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1pSPc5. Steerable parametric loudspeaker with preprocessing methods

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The emerging applications of the parametric loudspeaker, such as 3D audio, require both directivity control and high fidelity at the audible frequency (i.e. the difference frequency of the primary frequencies generated by the parametric loudspeaker). Although the phased array techniques have been applied and proved adequate to adjust the steering angles of the parametric loudspeaker, and preprocessing methods have been studied to reduce the harmonic distortions, there is no published work on the effectiveness of the combination of the beamsteering method and the preprocessing methods for the broadband steerable sound beam system. This paper aims to investigate on this unexplored problem. Firstly, the relation between the phases of the primary waves and the difference frequency wave is explored to prove the feasibility of achieving a broadband steerable sound beam from the parametric loudspeaker with preprocessing methods. Secondly, based on the derived relation, the beamsteering structure is proposed. Lastly, preprocessing methods are proposed for the steerable parametric loudspeaker using double sideband modulation (DSBAM) and square root amplitude modulation (SRAM) methods. Spatial performances of the steerable parametric loudspeaker with preprocessing methods are presented in this paper.

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INTRODUCTION

The fundamental theory of the parametric loudspeaker is based on the parametric array effect [1, 2]. When two primary waves are transmitted from the ultrasonic emitter of a parametric loudspeaker into air, the acoustic energy of the primary waves are transferred into new frequency components by the nonlinearity of air. The difference frequency wave, the sum frequency wave, and other high order harmonics are generated. Due to the absorption effect in air, the ultrasonic components decay rapidly with the propagation distance, but the difference frequency wave, being lower in frequency, is less attenuated. Thus, the difference frequency wave inherits the sharp directivities of the primary ultrasonic waves, and the parametric loudspeaker is known to be one of the most effective method to create a directional sound beam.

Recently, there is an increasing interest in generating controllable directional sound beams from the parametric loudspeaker to support interactive applications, such as multilingual teleconferencing and immersive 3D sound system [3]. However, these applications require the parametric loudspeaker to achieve high fidelity, in the other words, low distortion. Although several preprocessing methods have been proposed to reduce harmonic distortions of the parametric loudspeaker, there is no published work that reports the combination of the preprocessing methods and the beamsteering method. The state of the art in the validated research of the steerable parametric loudspeaker assumes that the primary waves consist of only two sine tones [4, 5], but the preprocessing methods commonly result in more than two frequency components in the primary waves, except the single sideband modulation. Meanwhile, there are two reported conceptual methods of achieving a steerable sound beam in the parametric loudspeaker with preprocessing methods: (1) a system that delays the modulated signal (after preprocessing) of each channel; and (2) a system that delays the modulating signal (before preprocessing) of each channel before mixing with the carrier signal. No experiments and theoretical derivations have yet been carried out to validate the two methods.

Therefore, in this paper, the relation between the phases of the primary waves and the difference frequency wave is explored. Based on the derived relation, a beamsteering structure for the parametric loudspeaker with preprocessing methods is proposed. Lastly, a simulation method is shown to predict spatial performance of the steerable parametric loudspeaker with preprocessing methods.

THEORY

It is assumed that the delay amounts τ_1 and τ_2 are applied to the two primary waves at angular frequencies ω_1 and ω_2 , respectively. Furthermore, it is assumed that $\omega_2 > \omega_1$ without loss of generality. The rest of the assumptions are kept to be the same as what Westervelt assumed in his derivation [2]. Thus, the primary sound field on the axis is described as

$$p_i(r, 0) = p_0 e^{-\alpha_0 r} \left[\cos \omega_1 (t - \tau_1 - r/c_0) + \cos \omega_2 (t - \tau_2 - r/c_0) \right], \quad (1)$$

where p_0 and c_0 is the initial sound pressure level and the speed of sound, respectively. When the primary source is assumed to be circular, the sound pressure p_d of the difference frequency wave ($\omega_d = \omega_2 - \omega_1$) on the axis at a distance of r can be calculated analytically and given by

$$p_d(r, 0) \propto \frac{\partial^2}{\partial t^2} \cos \left[\omega_d (t - \tau_2 - r/c_0) - \omega_1 (\tau_2 - \tau_1) \right]. \quad (2)$$

