WEIGHTED DOUBLE SIDEBAND MODULATION TOWARD HIGH QUALITY AUDIBLE SOUND ON PARAMETRIC LOUDSPEAKER

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ABSTRACT

Recently, parametric loudspeakers have been utilized to reproduce an audible sound in a particular area by an ultrasound. However, parametric loudspeakers have lower sound quality than general electrodynamic loudspeakers because it is difficult to reproduce an audible sound at lower frequency. Moreover, the reproduced sound includes harmonic distortions causing deterioration of sound quality. Thus, in this paper, we attempt to improve sound quality of parametric loudspeakers. It depends on a modulation technique for designing the amplitude modulated wave. Therefore, we propose a new modulation method to reproduce audible sound with high quality. The proposed method controls a weight of double sidebands for reducing harmonic distortions at higher frequency and emphasizing power at lower frequency. We carried out evaluation experiments to confirm the effectiveness of the proposed method. The results confirmed that the proposed method could improve sound quality of parametric loudspeakers.

Index Terms— Parametric loudspeaker, Modulation method, Amplitude modulation, Weighted sideband

1. INTRODUCTION

An electrodynamic loudspeaker is often utilized for reproducing sound to listeners. It is suitable for reproducing sound to many listeners because of wide directivity. On the other hand, it is unsuitable for reproducing sound in particular areas. Therefore, a parametric loudspeaker has recently been focused on for reproducing sound in only particular area at stations, museums and so on [1]. It can achieve the higher directivity by utilizing an ultrasound. The parametric loudspeaker emits an intense amplitude modulated (AM) wave. The AM wave is designed by modulating the amplitude of the ultrasound with an audible sound [2]. The emitted intense AM wave with the parametric loudspeaker is demodulated into the audible sound by the nonlinear interaction in the air [3]. The parametric loudspeaker, however, has lower sound quality than that of the general electrodynamic loudspeakers. For example, it has difficulty reproducing the audible sound at lower frequency. In addition, harmonic distortions are caused by demodulating the AM wave. In this paper, we therefore attempt to improve the sound quality of the parametric loudspeaker. This depends on a modulation technique for designing the AM wave. Thus, we propose a new modulation method that can improve the sound quality by collaborating the conventional modulation techniques. The proposed method specifically controls a weight of sideband amplitude at each frequency.

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2. CONVENTIONAL RESEARCH FOR PARAMETRIC LOUDSPEAKER

2.1. Principal of parametric loudspeaker

A parametric loudspeaker obtains a higher directivity by utilizing an ultrasound as a carrier wave. It emits an intense AM wave designed by amplitude modulating the carrier wave with an audible sound. The AM wave $V_{\mathrm{A}}(t)$ is derived from Eq. (1).

$$V_{\mathrm{A}}(t) = (1 + mV_{\mathrm{S}}(t))V_{\mathrm{C}}(t), \quad (1)$$

$$m = \frac{V_{\mathrm{sm}}}{V_{\mathrm{cm}}}, \quad (2)$$

$$V_{\mathrm{C}}(t) = V_{\mathrm{cm}} \cos(2\pi Ft), \quad (3)$$

$$V_{\mathrm{S}}(t) = V_{\mathrm{sm}} \cos(2\pi ft), \quad (4)$$

where t represents a time index, $V_{\mathrm{C}}(t)$ and $V_{\mathrm{S}}(t)$ represent the audible sound and the carrier wave, f and F represent their frequencies, V_{cm} and V_{sm} represent their maximum amplitudes, and m represents an amplitude modulation factor. The emitted intense AM wave is self-demodulated into the audible sound by the nonlinear interaction in the air [3]. The AM wave consists of F, $F+f$ (LSB : lower sideband), and $F-f$ (USB : upper sideband) in the frequency-domain. The demodulated audible sound is a different tone between F, $F+f$ and $F-f$ as shown in Fig. 1.

2.2. Conventional modulation technique

Conventionally, double sideband (DSB) and single sideband (SSB) modulations have been proposed as the AM wave design technique [4, 5]. The AM wave in the DSB modulation has a carrier frequency and double sidebands (LSB and

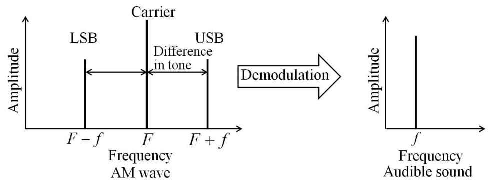

Fig. 1. Overview of the demodulation of the emitted AM wave in the frequency-domain.

