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# Demodulation distance control based on analytic model between film gas-lens depth and demodulation distance for parametric array loudspeaker

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## ABSTRACT

Parametric array loudspeaker (PAL) can transmit an audible sound to only a particular area by utilizing ultrasound. We have previously proposed a demodulation distance control using a film gas-lens with the gas different from the air to control a maximum demodulation distance (MDD), which is a distance with maximum demodulation of the audible sound. The method selects the gas and adjusts the film gas-lens depth to make the MDD equal to the desired MDD (D-MDD). In the method, the MDD has a large numerical error because it employs a simple linear approximation with the MDD and the film gas-lens depth. In this paper, we therefore propose a new MDD control based on an analytic model between film gas-lens depth and the MDD. To design the analytic model, we investigate the MDD corresponding to the film gas-lens depth set at equal intervals and design a regression curve. Next, to calculate the appropriate film gas-lens depth corresponding to the D-MDD, we design the analytic model as an inverse function of the regression curve. The analytic model can accurately adjust the film gas-lens depth to control the MDD. Finally, we confirmed the effectiveness of the proposed method through the evaluation experiments.

Keywords: Parametric array loudspeaker, Demodulation distance, Film gas-lens

## 1. INTRODUCTION

Acoustic sounds are usually emitted by an electrodynamic loudspeaker. It is suitable for transmitting the audible sound to many listeners because of its wider directivity. However, it is unsuitable for transmitting the audible sound in particular areas. Then, the attention has recently been focused on a parametric array loudspeaker (PAL) [1, 2]. PAL can achieve a higher directivity by utilizing ultrasound and transmit the audible sound to a particular area [3, 4]. The PAL utilizes the amplitude modulated (AM) wave which is designed by modulating an amplitude of ultrasound with an original audible sound. The AM wave is strongly emitted from the PAL, and it is gradually demodulated into the original audible sound by the nonlinear interaction in the air. It is known that the sound pressure level (SPL) of the demodulated audible sound depends on the distance between the PAL and the observed position [5, 6]. This is attributed that the demodulation insufficiently occurs at close to the PAL. Thus, it is difficult to transmit the demodulated audible sound with the maximum SPL to the listener at any positions. In this paper, we refer to the maximum demodulation distance (MDD) that the distance which the demodulated audible sound has the maximum SPL.

It is known that the MDD is changed by the density of the medium in which the emitted AM wave is transmitted. Based on it, we have previously proposed a demodulation distance control using a film gas-lens with the gas different from the air to control the MDD [7]. This method arranged the film gas-lens in front of the PAL as the container to enclose the gas. Then, this method selects the gas and adjusts the depth of film gas-lens to make the MDD equal to the desired MDD (D-MDD). However,

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this method has a large numerical error on controlling the MDD because it employs a simple linear approximation with the MDD and the film gas-lens depth. It is difficult to accurately control the MDD to any listener's positions.

In this paper, we therefore propose a new MDD control based on an analytic model between the film gas-lens depth and the observed MDD (O-MDD). First, to design the analytic model, we investigate the O-MDD corresponding to the film gas-lens depth set at equal intervals and design a regression curve in each gas through the preliminary experiments. Next, to calculate the appropriate film gas-lens depth corresponding to the D-MDD, we design the analytic model as an inverse function of the regression curve. The analytic model can accurately adjust the film gas-lens depth to control the MDD. Thus, we can achieve the accurate MDD control for PAL by utilizing the analytic model.

We evaluated carbon dioxide ($CO_2$), sulfur hexafluoride ($SF_6$), and helium (He) as the gas which has different density compared with the air in order to confirm the validity of the proposed method. As the results of the evaluation experiment, we confirmed the effectiveness of the proposed method.

