Audio spotlight using subdivided AM sideband wave delivery from separate ultrasonic array speakers

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Abstract

Parametric array speakers can deliver an audible sound beam by modulating sound using an ultrasonic carrier wave and playing this modulated signal from an ultrasonic transducer array at high levels. Audible sound is demodulated in a narrow beam due to the nonlinear aerial transfer characteristics. However, if sound can be delivered within a small region, *i. e.*, within a spot, sound can be delivered only to the intended subject, and avoid leakage to others. This is partially possible by generating the carrier wave and the sideband signal of the modulated signal from separate arrays, resulting in the full demodulation of an audible sound at the intersection of the two beams. However, we found that some audible noise was generated through demodulation of the sideband signal. We observed that the level of this noise is proportional to the relative frequency difference within the sideband signal. Thus, we divided the sideband signal into several sub-bands, limiting the frequency range of each sub-band, and generated them from separate arrays, intersecting only at the spotlight. By using 5 sub-bands, it was possible to limit the spotlight to an effective volume of 0.2 m by 0.2 m by 0.2 m, while the audible noise of the surrounding region was reduced to 20 dB lower levels.

Keywords: Parametric speaker, Audio spotlight, Subdivided sideband

1 INTRODUCTION

Parametric array loudspeakers (PALs) have been studied as a source for a highly-directional audio signal using an array of ultrasonic transducers generating ultrasonic carrier waves modulated using audible sound signals [1, 2]. The ultrasonic signals are produced at high levels, at which the propagation through the air exhibits non-linear characteristics. This, in turn, demodulates the signal and regenerates the audible sound which was used to modulate the ultrasonic carrier waves. Due to the highly directional propagation characteristics of ultrasonic waves, the demodulated audible waves also exhibit highly directional characteristics, *i.e.*, sound beams are created.

Parametric array speakers have become commercially available as products from several vendors, including American Technology Corp. and Mitsubishi Electric Engineering Co. [3]. It has been applied to some applications, such as for the audio introduction of exhibits at a gallery or a museum, or to play music and sound effect in a gaming booth [4].

These applications were designed so that only the listeners within the sound beam would be able to hear the sound, and all others would not be disturbed. However, if an unintended listener is within the range of the sound beam, they would also be exposed to the audio signal. Thus, in some applications, it would be preferable that audible sound is reproduced only within a limited region, not within a beam. For example, it would be preferable to limit the audible range to only around the intended listener if the content includes sensitive information regarding the listener, *i.e.*, financial or medical information.

Accordingly, Matsui *et al.* have proposed the creation of an audio spot using parametric speakers by separating the carrier waves from the modulated sideband signals, and generating them from separate parametric speakers, crossing at the audio spot where the audible sound is to be generated [5]. Their idea was that since the carrier and the sideband signal coexist only at the audio spot, the audible sound is created only at this location.

We found that audible sound is reproduced at the spot using separate parametric speakers, as proposed by

Matsui *et al.* However, as will be described in the next section, we found that considerable audible noise is also generated outside the spot, which is clearly not desirable. In the next section, we study the nature of the mechanism in which this noise is generated.

2 PROBLEM FORMULATION: AUDIBLE SOUND OUTSIDE THE AUDIO SPOT

As stated in the previous section, we attempted to separate the carrier signal from the sideband signal, and generated signals from two separate parametric arrays. We found that audible signal was reproduced at the intersecting spot, as intended. However, we also found that some noise was generated from the parametric array generating the sideband signal. On the other hand, no noise was apparently generated from the parametric speaker generating the carrier wave.

We observed that noise is generated by generating sideband signals with multiple frequency components. No noise is played out when the sideband consists of a single frequency signal (tone). This should give us a clue as to the mechanism from which the noise is generated from sideband signals.

Berktay defined a simplified expression that can be used to predict far-field array response on the propagating axis [6]. It is stated here that the demodulated waveform along the axis of propagation is proportional to the second time-derivative of the square of the envelope of the primary signal.

