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Spatial Aliasing Effects in a Steerable Parametric Loudspeaker for Stereophonic Sound Reproduction

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SUMMARY Earlier attempts to deploy two units of parametric loudspeakers have shown encouraging results in improving the accuracy of spatial audio reproductions. As compared to a pair of conventional loudspeakers, this improvement is mainly a result of being free of crosstalk due to the sharp directivity of the parametric loudspeaker. By replacing the normal parametric loudspeaker with the steerable parametric loudspeaker, a flexible sweet spot can be created that tolerates head movements of the listener. However, spatial aliasing effects of the primary frequency waves are always observed in the steerable parametric loudspeaker. We are motivated to make use of the spatial aliasing effects to create two sound beams from one unit of the steerable parametric loudspeaker. Hence, a reduction of power consumption and physical size can be achieved by cutting down the number of loudspeakers used in an audio system. By introducing a new parameter, namely the relative steering angle, we propose a stereophonic beamsteering method that can control the amplitude difference corresponding to the interaural level difference (ILD) between two sound beams. Currently, this proposed method does not support the reproduction of interaural time differences (ITD).

key words: *beamsteering, spatial aliasing, ultrasonic transducer array, parametric loudspeaker, nonlinear acoustics*

1. Introduction

The parametric loudspeaker has recently gained popularity as a new acoustic reproduction device that can generate a directional sound beam [1]. The sound principle of a parametric loudspeaker is the so-called parametric acoustic array. When two primary frequency waves are transmitted from the source, and due to the nonlinear nature of air, a sound beam of the difference frequency wave is formed along the propagation axis of the primary frequency waves [2]. The significant advantage of a parametric loudspeaker is that it requires a much smaller aperture size to transmit an equally narrow sound beam as compared to a conventional loudspeaker or a loudspeaker array. This is because the directivity of a parametric loudspeaker is determined by the primary frequency, which is much higher than the audible difference frequency.

A stereo reproduction system using two parametric loudspeakers has been examined through experiments and subjective tests [3]. The parametric loudspeaker has been proven to be able to transmit correct binaural information to the listener without any crosstalk cancellation. An attractive application of the parametric loudspeaker is thus to add directional sound feature in a portable device, when the installation size of the acoustic reproduction device is extremely limited [4]. Not only is the discomfort of wearing headphone for a long time avoided, at the same time the degradation of sound localization when a pair of loudspeakers are placed closely can be solved. However, due to the narrow sound beam of the parametric loudspeaker, the sweet spot is correspondingly smaller, so the effectiveness of an stereo reproduction system using two parametric loudspeakers may be reduced when the listener stretches his body or moves his head [5].

A flexible sweet spot can be achieved by using a pair of steerable parametric loudspeakers. The steerable parametric loudspeaker uses phased array techniques to generate a controllable sound beam [6]. It is usually built up by an array of ultrasonic transducers, which is then grouped into different channels and driven by individual amplifiers [7]. Spatial aliasing is the affecting factor in a steerable parametric loudspeaker. According to the spatial Nyquist criterion, the ultrasonic transducer array (UTA), consisting of transducers resonating at 40 kHz, requires an inter-channel spacing being less than 8.5 mm to avoid spatial aliasing. Such a narrow inter-channel spacing is difficult to be configured since most ultrasonic transducers have a diameter of 10 mm. In one of the earliest attempts to implement a steerable parametric loudspeaker [8], an inter-channel spacing of 80 mm was adopted. Therefore, the phased array techniques failed to work and ended up being a complementary to the mechanical panning system.

As it is a prominent issue, spatial aliasing effects of the steerable parametric loudspeaker have been studied by the authors [9], and a unique phenomenon, namely the grating lobe elimination, has been formulated in theory and validated in experiments [10]. The grating lobe elimination demonstrates that when the inter-channel spacing of the UTA is larger than the non-aliasing spacing implied by the spatial Nyquist criterion, spatial aliasing is observed at the primary frequencies, but not at the difference frequency wave. When a steerable parametric loudspeaker is designed to take advantage of the grating lobe elimination, its non-aliasing spacing can be extended to a few times wider than that is given by the spatial Nyquist criterion. The design rules and experimental validations can be found in [9] and [10]. An interesting extension to this work is to control

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the level of grating lobe elimination to generate two sound beams carrying the same audio contents from one unit of the steerable parametric loudspeaker, and the angular location of each sound beam is individually adjustable [11].