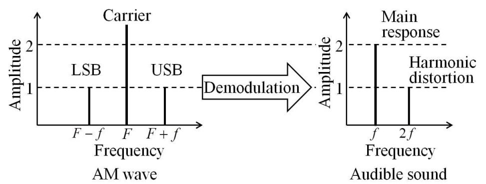

Fig. 2. Overview of the DSB modulation.

USB). The parametric loudspeaker can therefore reproduce a louder audible sound by the DSB modulation. Harmonic distortions however arise due to difference tone between LSB and USB. On the other hand, the SSB modulation designs the AM wave that has a carrier frequency and single sideband (LSB or USB). The SSB modulation obtains the single sideband by high-pass or low-pass filters. The parametric loudspeaker can reproduce the audible sound without harmonic distortions by the SSB modulation. The audible sound caused by the SSB modulation is, however, fainter than that caused by the DSB modulation. Figures 2 and 3 show the AM wave and the demodulated audible sound on each conventional modulation in the frequency-domain.

3. PROPOSED METHOD

A louder audible sound can be reproduced with the parametric loudspeaker by the DSB modulation. Meanwhile, the SSB modulation can reduce harmonic distortions. We therefore propose a new modulation method to emphasize lower frequency and reduce harmonic distortions by collaborating the double and single sidebands. Specifically, the proposed method utilizes the double sidebands on reproduction at lower frequency for emphasizing audible sound energy. Also, it utilizes the single sideband on reproduction at higher frequency for reducing harmonic distortions. Moreover, the proposed modulation method utilizes the single sideband that has higher conversion efficiency from electricity to acoustic in reproduction at higher frequency. However, the sound quality may be lower even if the sideband is limited as mentioned above, because the weight of sideband amplitude is the same at each frequency. Thus, the proposed modulation method also controls the weight of sideband amplitude at each frequency to improve sound quality greatly. Figure 4 shows the overview of the proposed method.

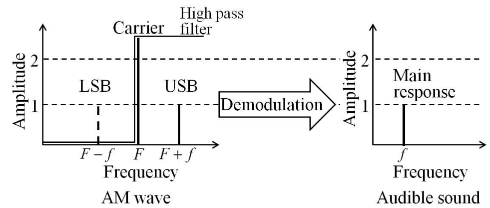

Fig. 3. Overview of the SSB modulation.

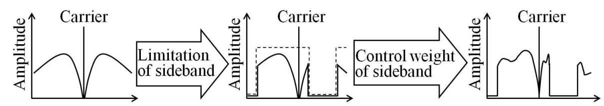

Fig. 4. Overview of the proposed method.

3.1. Limitation of sideband

For utilizing LSB and USB that have the higher conversion efficiency from electricity to acoustic, we carried out a pre-experiment to compare power spectra of the parametric loudspeaker on LSB and USB. The results showed the sound pressure levels (SPL) in 0.5$\sim$2 kHz are small on LSB and USB. Therefore, the proposed method should utilize DSB to emphasize the energy in 0.5$\sim$2 kHz. The parametric loudspeaker by LSB also reproduces the higher SPL audible sound than that by USB in 2$\sim$6 kHz. Thus, the proposed method utilizes LSB in 2$\sim$6 kHz for harmonic distortion reduction and high conversion efficiency. In contrast, it utilizes USB above 6 kHz. However, it may have lower sound quality due to only having bandlimited sideband. For this reason, the proposed method must keep the power spectrum flat.

3.2. Weight control of sideband amplitude

The proposed method should control the power spectrum of the parametric loudspeaker. It therefore utilizes the weighted sideband on amplitude based on the reproduced sound. In the proposed method, the sideband that has smaller amplitude needs the greater weight to control the power spectrum. The weight coefficients below the carrier frequency $W_L(F-f)$ and above the carrier frequency $W_U(F+f)$ are derived from Eqs. (5) and (6).

$$W_L(F-f) = \begin{cases} \frac{X_{Lmin}}{X_L(f)} & \text{if } X_L(f) > X_U(f), \\ 0 & \text{otherwise}, \end{cases} \tag{5}$$

$$W_U(F+f) = \begin{cases} \frac{X_{Umin}}{X_U(f)} & \text{if } X_L(f) < X_U(f), \\ 0 & \text{otherwise}, \end{cases} \tag{6}$$

where $X_L(f)$ and $X_U(f)$ represent the amplitude of the demodulated audible sound on LSB and USB, X_{Lmin} and X_{Umin} represent a minimum amplitude of $X_L(f)$ and $X_U(f)$. The frequencies $F-f$ and $F+f$ mean that f equals the difference in tone between F and $F \pm f$.

