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Formation of local quiet zones using the length-limited parametric array loudspeaker

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ABSTRACT

This paper presents a preliminary numerical study on the formation of local quiet zones using the length-limited parametric array loudspeaker (PAL). The PAL is a directional sound device using the nonlinear acoustic effect to generate an audio beam in air. The length-limited PAL aims to control the length of the audio beam by using two different ultrasonic carriers. The sound propagation curve and radiation pattern of the length-limited PAL are theoretically distinct from those of the conventional loudspeaker. Therefore, the local quiet zones formed by the length-limited PAL is of sufficient interest before any practical deployment of the length-limited PAL in active noise control (ANC). For comparison, the local quiet zones formed by the conventional loudspeaker and the normal PAL are also obtained and examined in the numerical simulation.

Keywords: Numerical simulation, Parametric array loudspeaker, Active noise control

1. INTRODUCTION

The PAL is a directional sound source using the nonlinear acoustic effect to generate an audio beam in air (1). It is often built up with a driver circuit and an ultrasonic emitter. The driver circuit modulates audio input signals on an ultrasonic carrier and amplifies the modulated signal to be transmitted by the ultrasonic emitter. The principle of the PAL is provided by the nonlinear acoustic effect: when two ultrasonic frequencies are transmitted into a nonlinear medium, the difference frequency is generated in a narrow beam, whose pattern is similar to that of an end-fire array (2). Although air is a weak nonlinear medium, the nonlinear acoustic effect is still sufficient to be applied in many sound field control applications (3).

The ANC creates a quiet zone by inferring the noise wave with an anti-noise wave (4). In a free space, the formation of a local quiet zone leads to the spillover problem, resulting in increased noise levels outside the quiet zone. It is believed that using a directional sound source to transmit the anti-noise wave can solve the spillover problem.

Brooks, Zander and Hansen investigated the feasibility of using the PAL in ANC in 2005 (5). They concluded three practical concerns, which were (i) the PAL had a weak low-frequency response and severe harmonic distortion; (ii) the precise control of amplitude and phase required for ANC was difficult to achieve; (iii) the ultrasonic exposure of the PAL has yet to be evaluated. However, several successful experiments of using PALs in ANC have been reported recently (6, 7). The noise frequency typically ranges from 500 Hz to 2.5 kHz.

The length-limited PAL has been proposed to use two carrier frequencies in order for the length of the difference frequency beam to be shortened (8, 9). Dedicated modulation methods are important for the difference frequency beam to be confined in the relative near field of the ultrasonic emitter. The use of the length-limited PAL in ANC has been experimentally investigated (10). However, the local quiet zones formed by the length-limited PAL needs to be examined further.

2. NUMERICAL CONFIGURATION

This paper presents a preliminary numerical study of forming local quiet zones using the length-limited PAL. The numerical simulation is carried out in a $0.488\text{m} \times 0.488\text{m}$ two dimensional space, which is surrounded by perfect matched layers to remove reverberation. The space is divided into 488×488 grids. Each side of the grid is 1 mm. The noise frequency is fixed at 1 kHz. The speed of sound and the nonlinear coefficient of air are set to 343.13 m/s and 1.2, respectively. The numerical simulation code is modified from the k-wave toolbox (11).

2.1 Primary Noise Sources

Two different positions of the primary noise source are simulated. The diameter of the primary noise source is 2 cm, which is approximately the size of a miniature speaker. Figure 1 shows the sound pressure distributions of the primary noise sources. The center of the simulation space is calibrated to 60 dB.