Since then, the feasibility of delivering two similar audio contents to two locations from a single steerable parametric loudspeaker attracted our interest, because the solution to this problem will potentially benefit the non-wearable stereophonic sound reproduction from a portable device. When a steerable parametric loudspeaker is installed in an ultrabook, for example, it allows the user to choose the number of sound beams (one or two) and the directions of sound beams. When the two sound beams are steered to the left and right ears of the user, a stereophonic sound can be thus reproduced without using earphones. In this paper, we aim to address this challenge and introduce the stereophonic beamsteering method that can generate two sound beams from a single steerable parametric loudspeaker and the ILD between the two sound beams are adjustable. The reproduction of ITD, which will be our future work, is not covered by this paper.

This paper is organized as follows. In Sect. 2, three cases of spatial aliasing effects occuring in the steerable parametric loudspeaker are reviewed and compared. This comparison leads to the derivation of the stereophonic beamsteering method presented in Sect. 3. In Sect. 4, the process of implementing HRTFs into a stereophonic steerable parametric loudspeaker is presented. Lastly, Sect. 5 summaries the contributions of this study.

2. Review of Spatial Aliasing in the Steerable Parametric Loudspeaker

The product directivity principle is adopted in this paper to model the relation between directivities of the primary frequency waves and the resultant difference frequency wave [12]. It states that the directivity of the difference frequency wave can be estimated by the product of directivities of the primary frequency waves. The accuracy of the product directivity principle has been proven in our previous experimental validations of the grating lobe elimination [9]. Based on the product directivity principle, when the two primary frequency waves are steered to the same direction, the difference frequency wave generated from the nonlinear interaction inherits this steering direction. This forms the fundamental idea of a steerable parametric loudspeaker.

A general structure of the steerable parametric loudspeaker is shown in Fig. 1. The UTA consists of M channels, and a weighting w_m is applied to the mth channel for $m = 0, 1, \cdots, M-1$. Two groups of delays τ_{m1} and τ_{m2} are respectively applied to the lower primary frequency wave at f_1 and the higher primary frequency wave at f_2, which are corresponding to their steering angles of θ_1 and θ_2. The directivity of the difference frequency wave can be computed based on the product directivity principle as

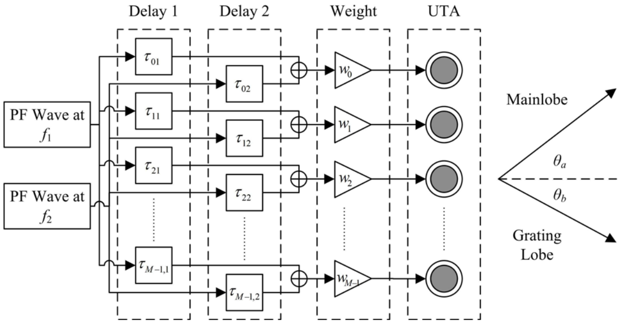

Fig. 1 A beamsteering structure to generate a difference frequency tone in the steerable parametric loudspeaker (extracted and modified from [5].

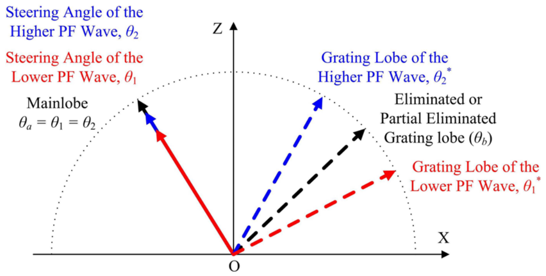

Fig. 2 Vectorized illustration of the case of grating lobe elimination.

$$D_{diff}(\theta) = \left|\sum_{m=0}^{M-1} w_m \exp\left[jmdk_1(\sin\theta - \sin\theta_1)\right]\right| \times \left|\sum_{m=0}^{M-1} w_m \exp\left[jmdk_2(\sin\theta - \sin\theta_2)\right]\right|, \quad (1)$$

where j is the imaginary unit; d is the inter-channel spacing; θ is the incidence angle; k_1 and k_2 are the wavenumbers of the primary frequency waves. The angular directions of the mainlobe and the first grating lobe are denoted as θ_a and θ_b for the resultant difference frequency wave, respectively.

