Development of A Steerable Stereophonic Parametric Loudspeaker

Chuang Shi*, Hideyuki Nomura†, Tomoo Kamakura‡, and Woon-Seng Gan§
*Department of Electrical and Electronic Engineering, Kansai University, Osaka, Japan
E-mail: r148005@kansai-u.ac.jp
†Department of Electronic Engineering, The University of Electro-Communications, Tokyo, Japan
E-mail: h.nomura@uec.ac.jp
‡Center for Industrial and Governmental Relations, The University of Electro-Communications, Tokyo, Japan
E-mail: kamakura@ee.uec.ac.jp
§School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore
E-mail: ewsgan@ntu.edu.sg

***Abstract*—The parametric loudspeaker is a type of directional loudspeakers making use of the nonlinear acoustic effects. The past studies to reproduce the three-dimensional audio contents with a pair of the parametric loudspeakers have demonstrated satisfactory performance. In this paper, the steerable parametric loudspeakers are proposed to relocate the sweet spot to follow the head movement of the listener. Although the spatial aliasing effects are observed in the steerable parametric loudspeaker, they can be converted to generate multiple sound beams simultaneously. A new case of the grating lobe elimination, namely the over elimination, is studied to extend the controllable level difference between the two sound beams. The simulation results to compare the equal and Chebyshev weights are also presented in this paper.**

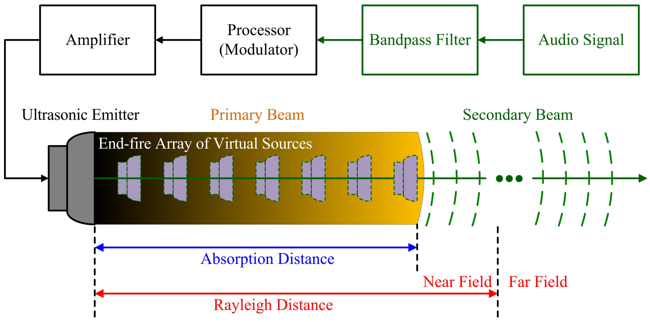

Fig. 1. Common structure of the parametric loudspeaker [3].

I. Introduction

The parametric loudspeaker is a type of directional loudspeakers that transmits a narrow sound beam with a relatively smaller emitter size as compared to a conventional loudspeaker or loudspeaker array [1]. As an application of the parametric transmitting array in air, the parametric loudspeaker generates a virtual endfire array from the parametric array effect. Hence, the parametric loudspeaker is understood to be a combination of the electronic hardware and the nonlinear acoustic effects. When the ultrasonic emitter of the parametric loudspeaker is blocked, it is muted, because there is no virtual source formed in the air [2].

A common structure of the parametric loudspeaker is shown in Fig. 1 [3]. In this structure, a bandpass filter is introduced to increase the reproduced sound pressure level and to reduce the intermodulation distortions, which is similar to the bandpass filter used in the telephone systems. The driving circuit consists of an amplifier and a processor or a hardware modulator. Preprocessing and modulation methods are often carried out in the driving circuit. The filtered audio signal will be modulated on an ultrasonic carrier. There is no demodulator required at the location of the listener, because of the self-demodulation effect [4]. The ultrasonic emitter has the resonance frequency equaling to the carrier frequency used in the modulator. The carrier frequency and emitter size determine the absorption and Rayleigh distances. The absorption distance gives the length of the virtual endfire array, while the Rayleigh distance defines the near field boundary of the ultrasonic emitter. In the early studies of the parametric loudspeaker, the Rayleigh distance was designed to be longer than the absorption distance, and the observation points were placed beyond the Rayleigh distance [5].

