1pSPc27.  A design of audio spot based on separating emission of the carrier and sideband waves

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Parametric loudspeaker, which utilizes an ultrasonic of non-linear interaction, is developed to achieve audio spot. The parametric loudspeaker has sharper directivity, but reflections and intercepts by emitted sounds become severe problems. This is because reflections and intercepts lead to an invasion of privacy, and become noise to other listeners except a target listener. Principle of the parametric loudspeaker can formulate as non-linear interaction of carrier and sideband waves in emitted ultrasonic sounds on air. This suggests that we can design audio spot by individually emitting the carrier and sideband waves. In the present paper, therefore, we propose the design method of audio spot with the separating emission of the carrier and sideband waves. More specifically, the audible sound is demodulated at an area where the carrier and sideband waves individually emitted from each parametric loudspeaker are overlapped. We carried out evaluation experiments to measure sound pressure level (SPL) of demodulated audible sound. In addition, we evaluated the speech articulation of the demodulated audible sound with the proposed method. As a result of evaluation experiments, we confirmed the effectiveness of the proposed method.

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INTRODUCTION

A parametric loudspeaker with sharper directivity can reproduce an audible sound in the particular area called “audio spot” [1–4]. The parametric loudspeaker emits an amplitude modulated (AM) wave which is generated by modulating amplitude of the ultrasound with the audible sound. The emitted AM wave is demodulated into the original audible sound by non-linear interaction in the air [4, 5]. The AM wave consists of the carrier and sideband waves. The demodulated audible sound is represented by the difference tone between the carrier and sideband waves. In the parametric loudspeaker, reflections and interceptions of emitted sounds become severe problems. These are because reflections and interceptions lead to an invasion of privacy. Moreover, reflections and intercepts become noise to non-listeners. Thus in this paper, we propose the design method of the audio spot for reducing reflections and interceptions. Specifically, we attempt to design audio spot with separating emission the carrier and sideband waves by using multiple parametric loudspeakers. Then, the audio spot is formed in the area including carrier and sideband waves. However, the harmonic distortions occur from the difference tone of the different frequency components included in the sideband wave. It is the problem that the harmonic distortions become the noise. Thus, we also try to reduce the harmonic distortions using the sideband wave with the band-division.

THE PRINCIPLE OF THE CONVENTIONAL PARAMETRIC LOUDSPEAKER

The parametric loudspeaker emits the AM wave designed by amplitude modulating the carrier wave with an original audible sound. AM wave consists of the carrier and sideband waves. The audible sound is reproduced as the difference tone between the carrier and sideband waves. The carrier wave \( v_c(t) \) and the original audible sound \( v_s(t) \) are indicated as follows:

\[
v_c(t) = A_c \sin 2\pi f_c t,
\]

\[
v_s(t) = A_s \cos 2\pi f_s t,
\]

where \( t \) is time index, \( A_c \) and \( A_s \) are maximum amplitudes of the carrier wave and audible sound, respectively. \( f_c \) and \( f_s \) are frequencies of the carrier wave and audible sound, respectively. From Eqs. (1) and (2), the AM wave \( v_{db}(t) \) is indicated as follows:

\[
v_{db}(t) = (v_s(t) + A_c) \sin 2\pi f_c t,
\]

\[
= (A_s \cos 2\pi f_s t + A_c) \sin 2\pi f_c t,
\]

\[
= A_c \sin 2\pi f_c t + A_s \frac{1}{2} \sin 2\pi (f_c + f_s) t + A_s \frac{1}{2} \sin 2\pi (f_c - f_s) t,
\]

where, \( A_c \sin 2\pi f_c t \) is a component of the carrier wave, \( \frac{A_s}{2} \sin 2\pi (f_c + f_s) t \) is a component of the upper sideband (USB), \( \frac{A_s}{2} \sin 2\pi (f_c - f_s) t \) is also a component of the lower sideband (LSB). The AM method using LSB and USB is called double sideband (DSB) modulation method, as shown in Eq. (3). The parametric loudspeaker can reproduce the louder audible sound by the DSB modulation method. However, the harmonic distortions occur by the difference tone between the LSB and the USB [6]. The single sideband (SSB) modulation method has been proposed to reduce the harmonic distortions. SSB modulation method designs the AM wave which has the carrier wave and single sideband wave (LSB or USB). SSB modulation method obtains the single sideband by eliminating LSB or USB from \( v_{db}(t) \). In this paper, we remove the USB from \( v_{db}(t) \) using the low pass filter and generate the AM wave which is designed by the SSB modulation method \( v_{ssb}(t) \). \( v_{ssb}(t) \) is indicated as follows:
\[ v_{\text{amb}}(t) = A_e \sin 2\pi f_c t + \frac{A_s}{2} \cos 2\pi (f_e - f_s) t. \] 