2.1 Grating Lobe Elimination

Three spatial aliasing cases are derived from (1). Firstly, the case of grating lobe elimination is shown in Fig. 2. When the primary frequency waves are steered to the same direction, the difference frequency wave is implicitly steered to the same direction, i.e. $\theta_1 = \theta_2 = \theta_a$. The frequency difference between the two primary waves leads to the difference between their spatial periods. Since the mainlobes of the two primary frequency waves coincide at the steering angle, their grating lobes result in different angular locations. Based on the product directivity principle, the resultant grating lobe of the difference frequency wave is fully or partially eliminated. The level of grating lobe elimination was numerically modeled by the intersection function and distance function derived in the normalized angular space [9].

2.2 Dual-beam Generation

Secondly, the case of dual-beam generation is shown in

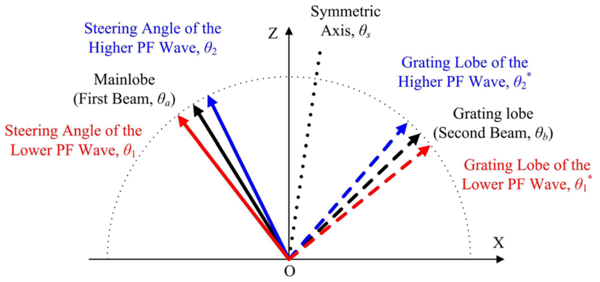

Fig. 3 Vectorized illustration of the case of dual-beam generation (extracted and modified from [5].

Fig. 3, when the mainlobe and one grating lobe of each primary frequency wave are controlled to be symmetric to one angular axis. In this case, the beamsteering structure is also known as the symmetric structure [5]. Based on the product directivity principle, the difference frequency wave has the same amplitudes at its mainlobe and the first grating lobe located within the beamwidth of the ultrasonic transducer used in the steerable parametric loudspeaker. The latter is referred as the first grating lobe in short for the rest of this paper. This can be explained by an analogy of the case of grating lobe elimination. The mainlobes of the primary frequency waves are apart from each other and the angular separation between these two mainlobes is equal to that between the first grating lobes of the primary frequency waves in the normalized angular space. Thus, the partial elimination occurs for both the mainlobe and the first grating lobe, and the levels of elimination are identical. As a result, the partially eliminated mainlobe and the partially eliminated first grating lobe have the same amplitude that can deliver the same audio content to two directions. The two directions remain symmetric to the same angular axis. This control strategy allows one unit of steerable parametric loudspeaker to create one sound beam and its duplication to another direction at the same time. The dual-beam generation is useful in portable devices that allows the user to share the listening experience with no additional hardware cost [11].

2.3 Stereophonic Beamsteering

Thirdly, the case of stereophonic beamsteering is shown in Fig. 4. This potential case is the focus of this paper. In spite of being derived from the case of dual-beam generation, it is a different and newly founded topic. In this case, the steerable parametric loudspeaker is enabled to generate two sound beams that are different in amplitude. It is found in the cases of grating lobe elimination and dual-beam generation that if the mainlobes of the primary frequency waves are located nearer in the normalized angular space as compared to that in the case of dual-beam generation, the first grating lobes of the primary frequency waves will be separated further, as illustrated in Fig. 4. Subsequently, the amplitude of the difference frequency wave will be higher at the mainlobe and lower at the first grating lobe than those in the case of dual-beam generation, respectively. Amplitude difference is achieved between the mainlobe and the first grating lobe of the difference frequency wave. When the mainlobes of the primary frequency waves get extremely close, the case of stereophonic beamsteering equals to the case of grating lobe elimination, in which the mainlobes of the primary frequency waves are steered to the same direction and the elimination level of the first grating lobe is maximized.

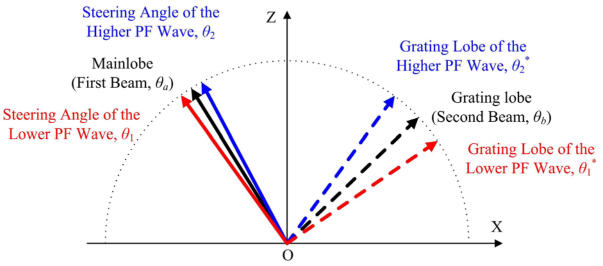

Fig. 4 Vectorized illustration of the potential case of stereophonic beamsteering.