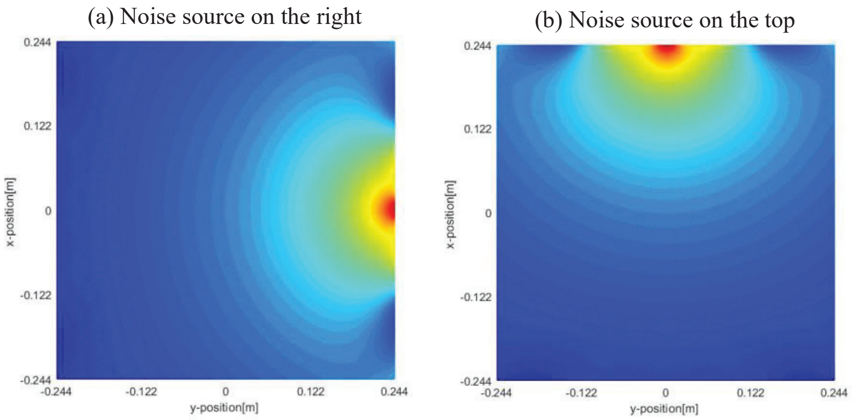

Figure 1 – Sound pressure distributions of primary noise sources

2.2 Linear Secondary Sources

Two types of linear secondary sources are simulated. Both sources are placed on the left with diameters of 2cm and 10cm, respectively. Figure 2 shows the sound pressure distributions of the linear secondary sources. The initial phase and amplitude are controllable, in order for the noise cancellation to be achievable at any particular position.

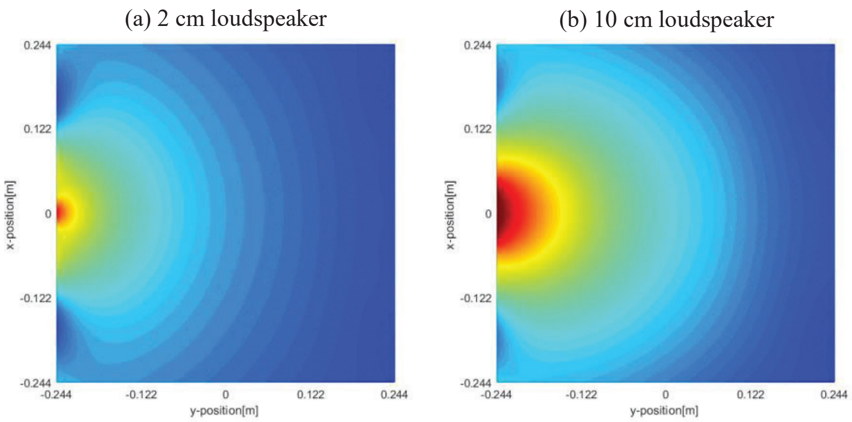

Figure 2 –Sound pressure distributions of the linear secondary sources

2.3 Nonlinear Secondary Sources

Three types of nonlinear secondary sources are simulated. They are the conventional PAL using a carrier of 40 kHz, the conventional PAL using a carrier of 90 kHz, and the length-limited PAL. All of them adopt the double sideband modulation.

The conventional PAL using a carrier of 40 kHz transmits a modulated ultrasonic sound, which is given by

$$p_1(t) = P_1[1 + mx(t)]\cos(2\pi f_1 t), \tag{1}$$

where P_1 is the initial pressure; $f_1 = 40$ kHz is the carrier frequency; $m = 0.7$ is the modulation index; and $x(t)$ is the input sine tone at 1 kHz.

The modulated signal of the conventional PAL using a carrier of 90 kHz is written as

$$p_2(t) = P_2[1 - mx(t)]\cos(2\pi f_2 t) \tag{2}$$

where P_2 is the initial pressure; $f_2 = 90$ kHz is the carrier frequency. Note that the sign in front of the modulation index has been changed.

In order for the difference frequency beams resultant from different carrier frequencies can cancel each other in the far field, their initial pressure levels have to obey with the following relation:

$$P_1/P_2 = \sqrt{\alpha_1/\alpha_2}, \tag{3}$$

where α_1 and α_2 are the absorption coefficients (12). Figure 3 shows the sound pressure distributions of the nonlinear secondary sources.