Table 1. Objective experimental conditions.

Parametric loudspeaker	MITSUBISHI, MSP-50E
Sampling frequency	192 kHz
Quantization	16 bits
Sound source	White noise (2 sec.) Sine wave (2 and 5 kHz)
Environment	Soundproof room
Ambient noise level	L_A=32.2 dB
Distance between microphone and loudspeaker	1.5 m

4. EVALUATION EXPERIMENTS

We carried out objective and subjective evaluation experiments to confirm the effectiveness of the proposed method. In evaluation experiments, the proposed method is compared with each conventional modulation on sound quality.

4.1. Objective evaluation experiments

First, the proposed method is evaluated in terms of emphasizing the energy at lower frequency and controlling the power spectrum of the reproduced sound. Table 1 shows the objective experimental conditions. In this paper, we defined 0.5∼2 kHz as lower frequency, 0.5∼10 kHz as reproduction frequency based on the reproducible band of the parametric loudspeaker. We employ SPL averages to evaluate the emphasizing of the energy in 0.5∼2 kHz. Achieving higher SPL averages in 0.5∼2 kHz with the proposed method demonstrates that the proposed method can emphasize the energy in 0.5∼2 kHz. We also employ average errors of SPL to evaluate controlling the power spectrum in 0.5∼10 kHz. Achieving lower average errors in 0.5∼10 kHz with the proposed method demonstrates that the proposed method can control the power spectrum in 0.5∼10 kHz. Second, we evaluated how well the proposed method reduced performance for harmonic distortions. Sine waves (2 and 5 kHz) were employed as evaluation sound source to measure SPL of second and third harmonic distortions.

4.2. Results of the objective evaluation experiments

Figure 5 shows power spectra of the reproduced white noise with the parametric loudspeaker by each modulation. Table 2 shows the SPL averages and average errors of the reproduced sound by each modulation. From Fig. 5, we confirmed that power spectrum is kept flat by the proposed method in 0.5∼10 kHz. Moreover, we confirmed the effectiveness of the proposed method in terms of emphasizing power in 0.5∼2 kHz and controlling the power spectrum from Table 2. Figure 6 shows the reduction performance for second and third harmonic distortions of each modulation. In Fig. 6, SPL of

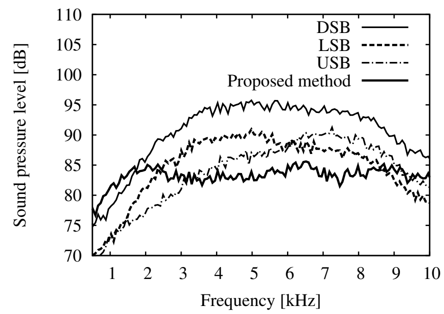

Fig. 5. Power spectra of the demodulated audible sound by each modulation.

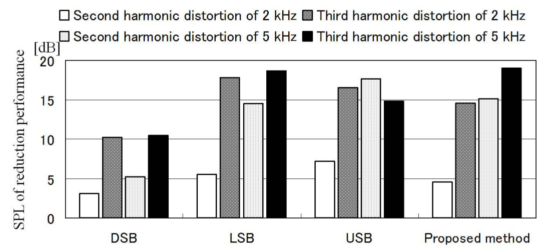

Fig. 6. Reduction performance of each modulation.

reduction performance represents the difference between SPL of the target sound and SPL of the harmonic distortion. The results show that the proposed method, which utilizes double sidebands, has better reduction performance than DSB modulation.

4.3. Subjective evaluation experiment

In the subjective evaluation experiment, we evaluate the proposed method in terms of the sound quality in 0.5∼2 kHz and 0.5∼10 kHz and the loudness in 0.5∼2 kHz. The sound quality attained by utilizing the proposed method is compared with that attained by the conventional modulations. Table 3 shows conditions of the subjective evaluation experiment. In this experiment, voice and music were employed as an evaluation sound source. Subjects evaluated loudness and sound quality by giving them one of five grades. For loudness, grade five represents ”loudest” and grade one represents ”quietest”. For sound quality, grade five represents ”excellent” and grade one represents ”bad”.