The secondary wave can be given as:

$$p_2 \propto P_0^2 \frac{\partial^2}{\partial t^2} E^2(t) \tag{1}$$

where P_0 is the initial carrier SPL, and $E(t)$ is the modulation envelope function. We assume that two tonal signals with frequencies f_1 and f_2 are modulated with an ultrasonic carrier wave with a frequency of f_c. We assume that we take only the lower sideband of the modulated signal. The modulated signal, excluding the carrier signal, can be simplified as follows.

$$\begin{aligned} & sin(f_c - f_1)t + sin(f_c - f_2)t \\ & \approx 2sinf_c t \cdot cos\frac{f_2 - f_1}{2}t \\ & = 2E(t)sin(f_c t) \end{aligned} \tag{2}$$

Then,

$$E(t) = 2cos\frac{f_2 - f_1}{2}t \tag{3}$$

$$E^2(t) = 2\{1 + cos(f_2 - f_1)t\} \tag{4}$$

$$\frac{\partial^2}{\partial t^2} E^2(t) = -2(f_2 - f_1)^2 cos(f_2 - f_1)t \tag{5}$$

Thus, the demodulated signal is audible only if the frequency difference of the two tonal signals, $f_2 - f_1$ is within the audible range. Also, the amplitude of the demodulated signal is proportional to the square of the frequency difference. Therefore, if we can keep the frequency difference that is generated from a PAL small enough, the amplitude of the demodulated signal can be kept small. For audible signals with more frequency components, this can be accomplished by subdividing the modulated signal into small bandwidths, and separately generating each bandwidth signal from separate PALs.

We shall explore this solution in the next section.

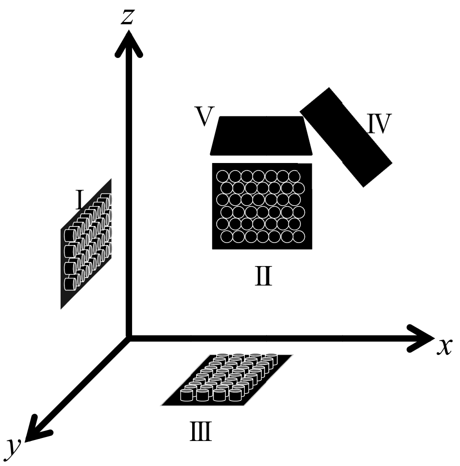

Figure 1. Arrangement of PAL for subdivided sideband delivery experiments

3 AUDIO SPOTLIGHT USING SUBDIVIDED SIDEBAND DELIVERY FROM MULTIPLE SPEAKERS

As described in the previous section, we propose to divide the sideband signal, including the carrier, into small sub-bands, and output each sub-band from separate PALs in order to reduce the unintended audible noise output from each PAL. Thus, the more sub-bands we divide the sideband signal into, the narrower the frequency range of each sub-band to be output from each PAL, and consequently, the smaller the audible noise generated from each PAL. The output from all PAL is to intersect at the intended audio spot, where the audible signal is regenerated. In principle, the smaller the volume of this intersection, the smaller the size of the audio spot will be. Even a partial overlap of the sub-band signal will result in a wider frequency distribution, thereby increasing the level of the potentially regenerated audible noise. Thus, the placement of the PALs should be arranged so that the intersection of the ultrasonic beams output from the PALs outside the intended audio spot is kept to a minimum.

In the next section, we will conduct experiments to find out the effect of the number of sub-bands, *i.e.*, the bandwidth of the sub-bands, will have on the generated noise levels, as well as its effect on the generated audio signal at the audio spot.

4 EXPERIMENTAL CONDITIONS

4.1 PAL and its placement

All PALs used in these experiments were 140 by 180 mm^2 boards with 100 air ultrasonic ceramic transducers (PROWAVE 400ST160). The modulated signals were created on a computer at a sampling frequency of 192 kHz. The modulated signal was generated, single sideband extracted and split into sub-bands using filters. Each sub-band signal was D/A converted, amplified, and fed to the PALs.

The PAL generating the sub-band signals need to be carefully placed around the intended audio spot in order to deliver each sub-band with minimum intersecting volume. We decided to locate the audio spot in the center position of a cube with a dimension of 1m by 1 m by 1 m. We decided to place five PALs surrounding this cubic area as shown in Fig. 1. As shown in this figure, PALs I through III can be placed perpendicular to each other on the $x-$, $y-$, and the $z-$plane, respectively. We decided to locate PALs IV and V facing 45 degrees downwards towards the audio spot, as shown in the figure. All PALs were placed 0.5 m from the audio spot.