In the steerable parametric loudspeaker, the ultrasonic emitter consists of hundreds of the piezoelectric ceramic transducers (PZTs). They are grouped into several channels and driven by individual amplifiers [6]. The phased array beamsteering is adopted in the steerable parametric loudspeaker to generate a controllable sound beam [7]. A diagram of the beamsteering structure is shown in Fig. 2. Individual delays and weights can be applied to the carrier and sideband frequencies. The spatial aliasing effects are adverse to the steerable parametric loudspeaker [8]. According to the Nyquist criterion, the ultrasonic emitter consisting of the PZTs resonating at 40 kHz requires the interchannel spacing being less than 8.5 mm to prevent the occurrence of grating lobes. This requirement is difficult to be carried out, for most of the PZTs have the diameter of 10mm or 16 mm. Some experimental configurations of the ultrasonic emitter are shown in Fig. 3.

There are three potential approaches to deal with the spatial aliasing effects in the steerable parametric loudspeaker. Firstly, the compact configuration can be adopted in the ultrasonic emitter as shown in Fig. 3(d) [9]. In the compact configuration, the interchannel spacing is reduced to only half of the diameter of the PZTs. An implementation of the compact configuration has been carried out in the steerable parametric loudspeaker for active noise control [10]. In contrast to the column configuration using the same number of PZTs in every channel as shown in Figs. 3(a)-3(c), the compact configuration contains different numbers of the PZTs in the odd and even channels. Hence, a larger number of the PZTs is usually required in the compact configuration to ensure the output power is equally spread across all the channels [11].

Secondly, the microelectromechanical (MEMS) technology helps to reduce the size of the PZTs. A MEMS PZT array has been fabricated and examined [12]. The diameter of every ultrasonic transducer in this array is as small as one eighth the diameter of the conventional PZTs. The piezoelectric thin film is specially designed to improve the acoustic efficiency of the MEMS PZT [13]. Therefore, the reproduced sound pressure level is not much compromised by the reduced emitter size.

Thirdly, the grating lobe elimination has been proposed in theory and validated by experiments [14]. When the interchannel spacing is too wide to fulfill the Nyquist criterion, grating lobes are observed at the carrier and sideband frequencies. However, there is little or no spatial aliasing observed at the difference frequency. The steerable parametric loudspeaker can be designed to take advantage of the grating lobe elimination, so the column configuration in Fig. 3(a) can be free from the spatial aliasing effects.

In this paper, the spatial aliasing effects are made use of to generate two sound beams. Thus, a stereophonic reproduction method is proposed to transmit different audio contents to two directions simultaneously from only one steerable parametric loudspeaker. The proposed method will benefit the nonwearable stereophonic sound reproduction [15]–[17]. For example, the steerable parametric loudspeaker can be installed in the portable device, where two sound beams can be steered to the left and right ears of the listener and the stereophonic audio contents can be reproduced without earphones.

II. Theory

A uniform linear array consisting of M channels has the equal interchannel spacing d. The input signal is assumed to represent a plane wave at the angular frequency of ω and wavenumber of k. When the weight w_m and delay τ_m are applied to the mth channel for $m = 0, 1, \cdots, M-1$, the output of each channel observed in the far field at the incidence angle of θ is written as

$$C_m(\theta) = w_m \exp(jmdk\sin\theta + j\omega\tau_m), \quad (1)$$

where $j = \sqrt{-1}$ is the imaginary unit.

The delay amount can be designed as

$$\tau_m(\theta_0) = -\frac{md\sin\theta_0}{c}, \quad (2)$$

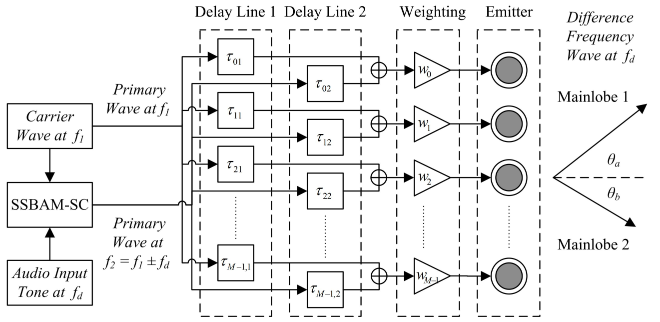

Fig. 2. Beamsteering structure of the steerable parametric loudspeaker, where SSBAM-SC is the abbreviation for the single sideband amplitude modulation suppressed carrier.