2.4 Comparisons

A group of comparative simulations are carried out to interpret the three spatial aliasing cases that are mentioned above. In the simulation configuration, the UTA is a uniform linear array consisting of 8 channels, and the resultant difference frequency wave ranges from 500 Hz to 16 kHz in frequency. This difference frequency range used in the simulations covers the frequency ranges generated by majority of commercial parametric loudspeakers [1], [11]. According to the control strategy of the case of dual-beam generation [5], the center frequency is determined by

$$f_c = \frac{f_1 + f_2}{2} = \frac{c_0}{d\,(\sin\theta_b - \sin\theta_a)}, \tag{2}$$

where c_0 is the speed of sound in air; θ_a and θ_b are given by the desired directions of the two sound beams. It is assumed that θ_b is larger than θ_a, without loss of generality.

Moreover, we assume an application scenario where the steerable parametric loudspeaker is placed around 50 cm away from the listener (see Fig. 5). This is a typical distance for people using laptops. In order to deliver stereophonic contents to the listener's left and right ears separately, the two sound beams should be generated at about $\theta_a = -10°$ and $\theta_b = 10°$. If the inter-channel spacing is fixed at $d = 2$ cm, the center frequency is computed as $f_c = 49.5$ kHz by (2). There are commercial parametric loudspeakers using ultrasonic carriers at 48 kHz [1]. Using this center frequency, the three spatial aliasing cases are compared in simulations based on the product directivity principle.

The steering angles of the primary frequency waves under different spatial aliasing cases are plotted in Fig. 6. In the case of grating lobe elimination, the steering angles of the two primary frequency waves are always the same, i.e. $\theta_1 = \theta_2 = -10°$. In the case of dual-beam generation, the primary frequency waves are steered to the angles given by

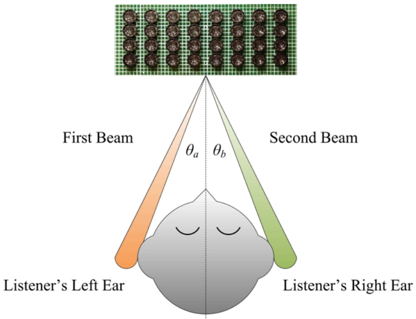

Fig. 5 An application scenario of the stereophonic beam generation.

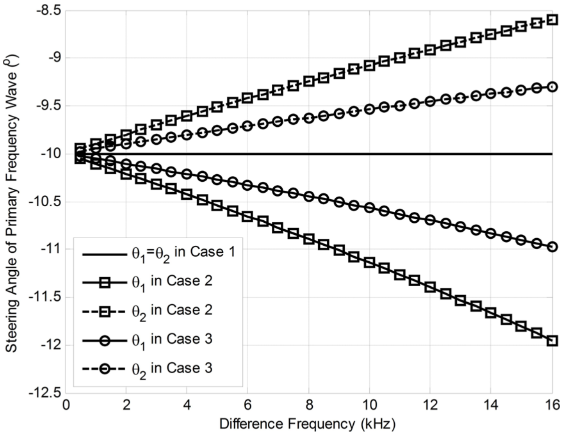

Fig. 6 Steering angles of the primary frequency waves under different spatial aliasing cases (case 1: case of grating lobe elimination; case 2: case of dual-beam generation; case 3: case of stereophonic beamsteering).

$$\sin\theta_1 = \frac{\sin\theta_a + \sin\theta_b}{2} - \frac{c_0}{2f_1 d} \tag{3}$$

and

$$\sin\theta_2 = \frac{\sin\theta_a + \sin\theta_b}{2} - \frac{c_0}{2f_2 d}. \tag{4}$$

In a sample case of stereophonic beamsteering, we select the steering angles of the primary frequency waves as the average of the two cases of grating lobe elimination and dual-beam generation, as plotted in Fig. 6.