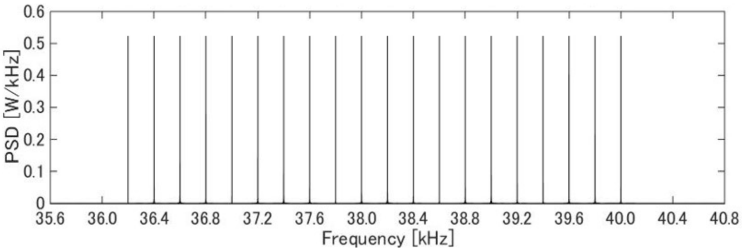

Figure 2. Power spectrum density of the test signal

4.2 Test signal

The test signal was an amplitude modulated single sideband signal as shown in Fig. 2. The modulation signal was a combination of 19 tonal signals, from 200 Hz to 3.8 kHz, each 200 Hz apart. The carrier signal was a 40 kHz sinusoidal signal. From this modulated signal, the upper side-band was attenuated using a low-pass filter, resulting in a signal consisting of only the lower side-band. Thus, the modulated signal included 20 sinusoidal signals, from 36.2 to 40.0 kHz. This signal was split into equal-size sub-bands, from one to 5. For example, for 2 sub-bands, the signal was split into a sub-band with 2 kHz bandwidths. We also included a condition where the sideband signal was generated from a single PAL with no subdivisions. Obviously, in this case, the audible sound will be generated in a beam, as a conventional parametric speaker.

To generate a sideband signal with no subdivision, only PAL I was used. In the case with one division (2 sub-bands), PALs I and II were used, for 2 divisions (3 sub-bands), I, II and III, for 3 divisions (4 sub-bands), I, through IV, and for 4 divisions (5 sub-bands), I, through V was used, respectively.

4.3 Reproduced sound level measurement

The auditory sound level was measured at each grid point within the 1 m by 1 m by 1 m cube, 0.1 m apart, using a sound level meter. Measurements were conducted in a sound-proof room with acoustically treated walls.

5 RESULTS AND DISCUSSIONS

5.1 Formulation of the audio spotlight

Fig. 3 shows the auditory signal level measurements when the signal is not divided, and output from a single PAL, while Figs. 4 to 7 show the level measurements when the signal is divided into 2, 3, 4 and 5 sub-bands and output from 2 to 5 PALs, respectively.

Fig. 3 shows the auditory signal is generated in a beam, *i. e.*, high levels of the auditory signal are concentrated in the center of each slice. A similar pattern is shown in Fig. 4, but with slightly higher levels in the slice at $x = 0.4$ m. However, for other Figs., with subdivisions of the sideband greater than one (2 to 5 sub-bands), a clear concentration of the generated level at the center portion, especially at the slice at $x = 0.4$ can be seen, *i. e.*, an audio spot can be observed. The level concentration at the audio spot is greater with more subdivisions, although the high level concentration is not significantly different for Figs. 6 and 7.

5.2 Audio spot size

Fig. 8 shows the output level with 4 subdivisions (5 sub-bands), sliced at x=0.5 m, y=0.5 m, and z=0.5 m, respectively. With 4 subdivisions, the audio spot, at which an SPL of more than 60 dB was observed, was a cubic volume with a dimension of 0.2 m by 0.2 m by 0.2 m. The level surrounding this spot was at least 10 dB lower than the level inside the spot. Thus, by subdividing the sub-band signal into more than 4 sub-bands, we were able to create an audio spot where the reproduced audio signal level is clearly higher than its surrounding regions.