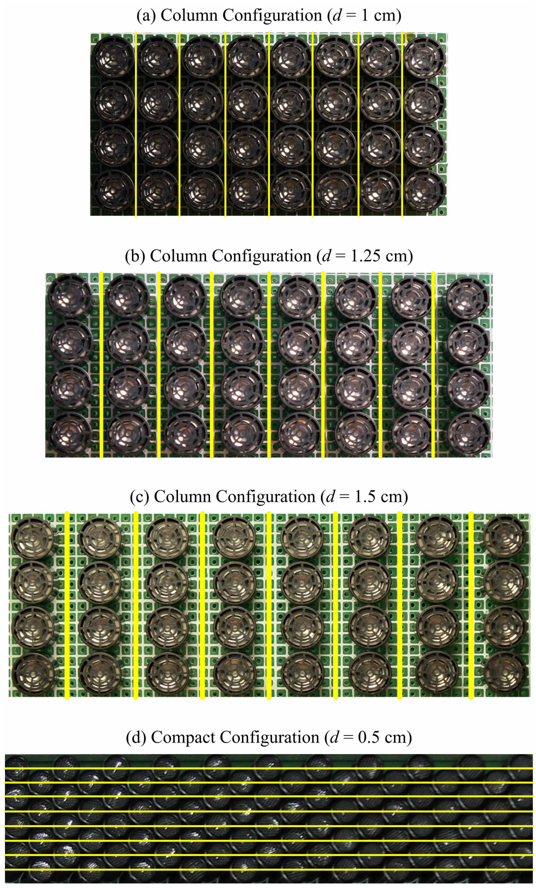

Fig. 3. Photos of ultrasonic emitters using different configurations, where the interchannel spacing is denoted as d.

where θ_0 is the steering angle, and c is the speed of sound. Thereby, the beampattern of this linear array is calculated by

$$D(\theta, f, \theta_0) = \left| \sum_{m=0}^{M-1} w_m \exp\left[j\frac{2\pi f}{c} md(\sin\theta - \sin\theta_0) \right] \right|. \quad (3)$$

As shown in Fig. 2, the delays τ_{m1} and τ_{m2} are applied to the first primary frequency f_1 and the second primary frequency $f_2 = f_1 + f_d$, respectively. The two groups of delays

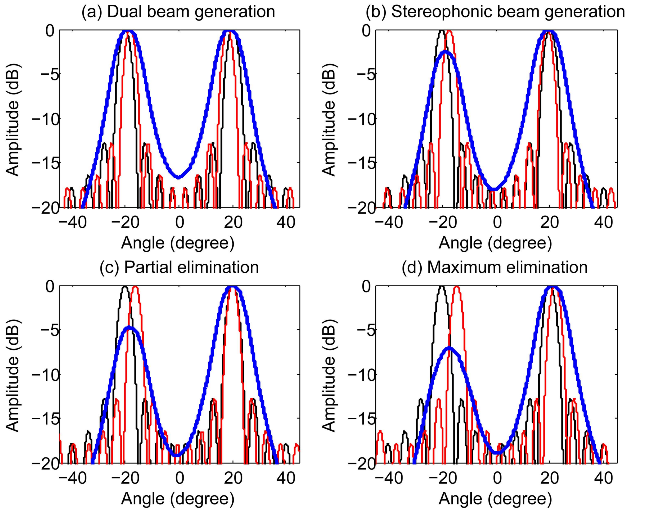

Fig. 4. Four cases of grating lobe elimination in the column configuration ($d = 1.25cm$), where the primary waves at 40 kHz and 44 kHz are plotted in black and red, respectively; and the difference frequency at 4 kHz is plotted in blue.