## 2. CONVENTIONAL MAXIMUM DEMODULATION DISTANCE CONTROL BASED ON THE LINEAR APPROXIMATION WITH FILM GAS-LENS

We have proposed the MDD control based on the linear approximation with the film gas-lens as the conventional method. This method arranged the film gas-lens in front of the PAL as the container to enclose the gas. Figure 1 shows the overview of the conventional MDD control with film gas-lens for PAL. In Fig. 1, $l$ represents the distance between the PAL and the listener's head (D-MDD), $x'_{\mathrm{max}}$ represents the controlled MDD, $w$ represents the film gas-lens depth, $x_{\mathrm{gas}}$ represents the MDD when the AM wave transmits through only the gas layer whose density is different from the air, $x_{\mathrm{air}}$ represents the one when the AM wave transmits through only the air, and $\gamma$ represents the ratio of $w$ to $l$. Conventionally, the controlled MDD $x'_{\mathrm{max}}$ and the ratio $\gamma$ of $w$ to $l$ are derived as following linear approximation [7].

$$x'_{\mathrm{max}} = \gamma x_{\mathrm{gas}} + (1-\gamma)x_{\mathrm{air}}, \tag{7}$$

$$\gamma = \frac{w}{l}, \tag{8}$$

$$x_{\mathrm{gas}} = \frac{\rho_{\mathrm{gas}} c_{\mathrm{gas}}^3}{\beta \omega p_0}, \tag{9}$$

$$x_{\mathrm{air}} = \frac{\rho_{\mathrm{air}} c_{\mathrm{air}}^3}{\beta \omega p_0}, \tag{10}$$

where $\rho_{\mathrm{gas}}$ represents the density of the gas whose density is different from the air, $\rho_{\mathrm{air}}$ represents the density of the air, $c_{\mathrm{gas}}$ represents the sound speed in the gas whose density is different from the air, and $c_{\mathrm{air}}$ represents the sound speed in the air. The method selects the gas (the density of the gas $\rho_{\mathrm{gas}}$) and adjusts the film gas-lens depth $w$ to make the MDD $x'_{\mathrm{max}}$ equal to the D-MDD $l$. However, this method has a large numerical error on controlling the MDD because it employs a simple linear

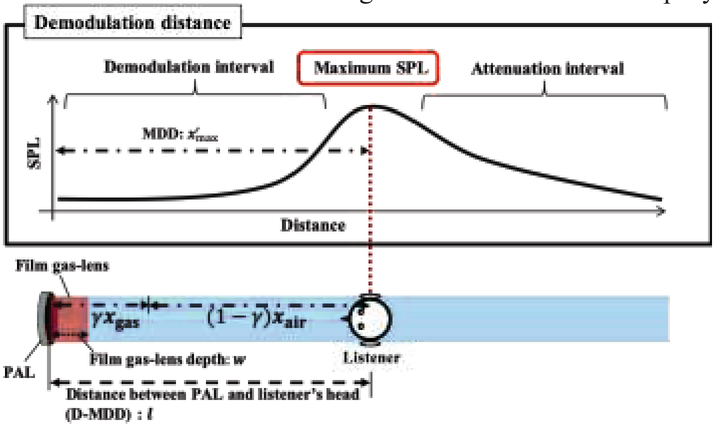


Figure 1 – Overview of the conventional MDD control based on the linear approximation with the film gas-lens for PAL.

approximation with the MDD and the film gas-lens depth as Eqs. (7) to (10). Therefore, it is difficult to accurately control the MDD to any listener's positions.

## 3. PROPOSAL OF MAXIMUM DEMODULATION CONTROL BASED ON ANALYTIC MODEL BETWEEN FILM GAS-LENS DEPTH AND DEMODULATION DISTANCE