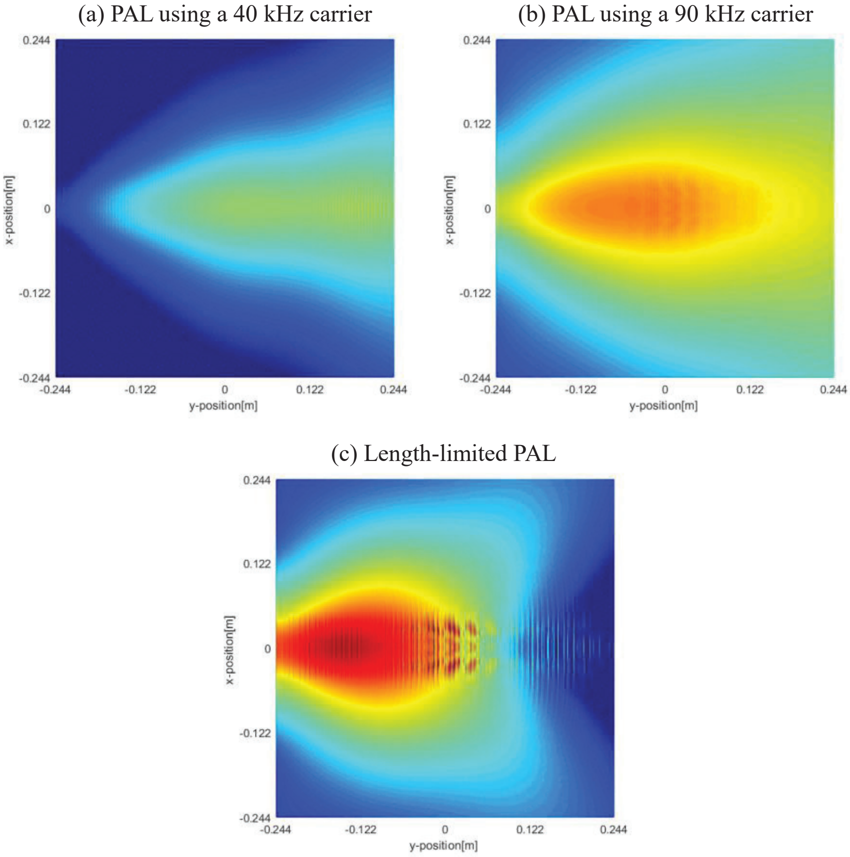

Figure 3 – Sound pressure distributions of the nonlinear secondary sources

2.4 Active Noise Control

Practical implementations of ANC may involve a complicated procedure of adaptive filtering and modeling. However, in the numerical simulation, ANC is carried out by adjusting the initial phase and amplitude of the input sine tone such that at a given control point, the primary and secondary waves can cancel each other completely.

Five control points illustrated in Figure 4(f) are simulated separately. Given the condition that the control point is at the center and the primary noise source is placed on the right, the noise reduction distributions of different secondary sources are shown in Figures 4(a)-(e). When linear secondary sources are used, the quiet zone is a straight line, of which the width is proportional to the wavelength. The quiet zone is curved and has a shorter length due to the PALs narrow directivities. However, when the length-limited PAL is adopted, the quiet zone becomes longer, which implies that the beamwidth of the length-limited PAL is broader than the conventional PALs at the distance of the control point. This can easily be validated in Figure 3(c).