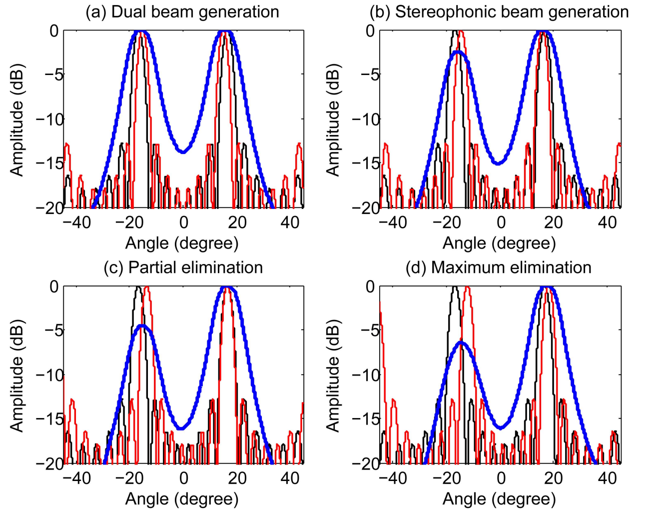

Fig. 5. Four cases of grating lobe elimination in the column configuration ($d = 1.5cm$), where the primary waves at 40 kHz and 44 kHz are plotted in black and red, respectively; and the difference frequency at 4 kHz is plotted in blue.

result in two steering angles of θ_1 and θ_2, respectively. Based on the product directivity principle [18]–[20], the directivity of the difference frequency f_d can be computed in a simplified expression as

$$D_d\left(\theta\right) = D\left(\theta, f_1, \theta_1\right) \times D\left(\theta, f_2, \theta_2\right). \tag{4}$$

In the directivity of the difference frequency, the angular directions of the mainlobe and the first grating lobe are denoted as θ_a and θ_b, respectively. Furthermore, an envelope method can improve the accuracy of the product directivity principle [20], which applies the spline interpolation between the local maxima of (4).

III. Four Cases of Grating Lobe Elimination

In this section, the column configurations in Figs. 3(b) and 3(c) are adopted, where $M = 8$. The interchannel spacings of them are given by 1.25 cm and 1.5 cm, respectively. Both the interchannel spacings are larger than the wavelength of the 40 kHz wave. The speed of sound is estimated at 344 m/s. The primary frequencies are selected at 40 kHz and 44 kHz, and the difference frequency at 4 kHz is expected to be generated. The steering angle of the first primary frequency is given by

$$\theta_1 = \sin^{-1}\frac{c}{2f_1 d}. \tag{5}$$

The mainlobe and grating lobe are steered to be symmetric to $0°$ [16]. The equal weights are used. When the second primary frequency is steered to different angles θ_2, four cases of grating lobe elimination can be derived from (4).

Firstly, the case of dual beam generation is shown in Figs. 4(a) and 5(a). In the dual beam generation, the steering angle of the second primary wave is given by

$$\theta_2 = \sin^{-1}\frac{c}{2f_2 d}, \tag{6}$$

so that the mainlobe and grating lobe occur symmetrically to $0°$ as well. This beamsteering structure is called the symmetric structure [16]. Based on the product directivity principle, the difference frequency has its mainlobe and grating lobe being symmetric to $0°$. The dual beam generation can transmit the same audio contents to two different directions simultaneously. From Figs. 4(a) to 5(a), the angular separation between the mainlobe and grating lobe of the difference frequency is narrowed from $38.3°$ to $31.8°$, because the increased interchannel spacing leads to the reduced spatial aliasing periods of the primary frequencies.