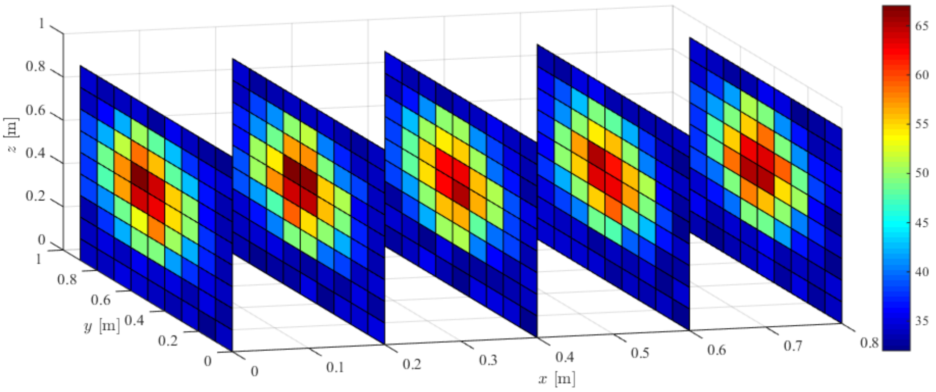

Figure 3. Output level with no subdivision of sideband

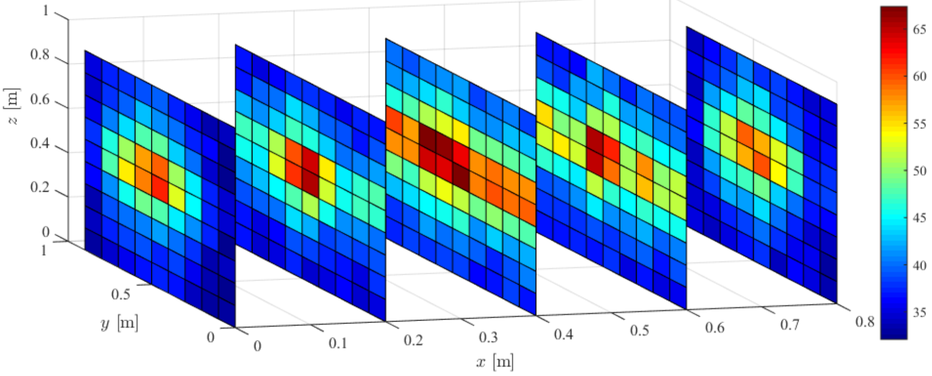

Figure 4. Output level with one subdivision (2 sidebands)

6 CONCLUSIONS

We investigated a method to generate an audio spot with only a small amount of spurious audible noise in the regions surrounding the audio spot. We proposed to subdivide the sideband signal output into multiple sub-bands with relatively narrow bandwidth, and generate each sub-band signal from separate PALs. The PALs were oriented so that the sideband signals intersect at only the audio spot.

We investigated the regenerated level within a volume of 1 m by 1 m by 1 m surrounding the audio spot using one to five PALs and found that by using five PALs, the size of the audio spot can be kept to a volume the size of 0.2 m by 0.2 m by 0.2 m. We also found that the average noise level outside the spot can be kept significantly lower compared to when using a single PAL.

The experiments described in this paper used an artificial sound signal, *i. e.*, multiple tonal signals 200 Hz apart. We would like to test with a more realistic sound, *e.g*, speech signal, and create an audio spot where the speech signal can be only heard at the audio spot, but not in the surrounding area. We also would like to apply the proposed audio delivery method into applications such as speech output maintaining content privacy, volume-confined active noise control using audio spots, among others.

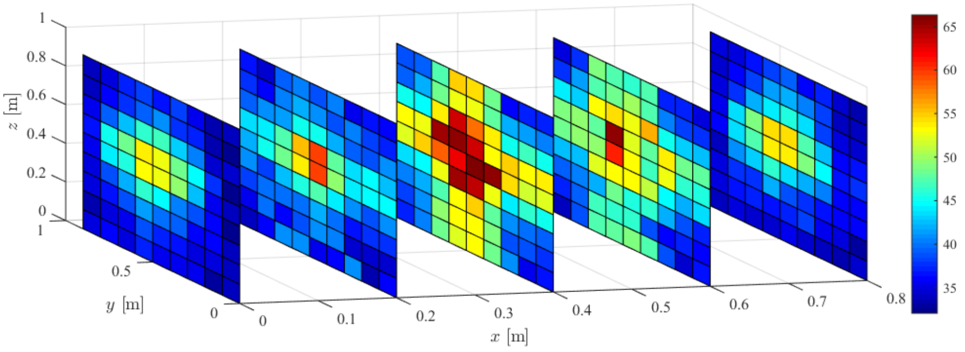

Figure 5. Output level with 2 subdivisions (3 sidebands)

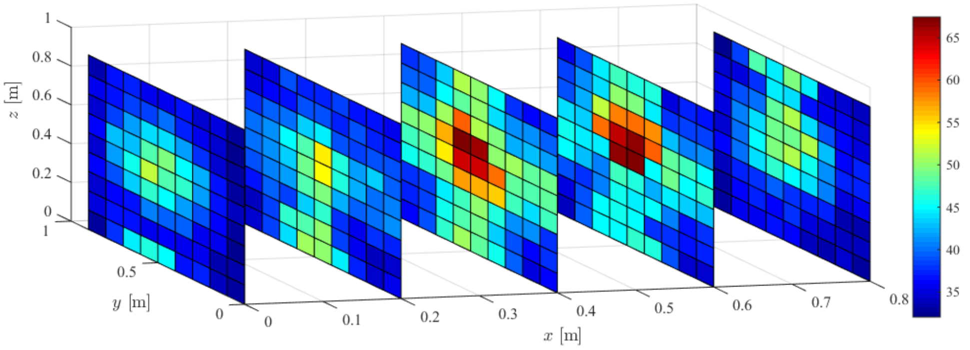

Figure 6. Output level with 3 subdivisions (4 sidebands)