The amplitude ratio of the mainlobe to the first grating lobe of the difference frequency wave is plotted in Fig. 7 for the three spatial aliasing cases, of which the steering angles are given in Fig. 6. A few measurement points that are extracted from the first author's dissertation [11] are also included for comparison. In the case of dual-beam generation, this amplitude ratio is kept as 0 dB for all the difference frequency waves. In the case of grating lobe elimination, the amplitude ratio agrees with the intersection function proposed in [9], [10]. For the sample case of stereophonic beamsteering, it is noted that the amplitude ratio of the mainlobe to the first grating lobe of the difference frequency wave lies in between those of the cases of grating lobe elimination and dual-beam generation. It shows that the relative level of the two sound beams generated from one unit of the steerable parametric loudspeaker is possible to be controlled by the steering angles of the primary frequency waves. As the ultrasonic transducer is not omnidirectional, the directivity of the ultrasonic transducer will lead to errors in real implementations of the three spatial aliasing cases, but array calibration methods may be applied to compensate the errors [13].

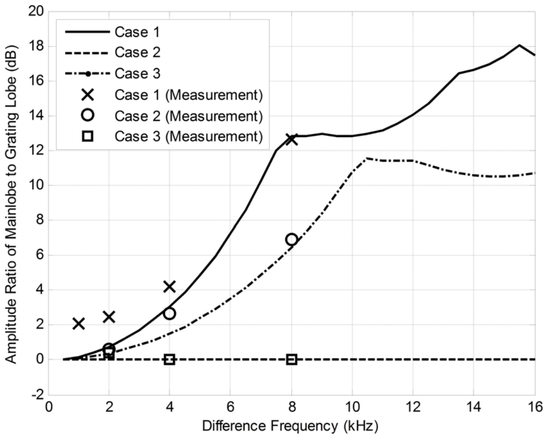

Fig. 7 Amplitude ratio of the mainlobe to the grating lobe of the difference frequency wave (case 1: case of grating lobe elimination; case 2: case of dual-beam generation; case 3: case of stereophonic beamsteering).

3. Stereophonic Beamsteering Method for the Steerable Parametric Loudspeaker

In order to control the two sound beams towards the listener's desired directions, the control strategy of the case of stereophonic beamsteering is adapted from that of the case of dual-beam generation. We introduce a new parameter $\Delta\theta$, which is non-negative and defines the relative steering angle of the primary frequency waves. The steering angles of the primary frequency waves are adjusted symmetrically in the normalized angular domain, i.e.

$$\sin\Delta\theta = \sin\theta_a - \sin\theta_1 = \sin\theta_2 - \sin\theta_a. \tag{5}$$

Using the relative steering angle, the first grating lobes of the primary frequency waves are located at

$$\sin\theta_1^* = \sin\theta_1 + \frac{c_0}{f_1 d} = \sin\theta_a + \frac{c_0}{f_1 d} - \sin\Delta\theta \tag{6}$$

and

$$\sin\theta_2^* = \sin\theta_2 + \frac{c_0}{f_2 d} = \sin\theta_a + \frac{c_0}{f_2 d} + \sin\Delta\theta. \tag{7}$$

Thus, the first grating lobe of the difference frequency wave, which is used as the second sound beam, is located at

$$\sin\theta_b = \frac{\sin\theta_1^* + \sin\theta_2^*}{2} = \sin\theta_a + \frac{c_0}{2f_1 d} + \frac{c_0}{2f_2 d}. \tag{8}$$

This is a rewritten expression of (2). It shows that the center frequency together with the inter-channel distance are the only two factors that determines the separation between the two sound beams in the normalized angular space, regardless to the relative steering angle. For a given steerable parametric loudspeaker and two known directions of interest, there is always a suitable center frequency that ensures the angular separation unchanged, which can be computed by (2). In the case of stereophonic beamsteering, the range of the relative steering angle is given by

$$0 \leq \sin\Delta\theta \leq \frac{c_0}{2f_1 d} - \frac{c_0}{2f_2 d}. \tag{9}$$

The upper bound is determined by the difference between the spatial periods of the primary frequency waves, while the lower bound leads to the case of grating lobe elimination. In the case of dual-beam generation, the relative steering angle is exactly given by the center of the range in (9), i.e.