From (2), it is found that when the delay amounts of the two primary waves are equal (*i.e.* $\tau_1 = \tau_2$), the difference frequency wave generated from the parametric loudspeaker obtains the same delay amount as the primary waves. If the delay amounts of the two primary waves are different and the two primary waves are very closely spaced in frequency, the initial phase of the difference frequency wave is approximated as the average of the primary waves' phases. This statement can be verified by a series of studies carried out by Kamakura *et al.* [6, 7]. In their simulations and experiments, two sets of parametric loudspeakers were used, and the two primary waves were chosen at 38 kHz and 40 kHz. When using the in-phase excitation, the initial phases of all the primary waves were 0° . When using the out-of-phase excitation, the initial phase of the 40 kHz wave in one parametric loudspeaker was changed to 180° , but the initial phases of the rest of the primary waves were kept at 0° . The results

showed that the amplitude of the 40 kHz wave was reduced significantly by the out-of-phase excitation. However, the amplitude of the difference frequency wave was less sensitive to the phase changing of the primary waves. Based on (2), the in-phase excitation of the primary waves generates the difference frequency wave with an initial phase of 0° , but the out-of-phase excitation of the primary waves generates the difference frequency wave with an initial phase of 92.3° . Thus, the reduction in the amplitude of the difference frequency wave by the out-of-phase excitation is estimated to be 3.2 dB, which agrees with the results obtained in [6, 7].

The analysis of the delay response can be further extended to the parametric loudspeaker that uses preprocessing methods based on amplitude modulation principle. The amounts of delays applied to the modulating wave and the carrier wave are denoted by τ_d and τ_c , respectively. The results are shown in Table 1. It shows that the delay amount of the difference frequency wave is only related to the envelope function but not to the carrier wave. Thus, the beamsteering structure of the parametric loudspeaker with preprocessing methods is proposed in Figure 1. The audible wave at ω_d is fed into the delay-and-sum beamsteering structure. Then, the preprocessing method is applied to each channel and the modulated carrier waves are transmitted from the ultrasonic transducer array. The wavefront of the difference frequency wave, generated from the proposed structure, retains the steering angle of the primary waves.

TABLE 1. Delay responses of the difference frequency wave generated from the parametric loudspeaker using different preprocessing methods based on the amplitude modulation (DSBAM: double sideband amplitude modulation; SRAM: square root of DSBAM).

Method	Modulated waves	Primary waves	Diff. Freq. wave
DSBAM	$[1 + \cos(\omega_d t - \omega_d \tau_d)]$ $\times \cos(\omega_c t - \omega_c \tau_c)$	$\cos(\omega_c t - \omega_c \tau_c)$ $+\frac{1}{2} \left[\cos(\omega_c t + \omega_d t - \omega_c \tau_c - \omega_d \tau_d) \right.$ $\left. + \cos(\omega_c t - \omega_d t - \omega_c \tau_c + \omega_d \tau_d) \right]$	$\cos(\omega_d t - \omega_d \tau_d)$
SRAM	$\sqrt{1 + \cos(\omega_d t - \omega_d \tau_d)}$ $\times \cos(\omega_c t - \omega_c \tau_c)$	$\frac{\sqrt{2}}{2} \left[\cos\left(\omega_c t + \frac{\omega_d}{2} t - \omega_c \tau_c - \frac{\omega_d}{2} \tau_d\right) \right.$ $\left. + \cos\left(\omega_c t - \frac{\omega_d}{2} t - \omega_c \tau_c + \frac{\omega_d}{2} \tau_d\right) \right]$	$\frac{\sqrt{2}}{2} \cos(\omega_d t - \omega_d \tau_d)$

FIGURE 1. Beamsteering structure of the parametric loudspeaker using preprocessing methods based on the amplitude modulation.

METHOD

Table 1 has shown that preprocessing methods, including DSBAM and SRAM, are applicable in the beamsteering structure proposed in Figure 1. In this section, the DF beampatterns are computed in simulation when preprocessing methods are applied in the parametric loudspeaker.

The envelope functions of the DSBAM is given by

$$f_{DSBAM}(t) = 1 + \cos \omega_d t. \quad (3)$$

Hence, the modulated wave is given by the product of the carrier wave and the envelope function, i.e.

$$\begin{aligned} f_{DSBAM}(t) \cos \omega_c t &= \frac{1}{2} \cos(\omega_c - \omega_d)t + \cos \omega_c t + \frac{1}{2} \cos(\omega_c + \omega_d)t \\ &= \frac{1}{2} [\cos(\omega_c - \omega_d)t + \cos \omega_c t] + \frac{1}{2} [\cos \omega_c t + \cos(\omega_c + \omega_d)t]. \end{aligned} \quad (4)$$

Equation (4) shows that the modulated wave of the DSBAM consists of three primary frequencies, and they can be divided into two pairs of $(\omega_c - \omega_0$ & $\omega_c)$ and $(\omega_c$ & $\omega_c + \omega_0)$. Thus, the directivity of the parametric loudspeaker using the DSBAM can be simulated by adding the two difference frequency beampatterns, which are resultant from these two pairs of primary frequencies. The method to predict the beampattern of the difference frequency wave based on the directivities of the two primary waves has been presented in [4, 5].

