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Modeling The Directivity Of Parametric Loudspeaker

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Abstract. The emerging applications of the parametric loudspeaker, such as 3D audio, demands accurate directivity control at the audible frequency (i.e. the difference frequency). Though the delay-and-sum beamforming has been proven adequate to adjust the steering angles of the parametric loudspeaker, accurate prediction of the mainlobe and sidelobes remains a challenging problem. It is mainly because of the approximations that are used to derive the directivity of the difference frequency from the directivity of the primary frequency, and the mismatches between the theoretical directivity and the measured directivity caused by system errors incurred at different stages of the implementation. In this paper, we propose a directivity model of the parametric loudspeaker. The directivity model consists of two tuning vectors corresponding to the spacing error and the weight error for the primary frequency. The directivity model adopts a modified form of the product directivity principle for the difference frequency to further improve the modeling accuracy.

Keywords: Parametric loudspeaker, product directivity, array calibration.

PACS: 43.25.Lj, 43.60.Fg

INTRODUCTION

Parametric loudspeaker was introduced by Yoneyama et al. [1] in 1983. Taking advantage of the nonlinear effect in air, an amplitude modulated primary signal, which is in the ultrasonic range, is able to be self-demodulated to an audible signal. Hence, a directional sound beam is created and inherit the directivity of the ultrasonic primary signal. With different configurations of the ultrasonic transducer array, which is used as the primary source emitter, beamforming (including beamsteering) of the audible signal is achieved by adopting phased array techniques [2]. However, mismatch is commonly observed between the theoretical and measured directivities. This is due to the system errors incurred at different stages of implementation. In a paper [3], we have verified the effectiveness of the calibration method for the steerable parametric loudspeaker with three tuning vectors that correspond to the spacing error, the weight error and the phase error. The weight error and the spacing error are constant to all the primary frequencies, but the phase error is frequency-dependent.

In this paper, we propose the beamforming structure of the parametric loudspeaker with system errors, as shown in Fig. 1. The system errors are categorized into physical

FIGURE 1. Beamforming structure of the parametric loudspeaker.

error (spacing error) and electronic error (characteristic filter). The physical error is incurred during building up the ultrasonic transducer array. The electronic error is caused by the variance in transducers' characteristics. Ideally, a group of characteristic filters are proposed to model the individual channels of the ultrasonic transducer array, which account for both the weight distortion and the phase distortion varying with the primary frequency. Furthermore, the ultrasonic transducer array in the parametric loudspeaker is transformed into an equivalent Gaussian source array. Thus, the directivity of the difference frequency is predicated based on the advanced product directivity (APD) model [4]. The APD model accounts for the effective radii of the Gaussian sources to give a better prediction of the directivity of the difference frequency than the original product directivity principle.

METHOD

Based on the proposed beamforming structure (shown in Fig. 1) and ignoring the phase distortion, we substitute the spacing error and the characteristic filter by a group of spacing distortion factors δ_D and weight distortion factors δ_W , respectively. Thus, the directivity of the primary frequency is simplified to ease the difficulty of analysis by

$$\tilde{H}(k, \theta) = \sum_{m=0}^{M-1} w_m \hat{w}_m \exp(jd_m k \sin \theta) = \sum_{m=0}^{M-1} \delta_W^m w_m \exp(j\delta_D^m mdk \sin \theta). \quad (1)$$

The distortion factors δ_D and δ_W are determined by measurements carried out in an anechoic chamber. The ultrasonic transducer array consists of 32 piezoelectric transducers arranged in 8 channels with inter-channel spacing of 1 cm. The primary-frequencies were captured in the measurement using the B&K 4138 microphone at 36 kHz, 38 kHz, 39.5 kHz, 39.75 kHz, 40.25 kHz, 40.5 kHz, 41 kHz, and 44 kHz. And correspondingly, the difference frequencies were captured at 0.5 kHz, 1 kHz, 4 kHz, and 8 kHz, using the B&K 4134 microphone. The distortion factors δ_D and δ_W are solved by minimizing the mismatch between the measured directivities H_M and the proposed directivity model at the primary frequency, which is given by

$$[\delta_D^m, \delta_W^m] = \arg \min_{\theta} \sum_{\theta} |H_M(k, \theta) - \tilde{H}(k, \theta)|^2. \quad (2)$$

TABLE 1. The distortion factors of the parametric loudspeaker in our experimental setup

Channel No.	1	2	3	4	5	6	7	8
δ_W	0.9428	1.1399	0.9234	0.8559	0.9637	1.1481	0.918	0.9276
δ_D	1.0396	1.0460	1.1341	1.1018	1.1256	0.9410	0.9819	0.9808

FIGURE 2. Beamforming structure of the parametric loudspeaker.

The results of the distortion factors δ_D and δ_W are shown in Table 1. Furthermore, the cross-validation measurement is also carried out for the primary frequencies at 39 kHz and 41 kHz, as well as the difference frequency at 2 kHz. We treat the measured directivity as an original signal, and the directivities computed based on the ideal array response and the proposed model as noisy approximations of the original signal. Therefore, the peak signal to noise ratio (PSNR) can be used to evaluate the mismatch level. Higher PSNR value represents a closer approximation between the theoretical directivity and the measured directivity. In Fig. 2(a), a significant improvement is observed when the proposed directivity model is used to predict the directivity at the primary frequency. In Fig. 2(b), the APD model provides better prediction of the directivity than the original product directivity principle for the difference frequency. Moreover, the cross-validation proves that by using two tuning vectors accounting for the spacing error and the weight error, the proposed directivity model is able to better predict the spatial performance of the parametric loudspeaker in our experiment.

DISCUSSION

It was reported in [2] that when the lower sideband modulation (LSB) is adopted in the parametric loudspeaker, the beamwidth of the demodulated audible signal is given by the beamwidth of the carrier ultrasonic signal; when the upper sideband modulation (USB) is used, the beamwidth of the audible signal is given by the beamwidth of the upper sideband signal, which is narrower with higher frequency. In this section, the LSB scenario is examined through simulation based on the proposed directivity model and the aforementioned experimental configuration of the ultrasonic transducer array.

The results are shown in Fig. 3. Sidelobes are seldom observed across the range of audible frequency. It is also noted that the expected constant null-to-null beamwidth is not shown in Fig. 3(b). In contrast, the half-power beamwidth decreases when the difference frequency increases. This observation agrees with the classic study in [5].

FIGURE 3. Directivity of the parametric loudspeaker adopting LSB modulation.

CONCLUSION

An applied directivity model of the parametric loudspeaker is proposed. This directivity model takes the spacing error and the weight error into account and introduces two tuning vectors corresponding to these two types of system errors. Subsequently, the directivity of the difference frequency is computed based on the advanced product directivity model, which provides better prediction of the spatial performance of the ultrasonic transducer array than the original product directivity principle. Measurements have been carried out to determine the tuning vectors for the experimental setup and the effectiveness of the proposed model has been verified. By applying the proposed directivity model, we investigate the parametric loudspeaker using LSB modulation. The simulation results agrees with Westervelt's observation that the half-power beamwidth is narrower at higher audible frequency and sidelobes are rarely observed in the parametric loudspeaker.

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