### 3.1 Overview of the Proposed Method

We propose a new MDD control based on an analytic model between the film gas-lens depth and the observed MDD (O-MDD). Figure 2 shows the overview of the proposed MDD control based on the analytic model between the film gas-lens depth and the O-MDD. The method selects the gas (the density of the gas $\rho_{\mathrm{gas}}$) and adjusts the film gas-lens depth $w$ to make the MDD $x'_{\mathrm{max}}$ equal to the desired MDD (D-MDD) $l$ as the same in the conventional method. First, to design the analytic model, we investigate the O-MDD $x'_{\mathrm{max}}$ corresponding to the film gas-lens depth $w$ set at equal intervals and design a regression curve in each gas through the preliminary experiments. Details about calculating regression curve are described in the next subsection. Next, to calculate the appropriate film gas-lens depth $w$ corresponding to the D-MDD $l$, we design the analytic model as an inverse function of the regression curve. The analytic model can accurately adjust the film gas-lens depth $w$ to control the MDD $x'_{\mathrm{max}}$. Thus, we can achieve the accurate MDD control for PAL by utilizing the analytic model. As the results of the preliminary experiment, the regression curve of the O-MDD $x'_{\mathrm{max}}$ corresponding to the film gas-lens depth $w$ set at equal intervals is derived as follows using an exponential function.

$$x'_{\mathrm{max}} = x_{\mathrm{air}}\exp(\alpha w), \tag{11}$$

where $\alpha$ represents the fitting parameters of the regression curve in each gas, and it is determined analytically from preliminary experimental results. Next, to calculate the appropriate film gas-lens depth $w$ corresponding to the D-MDD $l$, we design the analytic model as an inverse function of the regression curve. From Eq. (11), O-MDD $x'_{\mathrm{max}}$ is replaced with D-MDD $l$, the analytic model as an inverse function of the regression curve is derived as follows:

$$w = \log \sqrt[\alpha]{\frac{l}{x_{\mathrm{air}}}}. \tag{12}$$

In addition, we can confirm the controlled MDD $x'_{\mathrm{max}}$ is equal to D-MDD $l$ by substituting the $w$ of Eq. (12) into Eq. (11). The controlled MDD $x'_{\mathrm{max}}$ is derived as follows:

$$x'_{\mathrm{max}} = x_{\mathrm{air}}\exp(\alpha w) = x_{\mathrm{air}}\exp\left(\alpha \log \sqrt[\alpha]{\frac{l}{x_{\mathrm{air}}}}\right) = l. \tag{13}$$

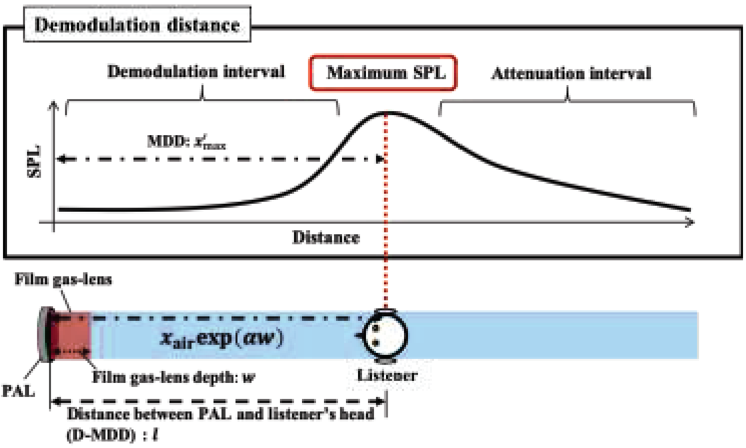


Figure 2 – Overview of the proposed MDD control based on the analytic model between the film gas-lens depth and the O-MDD.

From above, the proposed method can accurately adjust the film gas-lens depth $w$ to control the MDD $x'_{\max}$ to be equal to the D-MDD $l$. Thus, we can achieve the accurate MDD control for PAL by utilizing the analytic model.