4.4. Results of the subjective evaluation experiment

Figures 7 and 8 show the results of the subjective evaluation experiment. According to these results, the proposed method can achieve high-quality audible sound for the parametric loudspeaker. Specifically, we confirmed the high potency of the proposed method on the sound quality and the loudness in 0.5∼2 kHz.

Table 2. SPL averages and average errors in 0.5～2 kHz and 0.5～10 kHz by each modulation

	Carrier (40 kHz)	0.5～2 kHz		0.5～10 kHz	
	SPL [dB]	SPL average [dB]	Average error [dB]	SPL average [dB]	Average error [dB]
DSB	106.3	79.9	2.5	88.7	5.4
LSB	105.7	77.3	2.1	84.6	4.7
USB	104.5	77.0	1.7	82.9	4.2
Proposed method	**105.2**	**84.6**	**0.8**	**84.2**	**2.0**

Table 3. Subjective experimental conditions

Environment	Soundproof room
Evaluation item	Loudness in 0.5～2 kHz Sound quality in 0.5～2 kHz Sound quality in 0.5～10 kHz
Sound source	Voice Music
Subjects	10 persons

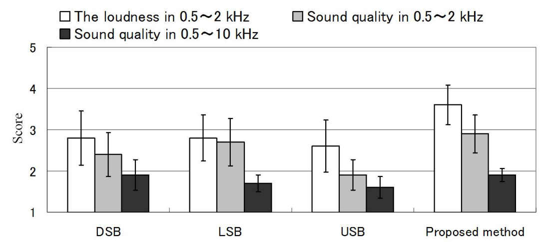

Fig. 7. Results of the subjective evaluation experiment on voice.

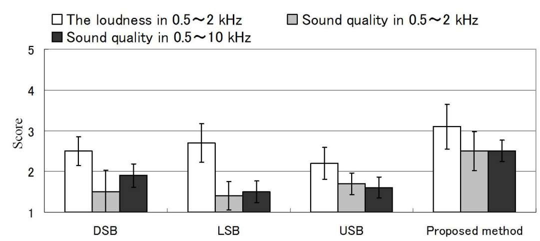

Fig. 8. Results of the subjective evaluation experiment on music.

4.5. Discussion

The results of the objective experiments confirmed that the proposed method can control the power spectrum of the parametric loudspeaker. Specifically, the results demonstrate that the proposed method can extremely accurately control the power spectrum in 0.5∼10 kHz. Furthermore, the proposed method reduces harmonic distortions more than DSB modulation does. The parametric loudspeaker, however, reproduces the faint audible sound in 0.5∼10 kHz produced by the proposed method due to single sideband in 0.5∼10 kHz. In the subjective experiment, we confirmed the high quality of the audible sound produced by the proposed method. However, the sound quality is insufficiently improved in 0.5∼10 kHz by the proposed method due to the faint audible sound in 0.5∼10 kHz. In the future, we will advance to develop the proposed method further to improve the sound quality greatly in 0.5∼10 kHz.

5. CONCLUSIONS

In this study, we tried to improve the sound quality of the parametric loudspeaker. To do this, we therefore proposed a new modulation method that controls the weight of the sideband. The proposed method utilized the double sidebands to emphasize power at lower frequency. It also utilized the single sideband to reduce harmonic distortions of the reproduced sound at higher frequency. Moreover, the proposed method could control the power spectrum of the parametric loudspeaker. The results of objective and subjective evaluation experiments confirmed the effectiveness of the proposed method.

6. RELATION TO PRIOR WORK

The parametric loudspeaker should be focused on as the ideal candidate to reproduce an audible sound in a particular area [1]. It has, however, lower sound quality than other loudspeakers due to a principal of the parametric loudspeaker [2, 3]. In the parametric loudspeaker, DSB modulation has been conventionally proposed for designing the AM wave [4]. Furthermore, SSB modulation also has been proposed to improve sound quality [5]. Sound quality is, however, insufficiently improved by DSB and SSB modulations. Thus, in this paper, we proposed the new modulation method that utilized suitable sideband at each frequency. In addition, the proposed method is unique in utilizing weighted sideband.

7. REFERENCES

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