ACKNOWLEDGMENTS

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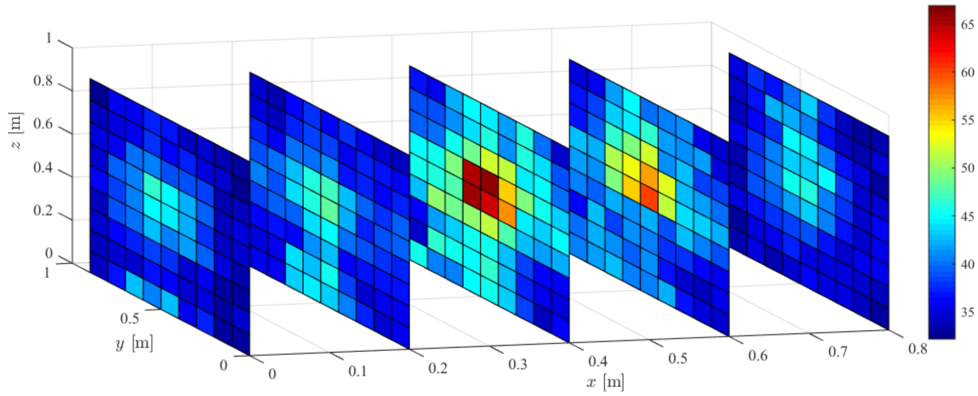

Figure 7. Output level with 4 subdivisions (5 sidebands)

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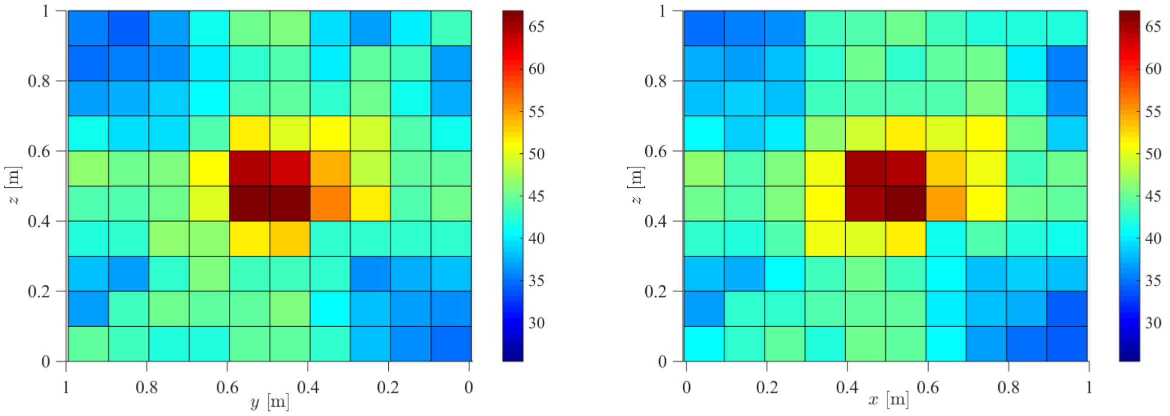
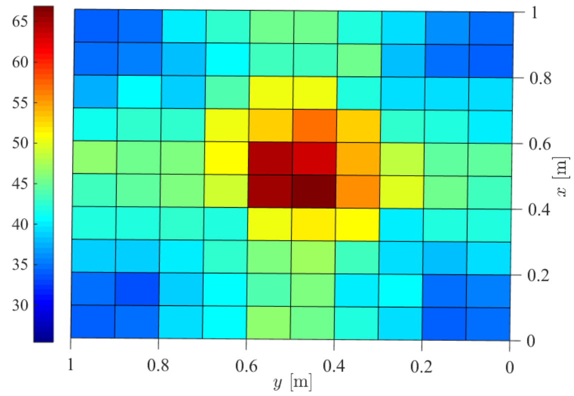


(a) $x = 0.5$m

(b) $y = 0.5$m



(c) $z = 0.5$m

Figure 8. Output level with 4 subdivisions at x, y and z slices