(4)

Smaller harmonic distortions occur by the emitted AM wave which is designed by SSB modulation method than that by DSB modulation method. However, the harmonic distortions occur by the difference tone of the different frequency components included in the sideband wave. In this paper, we define the emitting AM wave which is designed by the SSB modulation method as the conventional method. In the conventional method, the original audible sound is demodulated in the area of including emitted AM wave. The parametric loudspeaker emits the AM wave with sharper directivity. Consequently, audio spot is designed a linear shape. However, the initial reflections of the reproduced audible sound have higher sound pressure. Therefore, the initial reflections become a noise to non-listener who hears reflections.

THE PRINCIPLE OF SEPARATING EMISSION OF THE CARRIER AND SIDEBAND WAVES

The demodulated audible sound is represented by the difference tone between the carrier and sideband waves. In this paper, therefore, we propose the design method of the audio spot with separating emission of the carrier and sideband waves. Figure 1 shows the overview of the proposed method. In Fig. 1(a), \( PL_c \) is the parametric loudspeaker for the carrier wave \( p_c(t) \). \( PL_s \) is the parametric loudspeaker for the sideband wave \( p_s(t) \). \( p_c(t) \) and \( p_s(t) \) are indicated as follows:

\[ p_c(t) = A_c \sin 2\pi f_c t, \]

(5)

\[ p_s(t) = \frac{A_s}{2} \sin 2\pi (f_c - f_s) t. \]

(6)

In Fig. 1(a), in the area including both carrier and sideband waves, the observed sound \( p_{\text{wav}}(t) \) is indicated as follows:

\[ p_{\text{wav}}(t) = p_c(t - \tau_c) + p_s(t - \tau_s), \]

(7)

\[ \approx v_{\text{amb}}(t), \]

(8)

where, \( \tau_c \) and \( \tau_s \) are the time delays of the carrier and sideband waves, respectively. In the area including carrier and sideband waves, the frequency components of the observed audible sound \( p_{\text{wav}}(t) \) are similar to the frequency components of the AM wave. Therefore, the audio spot is formed in the area including both carrier and sideband waves. In this paper, the area including both carrier and sideband waves is called “audio spot”. On the other hand, it is impossible that audible sound is demodulated in the area including carrier wave \( p_c(t) \) without sideband wave \( p_s(t) \). However, the harmonic distortions may occur by the difference tone between two frequency components included in the sideband wave in the area including sideband wave \( p_s(t) \) without carrier wave \( p_c(t) \). Then, the harmonic distortions as noise will occur with the proposed method. Thus, we should intend to reduce the harmonic distortions using the sideband wave with the band-division. The harmonic distortions are reduced with the band-division because the frequency components included in the lower or higher frequency divided sideband wave are less than non-divided sideband wave.

In Fig. 1(b), \( PL_c \) is the parametric loudspeaker for the carrier wave \( p_c(t) \), \( PL_{sl} \) is the parametric loudspeaker for the lower frequency divided sideband wave \( p_{sl}(t) \), and \( PL_{sh} \) is also the parametric loudspeaker for the higher frequency divided sideband wave \( p_{sh}(t) \). \( p_{sl}(t) \) and \( p_{sh}(t) \) are indicated as follows:

\[ p_{sl}(t) = \frac{A_{sl}}{2} \sin 2\pi (f_c - f_{sl}) t, \]

(9)

\[ p_{sh}(t) = \frac{A_{sh}}{2} \sin 2\pi (f_c - f_{sh}) t, \]

(10)
The proposed method with non-divided sideband wave

The proposed method with divided sideband wave

FIGURE 1. Overview of the proposed method

\[ p_s(t) = p_{sl}(t) + p_{sh}(t). \] (11)

\( p_{sl}(t) \) and \( p_{sh}(t) \) are generated by the band-division for the audible sound \( v_s(t) \) with the border frequency \( f_b \), respectively. In Fig. 1(b), the observed sound \( p_{as2}(t) \) in the audio spot is indicated as follows:

\[ p_{as2}(t) = p_s(t - \tau_{sl}) + p_s(t - \tau_{sh}) + p_s(t), \] (12)

\[ \approx v_{sh}(t), \] (13)

where, \( \tau_{sl} \) and \( \tau_{sh} \) are the time delays of the lower and higher frequencies which divided sideband wave, respectively. Under the conditions that the time lag between the time delays \( \tau_{sl} \) and \( \tau_{sh} \) is longer, it should be necessary that adjusting the time lag.

