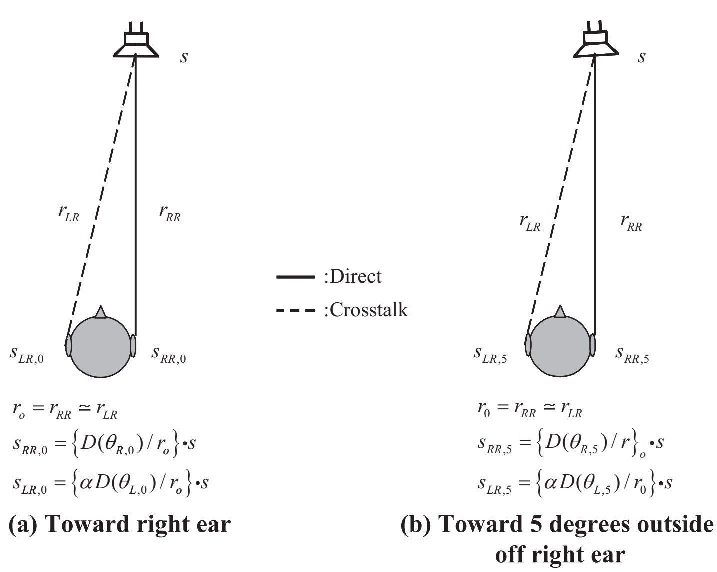


Fig. 7. Sounds of left and right ears from a front loudspeaker. (a) and (b) show the cases when the axis of the loudspeaker is toward right ear and when it is toward 5 deg outside off right ear.

The ILDs of the parametric loudspeaker are larger than those of the ordinary loudspeaker. The ILD of the parametric loudspeaker depends on the angle of the acoustic axis of loudspeaker.

5. Conclusions

In this paper, we focused on the parametric loudspeaker that is known as a super directivity loudspeaker. The characteristics of the sound localization in the vertical direction are clarified in the listening tests. The sound localization in the vertical direction using the upper and lower parametric loudspeakers is confirmed by listening tests and physical measurements. The vertical direction of sound localization can to be controlled not only when the acoustical axis was set to the right ear but also when it was set to rightward 5 deg from the right ear. The results are similar to those observed when ordinary loudspeakers are used. However, it is found that the left-right sound localization could be realized only with the upper and lower parametric loudspeakers. By setting the parametric loudspeaker the right ear, that is, by setting it only 3 deg to the right, the direction of sound localization moved approximately 10 deg rightward. The dependence of the parametric loudspeakers on the level difference between the upper and lower loudspeakers was weaker than those of the ordinary loudspeakers. Moreover, by setting the parametric loudspeaker 5 deg to the right, the direction of sound localization moves approximately 20 deg rightward. The main cues of sound localization in the horizontal plane are ILD (Interaural Level Difference) and ITD (Interaural Time Difference). In considering this listening test scheme, as the loudspeakers are set in the vertical plane, the ITDs are estimated to be almost zero. Only the ILD plays the main role in perception of sound localization in the horizontal direction. The measured ILD (Interaural Level Difference) of the parametric loudspeaker using the dummy head are analyzed. The obtained ILDs of the parametric loudspeaker are similar in spite of the level differences of the radiated signals between the upper and lower loudspeakers. The ILDs were larger than those of the ordinary loudspeaker. The ILD of the parametric loudspeaker depends strongly on the angle of the acoustic axis of loudspeaker. The dependence of the ordinary loudspeaker is notably weak. Because the higher frequency sound is harder to diffract, the cross talk level from the loudspeaker to the left ear becomes smaller. This finding helps to explain the measured result that the ILD of the higher frequency becomes larger. These listening test results and the measured ILDs with the dummy head lead to clarifications regarding the interesting characteristics of sound localization with parametric loudspeakers.

References

[1] Westervelt PJ. Parametric acoustic array. J Acoust Soc Am 1963;35(4):535–7.
[2] Bennett MB, Blackstock DT. Parametric array in air. J Acoust Soc Am 1975;57(3):562–8.
[3] Yoneyama M, Fujimoto J, Kawano Y, Ssabe S. The audio spotlight: an application of nonlinear interaction of sound waves to a new type of loudspeaker design. J Acoust Soc Am 1983;73(5):1532–6.
[4] Kamakura T. Fundamentals of nonlinear acoustics. Aichi publication; 1996.
[5] Kamakura T, Sakai Shinichi. Practical development of directive sopund system–examination from various research fields. Fund Rev IEICE 2008;1:37–43.
[6] Omori K, Kitayama I, Kamakura T, Sakai S. Guiding property of audible traffic signals using parametric speakers and sub-speakers. IEICE Trans (Jpn Ed) 2008; VoJ91-A 12:1174–80.
[7] Gan W, Yang J, Kamakura T. Parametric acoustic array: theory, advancement, and applications. Appl Acoust 2012;73(12):1209–10.
[8] Aoki Shigeaki, Toba Masayoshi, Tsujita Norihisa. Sound localization of stereo reproduction with parametric loudspeakers. Appl Acoust 2012;73(12):1289–95.
[9] Blauert J. Spatial hearing. MIT Press; 1983 [36-200126].
[10] Kurozumi K. Direction of sound image produced from tow loudspeakers placed in a vertical plane. Proc of autumn meeting of the acoust Soc Japan 1989:437–8.
[11] Kimura T, Ando H. Listening test for 3D audio system using multiple vertical panning. IEICE Technical Report EA2011-122; 2012. p. 13–18.
[12] Feddersen WE, Sandel TT, Teas DC, Jeffress LA. Localization of high-frequency tones. J Acoust Soc Am 1957:988–91.
[13] Shaw EAG, Vaillancourt MM. Transformation of sound-pressure level from the free field to the eardrum presented in numerical form. J Acoust Soc Am 1985:1120–3.
[14] Gardner B, Martin K. HRTF Measurements of a KEMAR dummy head microphone. MIT Media Lab Perceptual Computing Technical Report #280; 1994.