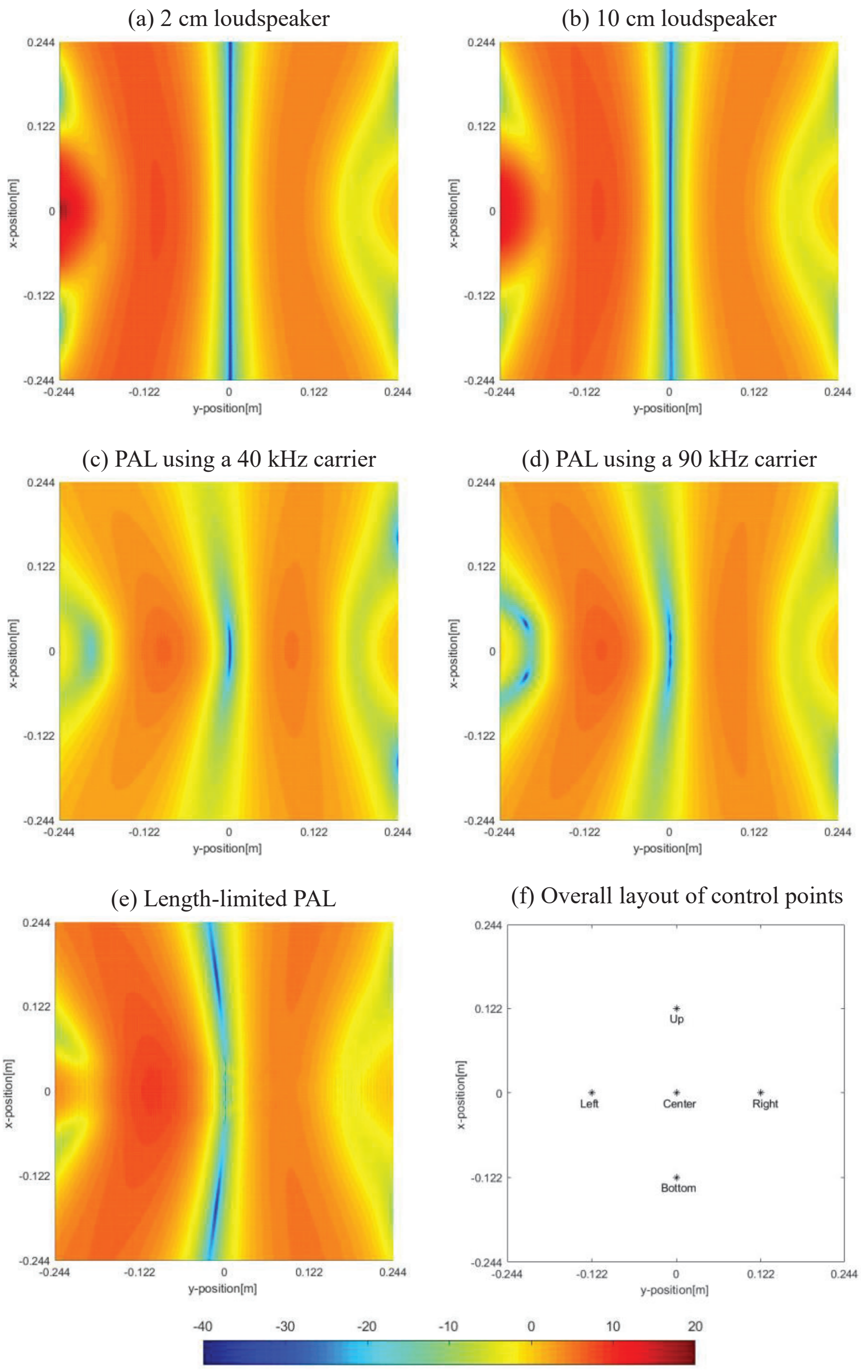

Figure 4 – Noise reduction distributions when the control point is set at the center and the primary noise source is placed on the right

3. ANALYSIS OF RESULTS

To summarize the results, two measures are considered. Firstly, the grids with noise reductions above 3dB, 10 dB, and 20 dB are counted as percentages of the total number of grids. This measure indicates clearly the size of the quiet zone. Secondly, the averaged sound pressure level of the primary noise in the whole simulation space is calculated. The change in the averaged sound pressure level after the introduction of the secondary source is recorded. This measure explains whether the average noise level has been increased noticeably as a result of the spillover problem.