EVALUATION EXPERIMENT

Objective Evaluation for Measuring Sound Pressure Level Distribution

We carried out the objective evaluation experiment to confirm the effectiveness of the proposed method. We measured the sound pressure level (SPL) of the audible sound with the proposed method, and with conventional method using a parametric loudspeaker with SSB moderation method. In the audio spot, the SPL of the audible sound is higher. Thus, we expect that SPL is higher in the area including both carrier and sideband waves with proposed method. Table 1 shows the experimental equipments and Table 2 shows the experimental conditions. Figure 2 shows the experimental environment. In Fig. 2, PLc is the parametric loudspeaker for the carrier wave, PLs is the parametric loudspeaker for the sideband wave. We measured the SPL distribution for confirming our expectation. Under the condition that PLs is set on 0 deg., PLs is put on PLc.

Figure 3 shows the SPL distribution with the conventional method. From Fig. 3, we confirmed that the audible sound was reproduced in the linear area with the conventional method. Figures 4(a) ~ (d) show the distribution of SPL under the condition that PLs is set on 0, 30, 90 and 150 deg., respectively. From Figs. 4(a) ~ (c), we confirmed that SPL with the proposed method is similar to SPL with the conventional method in the audio spot. In addition, SPL out of the audio spot with the proposed method is lower. To take an example, in Fig. 3, with conventional method, the SPL is 47 dB in the point of 0 m depth and 0 m width, and that is 38 dB in the point of -0.3 m depth and 0 m width. On the other hand, in Fig. 4(b), with proposed method, the SPL is 46 dB in the point of 0 m depth and 0 m width, and that is 25 dB in the point of -0.3 m depth and 0 m width. Thus, the SPL with proposed method is similar to the SPL with conventional method in the point of depth 0 m and width 0 m as the audio spot. In addition, the SPL with proposed method is lower 13 dB than the SPL with conventional method in the point of depth -0.3 m and width 0 m. These show that the audio spot formed in the area including the both carrier and sideband waves with proposed method. Therefore, we confirmed the effectiveness of the proposed method. In Fig. 4(d), however, the SPL of the audible sound is lower than 30 dB in all areas. This is because that the direction difference between the carrier and sideband waves is larger. Thus, the non-linear interaction of ultrasonic scarcely influences the waves in the area including both carrier and sideband waves.
FIGURE 2. Experimental environment in the objective evaluation for measuring the SPL distribution

![Diagram showing experimental setup](image)

**TABLE 1.** Experimental equipments

<table>
<thead>
<tr>
<th>Item</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parametric loudspeaker</td>
<td>MITSUBISHI, MSP-50E</td>
</tr>
<tr>
<td>Loudspeaker amplifier</td>
<td>VICTOR, PS-A2002</td>
</tr>
<tr>
<td>Microphone</td>
<td>SONY, ECM-88B</td>
</tr>
<tr>
<td>A/D, D/A converter</td>
<td>ROLAND, UA-1010</td>
</tr>
</tbody>
</table>

**TABLE 2.** Experimental conditions in the objective evaluation for measuring sound pressure level distribution

<table>
<thead>
<tr>
<th>Item</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling frequency</td>
<td>192 kHz</td>
</tr>
<tr>
<td>Quantization</td>
<td>16 bits</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>40 kHz</td>
</tr>
<tr>
<td>Ambient noise level (Lₐ)</td>
<td>37 dB</td>
</tr>
<tr>
<td>Sound source</td>
<td>Japanese isolated word /tik/ak</td>
</tr>
</tbody>
</table>
We carried out the subjective evaluation experiment to confirm the effectiveness of the proposed method. We evaluated the speech articulation of the demodulated audible both sounds in the audio spot and out of the audio spot with the proposed and with conventional methods. In the conventional method, a parametric loudspeaker emits AM wave with SSB moderation method. The experimental equipments are the same as the objective evaluation. Figure 5 shows the experimental environments. Table 3 shows the experimental conditions. In Fig. 5, Mic.1 is set in the audio spot and Mic. 2 is also set out of the audio spot. The experiment is conducted by the following processes.

1) The parametric loudspeakers emit the syllable words.
2) Mic. 1 and Mic. 2 observe the audible sound and record that.
3) The subjects listen to the recorded audible sound with a headphone.
4) The subjects answer the syllable words.