$$\sin\Delta\theta = \frac{c_0}{4f_1 d} - \frac{c_0}{4f_2 d}. \tag{10}$$

For the relative steering angle given in (10), the mainlobe and the first grating lobe of the difference frequency wave are controlled at the same amplitude. When the relative steering angle is smaller than that of the case of dual-beam generation, a mainlobe higher than the first grating lobe of the difference frequency wave is generated. Vice versa, when the relative steering angle is larger than that of the case of dual-beam generation, a mainlobe lower than the first grating lobe of the difference frequency wave is generated. The key step to design a stereophonic steerable parametric loudspeaker is to figure out the relation between the relative steering angle and the resultant amplitude ratio between the mainlobe and the first grating lobe of the difference frequency wave. In consistent with Fig. 7, the maximum amplitude ratio between the two sound beams occurs in the case of grating lobe elimination and the lowest amplitude ratio occurs in the case of dual-beam generation. The cases of grating lobe elimination and dual-beam generation set the upper and lower bounds of the ratio of between amplitudes of the two sound beams that the case of stereophonic beamsteering can achieve.

Once the mainlobes of the primary frequency waves are located apart, a drop in sound pressure level of the difference frequency wave is expected. Using the same simulation configuration as that in the previous section, amplitudes of mainlobes of difference frequency waves from 500 Hz to 16 kHz with an interval of 500 Hz are plotted versus the relative steering angles from 0° to 3.3° with an interval of 0.05° in Fig. 8. The range of the relative steering angle used in this simulation is computed by (9). It can be observed that the relative steering angle is the affecting factor and the difference frequency has only trivial effect on the amplitude of its mainlobe. For simplicity, we define a simplified intersection function $I(\Delta\theta)$ to describe the curves in Fig. 8. If the wavenumber of the center frequency is denoted as k_c, the simplified intersection function is written as

$$I(\Delta\theta) = \left|\sum_{m=0}^{M-1} \exp\left[jmdk_c(-\sin\Delta\theta)\right]\right| \times \left|\sum_{m=0}^{M-1} \exp\left[jmdk_c(\sin\Delta\theta)\right]\right|. \tag{11}$$

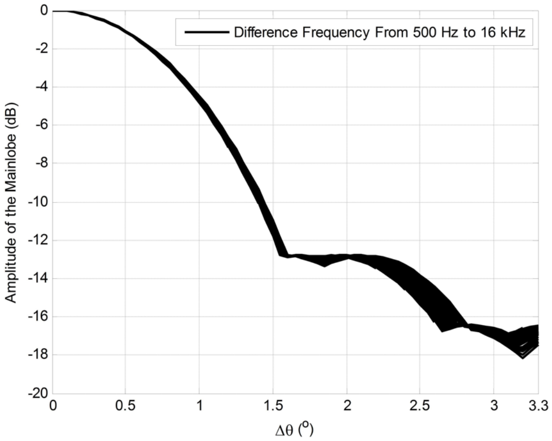

Fig. 8 Amplitude of the mainlobe of the difference frequency wave with respect to the relative steering angle.

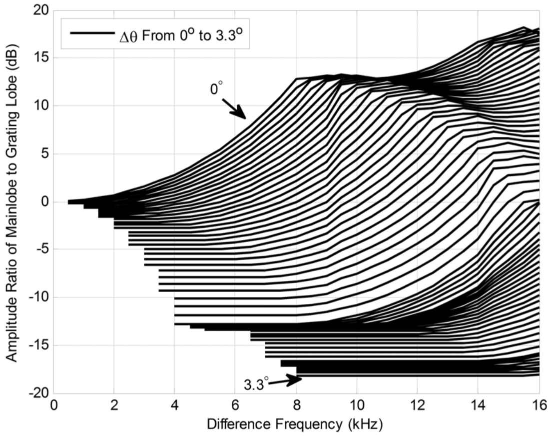

Fig. 9 Design curves of the stereophonic beamsteering method.

The amplitude ratio of the mainlobe to the first grating lobe of the difference frequency wave can be calculated using the intersection function as

$$amplitude\ ratio = \frac{I(\Delta\theta)}{I\left[\sin^{-1}\left(\frac{c_0}{2f_1 d} - \frac{c_0}{2f_2 d} - \sin\Delta\theta\right)\right]}, \tag{12}$$

because when a relative steering angle $\Delta\theta$ is applied to the mainlobes of the primary frequency waves, the resultant relative steering angle at the first grating lobes are also determined in the symmetric structure as illustrated in Figs. 3 and 4.