The second case, namely, the stereophonic beam generation, is shown in Figs. 4(b) and 5(b). In the stereophonic beam generation, the steering angle of the second primary frequency is adjustable to control the level difference between the two sound beams [15]. In comparison with the dual beam generation, the mainlobe of the second primary frequency is steered closer to the mainlobe of the first primary frequency. Here, an example of the steering angle of the second primary frequency is given by

$$\theta_2 = \frac{1}{2}\left(\sin^{-1}\frac{c}{2f_1 d} + \sin^{-1}\frac{c}{2f_2 d}\right). \tag{7}$$

The third case is the steerable parametric loudspeaker, where the steering angles of the two primary frequencies equal to the intended steering angle of the difference frequency, *i.e.*

$$\theta_2 = \theta_1 = \sin^{-1}\frac{c}{2f_1 d}. \tag{8}$$

In Figs. 4(c) and 5(c), the mainlobes of the primary frequencies coincide with each other. However, the grating lobes of the primary frequencies occur apart, due to the difference in the spatial aliasing periods of the primary frequencies. The resultant grating lobe of the difference frequency will be eliminated.

The high difference frequency leads to the full elimination of grating lobes, while the low difference frequency results in the partial grating lobe elimination only [14].

In this paper, the fourth case of grating lobe elimination is derived, which is called the over elimination as demonstrated in Figs. 4(d) and 5(d). The maximum level difference between the two sound beams in the stereophonic beam generation is used to be constrained by the partial grating lobe elimination [15]. The over elimination provides a significant increment of the maximum level difference between the two sound beams generated from one steerable parametric loudspeaker.

IV. Simulation Results

The intersection function was originally proposed in [8] and experimentally validated in [14]. With the variables defined in this paper, the original intersection function is rewritten as

$$I_{old}\left(f_d\right)=\max_{-\theta_\triangle<\theta<3\theta_\triangle}\left[D\left(\theta,f_1,0\right)\times D\left(\theta,f_2,\theta_\triangle\right)\right], \tag{9}$$

where

$$\theta_\triangle=\sin^{-1}\frac{f_d d}{c}. \tag{10}$$

In order to comparatively study the four cases of grating lobe elimination, the intersection function has to be modified as

$$I_{new}\left(f_d,\phi\right)=\frac{\max\limits_{-\theta_\triangle<\theta<3\theta_\triangle}\left[D\left(\theta,f_1,0\right)\times D\left(\theta,f_2,\theta_\triangle\right)\right]}{\max\limits_{-\phi<\theta<3\phi}\left[D\left(\theta,f_1,0\right)\times D\left(\theta,f_2,\phi\right)\right]}, \tag{11}$$

where $\phi=\theta_1-\theta_2$ is the angular separation between the mainlobes of the primary frequencies, and

$$\theta_\triangle=\sin^{-1}\left(\sin\phi+\frac{c}{f_2 d}-\frac{c}{f_1 d}\right) \tag{12}$$

is the angular separation between the grating lobes of the primary frequencies. The modified intersection function can calculate the maximum level difference between the two sound beams generated from one steerable parametric loudspeaker.

The results obtained from (9) and (11) using four sets of weights are plotted in Fig. 6. The four sets of weights include one set of equal weights and three sets of Chebyshev weights resulting in sidelobe attenuations of 13 dB, 20 dB, and 30 dB. It is observed in Fig. 6 that the proposed over elimination has resulted in a wider range of level difference between the two sound beams when compared with the previous stereophonic beam generation, in spite of the set of weights adopted. In the previous method, the set of Chebyshev weights with the largest sidelobe attenuation results in the worst performance in terms of the maximum level difference. However, the same set of Chebyshev weights demonstrates the best performance when using the proposed over elimination.

Although the over elimination can improve the maximum level difference, the mainlobe level is compromised for the low difference frequency. Similarly, the dual beam generation achieves the same levels of the two sound beams, but the mainlobe level is compromised for the high difference frequency. In Fig. 7, the mainlobe levels are compared between the over elimination and the dual beam generation to demonstrate