Figures 5 and 6 present the simulation results when the primary noise source is placed on the right and on the top, respectively. In Figures 5(a) and 6(a), the number of grids where the noise reduction is above 10 dB is likely to be independent from the secondary sources. For noise reduction above 20 dB, using the linear secondary sources is more advantageous than using the nonlinear secondary sources. However, using the conventional PALs result in more grids with noise reduction above 3 dB. This probably explains the previously reported observation that the quiet zone created by the PAL is perceived to be broader.

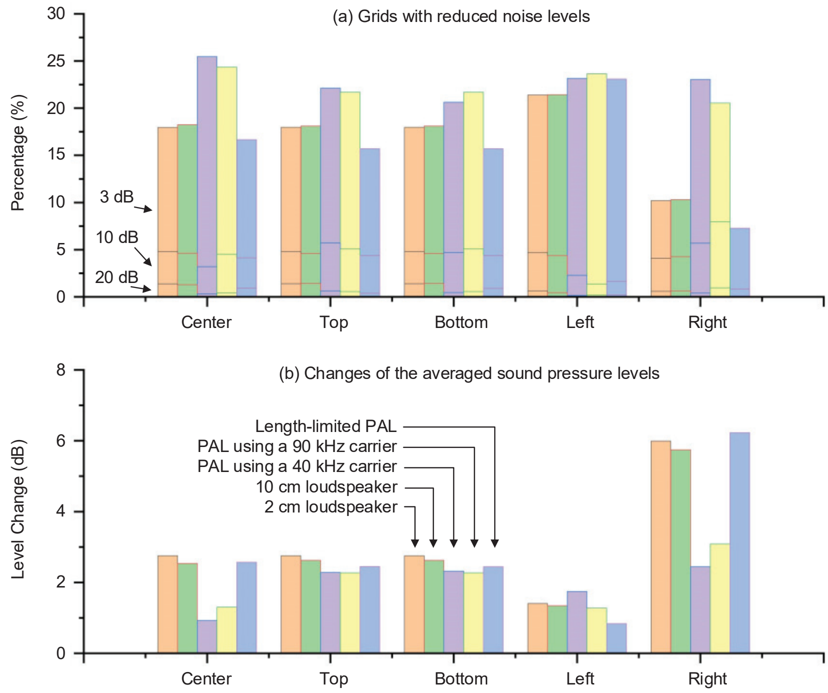

Figure 5 – Simulation results when the primary noise source is placed on the right