Similarly, the envelope functions of the SRAM is given by

$$f_{SRAM}(t) = \sqrt{1 + \cos \omega_d t}. \quad (5)$$

Using the double-angle and tri-angle formulae, the Taylor expansion of (5) up to the forth order is manipulated as

$$f_{SRAM}(t) \approx \frac{945}{1024} + \frac{35}{64} \cos \omega_d t - \frac{21}{256} \cos 2\omega_d t + \frac{1}{64} \cos 3\omega_d t - \frac{5}{1024} \cos 4\omega_d t. \quad (6)$$

Thus, the modulated wave of the SRAM can be manipulated as

$$\begin{aligned} f_{SRAM}(t) \cos \omega_c t &= \frac{35}{128} [\cos(\omega_c - \omega_d)t + \cos \omega_c t] + \frac{35}{128} [\cos \omega_c t + \cos(\omega_c + \omega_d)t] \\ &\quad - \frac{21}{512} [\cos(\omega_c - 2\omega_d)t + \cos \omega_c t] - \frac{21}{512} [\cos \omega_c t + \cos(\omega_c + 2\omega_d)t] \\ &\quad + \frac{1}{128} [\cos(\omega_c - 3\omega_d)t + \cos \omega_c t] + \frac{1}{128} [\cos \omega_c t + \cos(\omega_c + 3\omega_d)t] \\ &\quad - \frac{5}{2048} [\cos(\omega_c - 4\omega_d)t + \cos \omega_c t] - \frac{5}{2048} [\cos \omega_c t + \cos(\omega_c + 4\omega_d)t] \\ &\quad + \frac{458}{1024} \cos \omega_c t. \end{aligned} \quad (7)$$

Equation (7) shows that the modulated wave of the SRAM consists of nine primary frequencies, and they can be divided into 8 pairs of $(\omega_c$ & $\omega_c \pm h\omega_0)$ for $h = 1, 2, 3, 4$. Thus, the directivity of the parametric loudspeaker using the SRAM can be simulated by adding eight difference frequency beampatterns together, which are resultant from these eight pairs of primary frequencies

SIMULATION

The comparison between the preprocessing methods of DSBAM and SRAM is carried out in the steerable parametric loudspeaker. The spacing of the ultrasonic transducer array is set to 1 cm and the carrier wave is generated at 40 kHz. The modulating waves vary from 1 kHz to 20 kHz with frequency interval of 1 kHz. The steering angle is firstly fixed at 0° and then changed to 30° . The directivities of the steerable parametric loudspeakers using the DSBAM and the SRAM are plotted in Figures 2 and Figure 3, respectively.

FIGURE 2. Beam patterns of a parametric loudspeaker using DSBAM method when the mainlobes are steered to (a) 0° and (b) 30° , respectively.

FIGURE 3. Beam patterns of a parametric loudspeaker using SRAM method when the mainlobes are steered to (a) 0° and (b) 30° , respectively.

In Figure 2, when the steering angle increases to 30° and the difference frequency is low (< 4 kHz), grating lobes are observed at -20° . However, in Figure 3, when SRAM is applied, spatial aliasing does not occur, due to the averaging effect of these eight pairs of the primary frequencies. However, the beamwidth is wider for the steerable parametric loudspeaker using SRAM than the one using DSBAM. Generally, both preprocessing methods achieve constant beamwidth across the difference frequency range. These simulation results will be verified through experiments in the future.

CONCLUSION

An attempt to analyze and simulate the directivity of the steerable parametric loudspeaker with preprocessing methods was reported in this paper. The phase response of the difference frequency wave corresponding to the phases of the primary waves were derived. It was found that the delay amount of the difference frequency wave is only related to the envelope function but not to the carrier wave. Thus, the beamsteering structure of the parametric loudspeaker with preprocessing methods were proposed. Hence, the modulated waves of the DSBAM and the SRAM were divided into several pairs of the primary frequencies. Thus, the directivity of the parametric loudspeaker using the DSBAM and the SRAM were simulated by adding the difference frequency beam patterns resulted from every pair of the

primary frequencies. The simulation results showed that the parametric loudspeaker using the SRAM achieved the better spatial performance, which is with no occurrence of spatial aliasing, than the one using DSBAM. Both preprocessing methods lead to almost constant beamwidth of the steerable parametric loudspeaker.

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