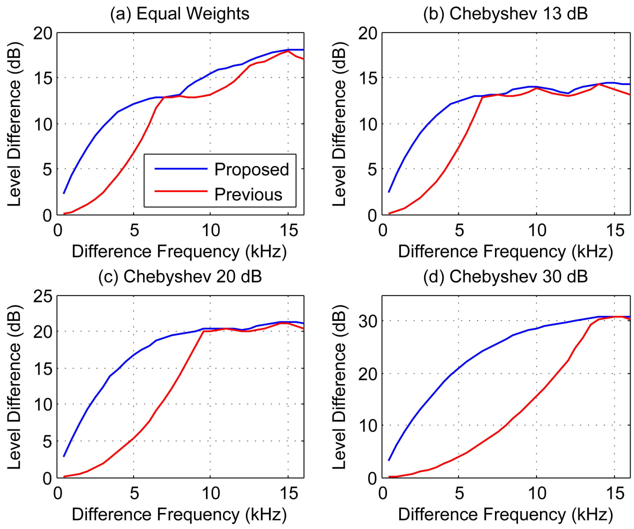

Fig. 6. Maximum level difference between the two sound beams generated in the over elimination and the stereophonic beam generation, where blue lines represent the over elimination; and red lines represent the stereophonic beam generation.

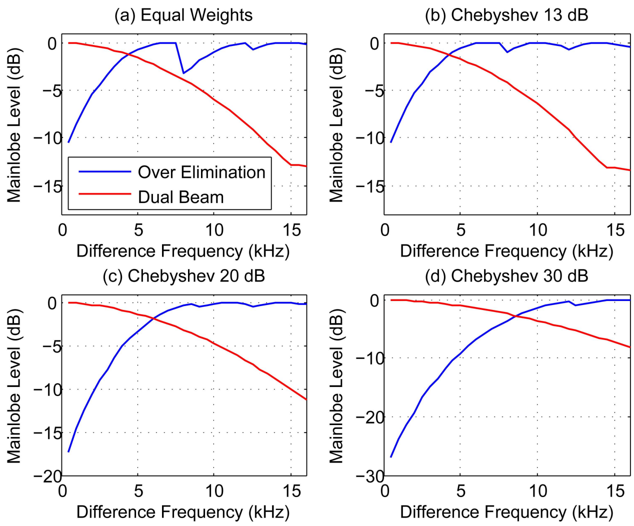

Fig. 7. Mainlobe level in the over elimination and the dual beam generation, where blue lines represent the over elimination; and red lines represent the dual beam generation elimination.

the power efficiency of the steerable stereophonic parametric loudspeaker. The input power is kept consistent. The set of Chebyshev weights with the largest sidelobe attenuation results in the lowest power efficiency to generate the low difference frequency, but the highest power efficiency to generate the high difference frequency. It shows that a wider range of the level difference between the two sound beams would request higher power input of the steerable stereophonic parametric loudspeaker. In the future, we will carry out acoustic measurements to find the tradeoff settings and examine the sound quality by subjective assessments.

V. Conclusions

Complementing to the three known cases of grating lobe elimination, the fourth case, namely the over elimination, has been demonstrated in this paper. The intersection function, which used to describe the level of grating lobe elimination, has been modified to evaluate the maximum level difference between the two sound beams generated from one steerable parametric loudspeaker. By accounting for the over elimination, the steerable stereophonic parametric loudspeaker has achieved a wider range of the level difference between the two sound beams as compared to the previous method. Four sets of weights have also been compared in the simulation. The set of Chebyshev weights with the largest sidelobe attenuation can lead to the best performance of the stereophonic beamsteering. However, there is a remaining issue to improve the power efficiency of the steerable stereophonic parametric loudspeaker.

Acknowledgment

This work is partially supported by MEXT-Supported Program for the Strategic Research Foundation at Private University, 2013-2017.

References

[1] M. Yoneyama, J. Fujimoto, Y. Kawamo, and S. Sasabe, "The audio spotlight: An application of nonlinear interaction of sound waves to a new type of loudspeaker design," *J. Acoust. Soc. Am.*, vol. 73, no. 5, pp. 1013-1020, 1983.

[2] C. Shi and Y. Kajikawa, "An introduction to parametric array loudspeaker and its application in active noise control," in *Proc. 1st Joint Symp. Signal Process. Control Syst.*, Jungli, Taiwan, June 2014.