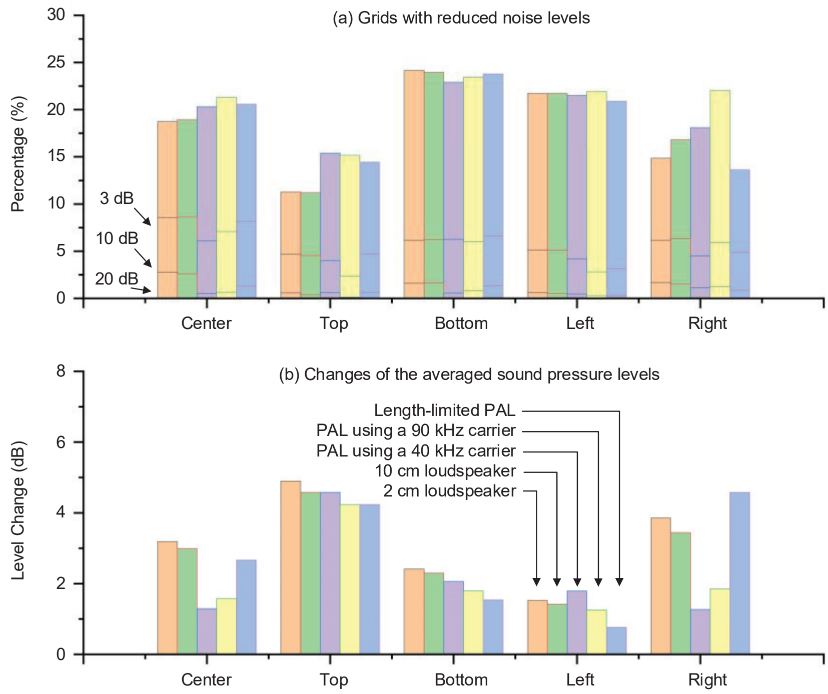

Figure 6 – Simulation results when the primary noise source is placed on the top

Moreover, the simulation space is relatively small as compared to practical situations. Using any type of secondary source increases the averaged sound pressure level, but most of the increments are less than 3 dB. Figures 5(b) and 6(b) shows that the nonlinear secondary sources demonstrate the merit of less increments as compared to the linear secondary sources. When the control point is set on the right half plane, using the length-limited PAL is an exception. It results in a significant increment in the averaged sound pressure level after noise cancellation. This is because the shortened length of the difference frequency beam cannot reach the control point as shown in Figure 3(c). On the other hand, when the control point is on the left within the beam of the length-limited PAL, it achieves the smallest spillover.

4. CONCLUSIONS

A preliminary numerical study of local ANC has been conducted with different types of secondary sources, including conventional loudspeakers, PALs and the length-limited PAL. Using the PALs can result in less spillover as compared to the linear loudspeakers. It has been proved that when the control point is within the beam of the length-limited PAL, the spillover problem can be further resolved. However, there has been no observation that clearly supports the enlargement of the quiet zone by using PALs in ANC.

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REFERENCES

1. Yoneyama M., Fujimoto J., Kawamo Y., Sasabe S. The audio spotlight: An application of nonlinear interaction of sound waves to a new type of loudspeaker design. J Acoust Soc Am. 1983; 73(5): 1532–1536.
2. Westervelt PJ. Parametric acoustic array. J Acoust Soc Am. 1963; 35(4): 535–537.
3. Takeoka S, Yamasaki Y. Acoustic projector using directivity controllable parametric loudspeaker array. Proc. 20th ICA; 23-27 August 2010; Sydney, Australia, 2010.
4. Shi C, Xie R, Jiang N, Li H, Kajikawa Y. Selective virtual sensing technique for multi-channel feedforward active noise control systems. Proc 2019 ICASSP; 12-17 May 2019; Brighton, UK, 2019.
5. Brooks LA, Zander AC, Hansen CH. Investigation into the feasibility of using a parametric array control source in an active noise control system. Proc Acoust 2005; 9-11 November 2005; Busselton, Australia, 2005.
6. Tanaka N, Tanaka M. Active noise control using a steerable parametric array loudspeaker. J Acoust Soc Am. 2010; 127 (6): 3526–3537.
7. Tanaka K, Shi C, Kajikawa Y. Binaural active noise control using parametric array loudspeakers. Applied Acoust. 2017; 116: 170–176.
8. Hedberg CM, Haller KCE, Kamakura T. A self-silenced sound beam. Acoust Physics. 2010; 56(5): 637–639.
9. Nomura H, Hedberg CM, Kamakura T. Numerical simulation of parametric sound generation and its application to length-limited sound beam. Applied Acoust. 2012; 73(12): 1231–1238.
10. Lam B, Gan WS, Shi C. Feasibility of a length-limited parametric source for active noise control applications. Proc 21st ICSV; 6-10 July 2014; Beijing, China, 2014.
11. Treeby BE, Cox BT. A k-space Green's function solution for acoustic initial value problems in homogeneous media with power law absorption. J Acoust Soc Am. 2011; 129(6): 3652–3660.
12. Shi C. Theory and modulation methods of the length-limited parametric array loudspeaker. Proc 25th ICSV; 8-12 July 2018; Hiroshima, Japan, 2018.