## 3.2 Preliminary Experiment to Calculate the Regression Curve

### 3.2.1 Preliminary Experimental Conditions

Table 1 shows the experimental conditions in the preliminary experiment. In this experiment, we utilized $CO_2$, $SF_6$, and He as the gas which has different density compared with the air. Table 2 shows the experimental equipment and Table 3 shows the physical parameters of gases. We measured the SPL of the demodulated audible sound in the front direction of the PAL at each distance and calculated the O-MDD $x'_{\max}$. Figure 3 shows the experimental arrangement of the PAL and film gas-lens. In this preliminary experiment, we arranged the film gas-lens to enclose the gas in front of the PAL as shown in Fig. 3. The film gas-lens is constructed by the thin film about 2 $\mu$m and metallic frames. Besides, the film gas-lens depth $w$ can expand and contract flexibly. We confirmed that the SPL of the demodulated audible sound transmitted through the film gas-lens attenuated about 3 dB.

Table 1 – Experimental conditions.

| | |
|---|---|
| Ambient noise level | $L_A = 27.6$ dB |
| Sampling frequency | 192 kHz |
| Quantization bit rate | 32 bits |
| Sound source | TSP signal ($2^{19}$ points) |
| Evaluation frequency band | 0~10 kHz |
| Evaluation distance | 0, 0.30, and 0.50~3.50 m (0.25 m spacing) |
| Environment | Office room ($T_{60} = 400$ ms) |
| Film gas-lens depth $w$ | 0.05~0.30 m (0.05 m spacing) |
| O-MDD when transmits through only the air $x_{\mathrm{air}}$ | 1.00 m |

Table 2 – Experimental equipment.

| | |
|---|---|
| Parametric array loudspeaker | MITSUBISHI, MSP-50E |
| Microphone | SONY, ECM-88B |
| Microphone amplifier | THINKNET, MA-2016C |
| Power amplifier | VICTOR, PS-A2002 |
| A/D, D/A converter | RME, FIREFACE UFX |

Table 3 – Physical parameters of gases.

| Gas | Density | Sound speed |
|---|---|---|
| Air | 1.29 kg/m$^3$ | 340 m/s |
| $CO_2$ | 1.98 kg/m$^3$ | 260 m/s |
| $SF_6$ | 6.16 kg/m$^3$ | 134 m/s |
| He | 0.18 kg/m$^3$ | 970 m/s |

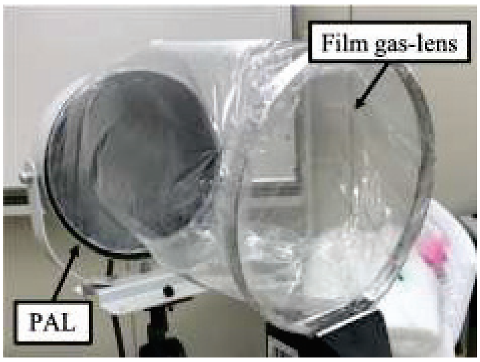
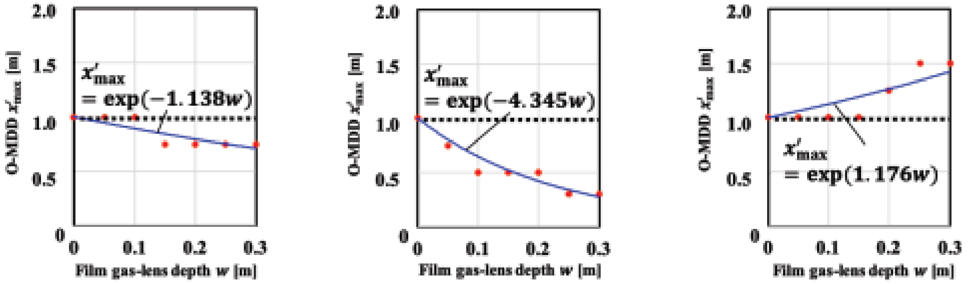


Figure 3 – Experimental arrangement of the PAL and the film gas-lens.

Table 4 – Fitting parameters $\alpha$ of the regression curve in each gas.

| Gas | Fitting parameter $\alpha$ |
|---|---|
| $CO_2$ | -1.138 |
| $SF_6$ | -4.345 |
| He | 1.176 |



(a) $CO_2$ (b) $SF_6$ (c) He

Figure 4 – O-MDD $x'_{max}$ corresponding to the film gas-lens depth $w$ set at equal intervals.