The syllable words include vowels and consonants. The speech articulation is higher when the audible sound is reproduced with the high sound quality. Therefore, the rate of correct answers in the audio spot is higher, and that out of the audio spot is lower when the audio spot is formed with proposed method. In addition, the rate of correct answers is higher when the harmonic distortions occur by the difference tone between the two frequency components included the sideband wave under the condition of emitting the sideband wave without the carrier wave. This is because the harmonic distortions have the frequency components similar to the original audible sound. However, the harmonic distortions are the lower sound quality. Thus, we expect that the rate of correct answers in the audio spot is higher and out of the audio spot is lower. In addition, the rate of correct answers with emitting the sideband wave without the carrier wave is lower than emitting the sideband and carrier waves.

Figures 6(a) ~ (d) show the results of the experiment for the speech articulation of the demodulated audible sound. The conditions in Figs.6 are indicated as follows:

Subjective Evaluation for Evaluating the Speech Articulation
CM: the conventional method emitting the AM wave  
PM1: the proposed method emitting the carrier and sideband waves  
PM2: the proposed method emitting the carrier and divided sideband waves  
SB: the proposed method emitting the sideband wave  
SBH: the proposed method emitting the higher frequency divided sideband wave  
SBL: the proposed method emitting the lower frequency divided sideband wave

From Figs. 6(a) ~ (d), we confirmed that the rate of the correct answers in the vowel is 90 % and that in the consonant is 50 %, with the condition PM1. The rates of the correct answer at the Mic. 1 with the condition PM1 are higher than that at the Mic. 2 with the condition PM1. Therefore, we confirmed that the audio spot is formed with the proposed method. On the other hand, the rates of the correct answer with the condition PM1 are lower than that with the condition CM. It shows that the speech articulation of the demodulated audible sound with the condition PM1 is worse than that with the condition CM. The rate of the correct answers in the vowel is 40 % and that in the consonant is 20 %, with the condition SB. It shows that the harmonic distortions occur by the difference tone between the two frequency components included in the sideband wave. The rates of the correct answers with proposed method emitting the sideband wave with the band-division as conditions SBH and SBL are lower than the rates of the correct answers emitting the sideband wave without the band-division as condition SB at Mic.1. It shows that the proposed method emitting the sideband wave with the band-division is effective for reducing the harmonic distortions in the audio spot. However, the rates of the correct answer with the condition PM2 are lower than the rates of the correct answer without the band-division PM1. Thus, it is necessary to carry out more examinations about improvement of the sound quality.

![Diagram of experimental environments](image)

(a) Proposed method with non-divided sideband wave  
(b) Proposed method with divided sideband wave

**FIGURE 5.** Experimental environments in the subjective evaluation for evaluating the speech articulation

**TABLE 3.** Experimental conditions in the subjective evaluation for evaluating the speech articulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
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</thead>
<tbody>
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<td>Sampling frequency</td>
<td>96 kHz</td>
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<tr>
<td>Quantization</td>
<td>16 bits</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>40 kHz</td>
</tr>
<tr>
<td>Ambient noise level (L_{A})</td>
<td>36 dB</td>
</tr>
<tr>
<td>Sound source</td>
<td>Japanese syllable words (2 speakers * 10 words)</td>
</tr>
<tr>
<td>Dividing frequency ( f_d )</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Subject</td>
<td>5 persons</td>
</tr>
</tbody>
</table>
CONCLUSIONS

The parametric loudspeaker reproduces an audible sound in the particular area that is called “audio spot”. However, reflections and intercepts by emitted sounds become severe problems. This is because reflections and interceptions lead to an invasion of privacy. In this paper, we proposed the design method of the audio spot with separating emission of the carrier and sideband waves. When, parametric loudspeaker emits sideband waves, the harmonic distortions may occur by the difference tone between two frequency components included in the sideband wave. Thus, we also proposed the method of reducing the harmonic distortions using divided sideband wave with band-divided.

We carried out the objective evaluation experiment to measure the SPL of the demodulated audible sound. In addition, we carried out the subjective evaluation experiment to evaluate the speech articulation of the demodulated audible sound. As a result, we confirmed that that audio spot was formed in the area including both carrier and sideband waves with the proposed method. In addition, we confirmed that the proposed method with the divided sideband wave is effective for reducing the harmonic distortions.

Therefore, we confirmed the effectiveness of the proposed method. In future work, we will have to improve the sound quality and the SPL of the demodulated audible sound using more parametric loudspeakers.

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REFERENCES