Hence, the design curves of the simulation configuration are obtained for difference frequency waves from 500 Hz to 16 kHz with an interval of 500 Hz using the simplified intersection function. The design curves are plotted in Fig. 9 with respect to the relative steering angles from 0° to 3.3° with an interval of 0.05°. When the relative steering angle is 0°, the design curve has the same values as the case of grating lobe elimination as shown in Fig. 7. Further-more, zeros in the design curves correspond to the case of dual-beam generation as shown in Fig. 6.

4. Implementing ILD Information of the HRTFs in a Stereophonic Steerable Parametric Loudspeaker

In this section, the process of using the design curves to implement ILD information of the HRTFs in a steerable parametric loudspeaker is presented as an example of the proposed stereophonic beamsteering method. Thus, the phase responses of the HRTFs are not taken into account. A step-by-step process is stated as follows: (a) Extract the HRTF data with a given combination of azimuth and elevation; (b) Compute magnitude responses of the left and right channels; (c) Calculate the amplitude ratio between the left and right channels; (d) For each frequency component, look up in the design curve for the value of relative steering angle $\Delta\theta$ that can match or give the closest approximation to the value indicated by the HRTF; (e) Filter-and-sum beamsteering structure can be adopted to control each frequency component to be transmitted to its corresponding actual steering angle.

Six groups of 128 point symmetrical HRTFs derived from only the left ear responses of the KEMAR HRTFs measured by the media laboratory at the Massachusetts Institute of Technology [14] are adopted. The selected HRTFs represent the azimuth of 10°, 20°, and 30° when the elevation is 0°, and the elevation of −30°, 30°, and 60° when the azimuth is 30°. The magnitude response of each group of HRTF is computed, and the amplitude ratio between frequency responses of the left and right channels is plotted in Fig. 10 when the elevation is fixed at 0° and in Fig. 11 when the azimuth is fixed at 30°.

Following the steps stated above, we have obtained the relative steering angles across the difference frequency range for implementing these six groups of HRTFs. The results are plotted in Fig. 12 and Fig. 13 for when the elevation is fixed at 0° and when the azimuth is fixed at 30°, respectively.

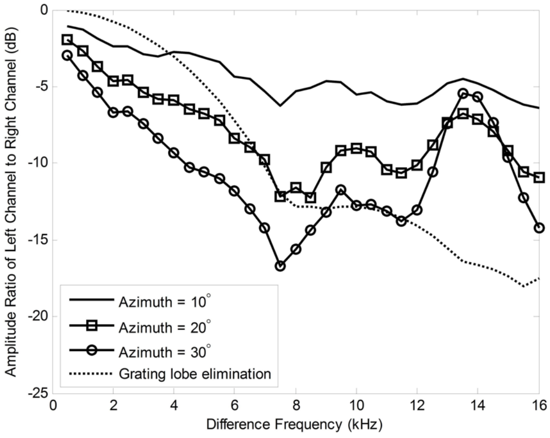

Fig. 10 Amplitude ratio of the left channel to the right channel when the elevation is 0° (KEMAR HRTF data are extracted from [14]).

4.1 Elevation of 0°

As shown in Fig. 10, the amplitude ratio of the HRFT, of

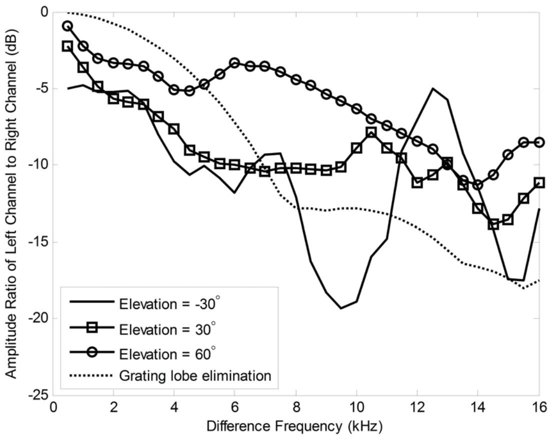

Fig. 11 Amplitude ratio of the left channel to the right channel when the azimuth is 30° (KEMAR HRTF data are extracted from [14]).