[3] C. Shi, "Investigation of the steerable parametric loudspeaker based on phased array techniques," Ph.D. Thesis, Nanyang Technological University, Singapore, 2013.

[4] H. O. Berktay, "Possible exploitation of nonlinear acoustics in underwater transmitting applications," *J. Sound Vib.*, vol. 2, no. 4, pp. 435-461, 1965.

[5] P. J. Westervelt, "Parametric acoustic array," *J. Acoust. Soc. Am.*, vol. 35, no. 4, pp. 535-537, 1963.

[6] S. Takeoka and Y. Yamasaki, "Acoustic projector using directivity controllable parametric loudspeaker array," in *Proc. 20th Int. Congr. Acoust.*, Sydney, Australia, 2010.

[7] D. Olszewski, F. Prasetyo, and K. Linhard, "Steerable highly directional audio beam loudspeaker," in *Proc. Interspeech 2005*, Lisbon, Portugal, 2005.

[8] C. Shi and W. S. Gan, "On grating lobe elimination of difference frequency in parametric loudspeaker," in *Proc.2010 APSIPA Annu. Summit Conf.*, Singapore, 2010.

[9] W. S. Gan, J. Yang, K. S. Tan, and M. H. Er, "A digital beamsteerer for difference frequency in a parametric array," *IEEE Trans. Audio Speech Lang. Process.*, vol. 14, no. 3, pp. 1018-1025, 2006.

[10] N. Tanaka and M. Tanaka, "Active noise control using a steerable parametric array loudspeaker," *J. Acoust. Soc. Am.*, vol. 127, no. 6, pp. 3526-3537, 2010.

[11] S. Wu, M. Wu, C. Huang, and J. Yang, "FPGA-based implementation of steerable parametric loudspeaker using fractional delay filter," *Applied Acoust.*, vol. 73, no. 12, pp. 1271-1281, 2012.

[12] H. Lee, D. Kang, and W. Moon, "A micro-machined source transducer for a parametric array in air," *J. Acoust. Soc. Am.*, vol. 125, no. 4, pp. 1879-1893, 2009.

[13] Y. Je, H. Lee, and W. Moon, "The impact of micromachined ultrasonic radiators on the efficiency of transducers in air," *Ultrasonics.*, vol. 53, no. 6, pp. 1124-1134, 2013.

[14] C. Shi and W. S. Gan, "Grating lobe elimination in steerable parametric loudspeaker," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 58, no. 2, pp. 437-450, 2011.

[15] C. Shi, H. Nomura, T. Kamakura, and W. S. Gan, "Spatial aliasing effects in a steerable parametric loudspeaker for stereophonic sound reproduction," *IEICE Trans. Fund. Electron. Commun. Computer Sci.*, vol. E97-A, no.9, pp. 1859-1866, 2014.

[16] C. Shi, E. L. Tan, and W. S. Gan, "Hybrid immersive three-dimensional sound reproduction system with steerable parametric loudspeakers," in *Proc. 21st Int. Congr. Acoust.*, Montreal, Canada, 2013.

[17] S. Aoki, M. Toba, and N. Tsujita, "Sound localization of stereo reproduction with parametric loudspeakers," *Applied Acoust.*, vol. 73, no. 12, pp. 1289-1295, 2012.

[18] C. Shi and W. S. Gan, "Product directivity models for parametric loudspeakers," *J. Acoust. Soc. Am.*, vol. 131, no. 3, pp. 1938-1945, 2012.

[19] C. Shi and W. S. Gan, "Modeling the directivity of parametric loudspeaker," in *Proc. 19th Int. Symp. Nonlinear Acoust.*, Tokyo, Japan, 2012.

[20] C. Shi, H. Nomura, T. Kamakura, and W. S. Gan, "An envelope method for improving the product directivity models of the parametric loudspeaker," *IEICE Tech. Report*, vol. 113, no. 412, pp. 7-10, 2014