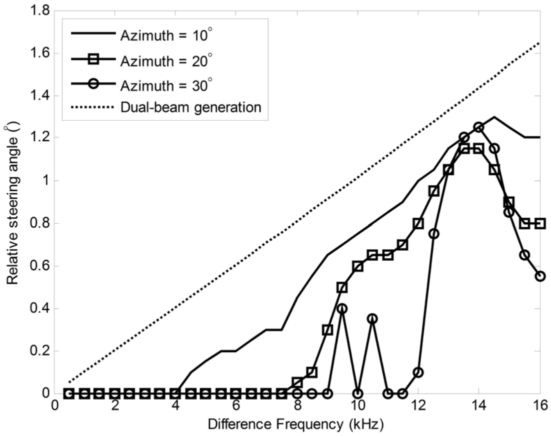

Fig. 12 Relative steering angle $\Delta\theta$ achieving the amplitude responses of given HRTFs when the elevation is 0°.

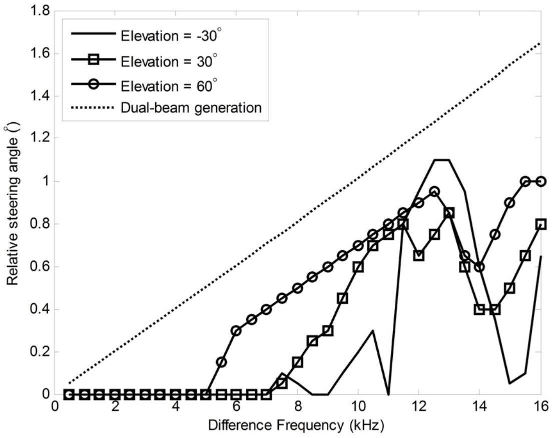

Fig. 13 Relative steering angle $\Delta\theta$ achieving the amplitude responses of given HRTFs when the azimuth is 30°.

which the azimuth is 10° and the elevation is 0°, is above the amplitude ratio of the case of grating lobe elimination when the difference frequency is above 4 kHz. Correspondingly in Fig. 12, the relative steering angle remains at zero until the difference frequency increases to 4 kHz. The relative steering angle is observed below that of the case of dual-beam generation as in the simulation the azimuths are chosen to be positive so that the sound pressure of the left channel is weaker than the right channel all the time. Similar observations can be made when the azimuth is 20° and 30°. In these two cases, the stereophonic beamsteering method works for the difference frequency waves above 7 kHz and 9 kHz, respectively. When the azimuth becomes larger, the amplitude difference between the left and right channels increases. Since the case of grating lobe elimination determining the upper bound of the stereophonic beamsteering method is more likely to occur for high frequency components [9], [10], it is found that the stereophonic beamsteering method works better for reproducing high frequency components or when the azimuth is small.

4.2 Azimuth of 30°

In Fig. 11, where the azimuth is fixed at 30°, the amplitude ratio of when the elevation is −30° is less significant than that of when the elevation is 30°. The change of elevation does not request a significant change of amplitude ratio corresponding to the ILD between the left and right channels. Therefore, the elevation does not change the effective frequency range of the proposed method significantly. In fact, negative elevations enlarge the effective frequency range of the proposed method. In Fig. 13, the proposed stereophonic beamsteering method works for the difference frequency wave starting from 5 kHz, rather than from 7 kHz for the rest of elevations when the azimuth is fixed at 30°. Moreover, the relative steering angle in Fig. 13 shows a similar trend to its corresponding amplitude ratio in Fig. 11.

5. Conclusions

This paper begins with analyses and simulations of three cases of spatial aliasing in a steerable parametric loudspeaker. The two cases of grating lobe elimination and dual-beam generation are reviewed as they have been previously validated through experiments [11]. Emphasis is placed on the discussion of the potential case of stereophonic beamsteering. The feasibility of generating stereophonic sound from a single unit of the steerable parametric loudspeaker has been demonstrated. Examples of implementing the ILD information extracted from the KEMAR HRTFs have been presented. Our proposed stereophonic beamsteering method presently have two drawbacks: (1) it can only reproduce a narrow range of ILD for low frequency components; (2) it does not account for the ITD information. In our future works, the reproduction of ITD from a single steerable parametric loudspeaker will be developed and subjective tests will be conducted to validate the effectiveness of the proposed stereophonic parametric loudspeaker when the spatial information of the low frequency components are ignored.

Acknowledgments

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