### 3.2.2 Preliminary Experimental Results

As the results of the preliminary experiment, Fig. 4 shows the O-MDD $x'_{max}$ corresponding to the film gas-lens depth $w$ set at equal intervals. In Fig. 4, the horizontal axis shows the film gas-lens depth $w$ and the vertical axis shows the O-MDD $x'_{max}$. In addition, Table 4 shows the fitting parameters $\alpha$ of the regression curve in each gas. As shown in Table 1 and Fig. 4, since the O-MDD when transmits through only the air $x_{air}$ was 1.00 m, the O-MDD $x'_{max}$ is 1.00 m in the case of the film gas-lens depth $w = 0$ m. As shown in Fig. 4 (a), (b), in the case of enclosing $CO_2$ or $SF_6$, gases whose density is higher than air, the O-MDD $x'_{max}$ decreases with the increase of the film gas-lens depth $w$. In addition, we can confirm that the O-MDD $x'_{max}$ changes more sharply in the case of enclosing $SF_6$ than that in the case of enclosing $CO_2$. This is because $SF_6$ has a larger density difference with air than $CO_2$. On the other hand, in the case of enclosing He, the gas whose density is lower than air, the O-MDD $x'_{max}$ increases with the increase of the film gas-lens depth $w$ as shown in Fig. 4 (c).

## 4. EVALUATION EXPERIMENT ON CONTROL OF MAXIMUM DEMODULATION DISTANCE

### 4.1 Experimental Conditions

In order to confirm the effectiveness of the proposed method, we conducted an evaluation experiment on control of the MDD. Table 5 shows the evaluation distance and Fig. 5 shows the experimental environment for the measuring the sound pressure distributions. We measured the SPL of the demodulated audible sound at the 94 microphone positions as shown in Fig. 5. In this experiment, we evaluated at 0.125 m spacing in the range of 0.5~1.5 m in order to confirm the detailed MDD change as shown in Table 5 and Fig. 5. In addition, in order to confirm the reproducibility, the number of trials was set to 5. Other experimental conditions and equipment are the same as in Tables 1, 2. Table 6 shows the gas and film gas-lens depth $w$ corresponding the D-MDD $l$ calculated from Eq. (12). We enclosed the gas and adjusted the film gas-lens depth $w$ in each condition in Table 6. We calculate the average distance error (ADE) between the D-MDD $l$ and the O-MDD $x'_{max}$ in each condition in Table 6 and evaluated whether the O-MDD $x'_{max}$ could be controlled to the D-MDD $l$. ADE is derived as follows:

$$\mathrm{ADE} = \frac{1}{T}\sum_{i=1}^{T}\left|x'_{\max,i} - l\right|, \tag{14}$$

where $T$ represents the number of trials, $x'_{\max,i}$ represents the $i$ th O-MDD. In addition, we calculated the radiation angle from observed sound pressure distribution in each condition and evaluated the change of radiation characteristics. The radiation angle is defined as the angle to the

Table 5 – Evaluation distance in the evaluation experiment on control of the MDD.

| | |
|---|---|
| Evaluation distance | 0, 0.30, 0.50~1.50 m (0.125 m spacing), and 1.50~3.50 m (0.25 m spacing) |

Table 6 – Gas and film gas-lens depth $w$ corresponding the D-MDD $l$.

| D-MDD $l$ | Gas | Film gas-lens depth $w$ |
|---|---|---|
| 0.500 m | $SF_6$ | 0.16 m |
| 0.625 m | $SF_6$ | 0.11 m |
| 0.750 m | $CO_2$ | 0.25 m |
| 0.875 m | $CO_2$ | 0.12 m |
| 1.125 m | He | 0.10 m |
| 1.250 m | He | 0.19 m |
| 1.375 m | He | 0.27 m |
| 1.500 m | He | 0.34 m |

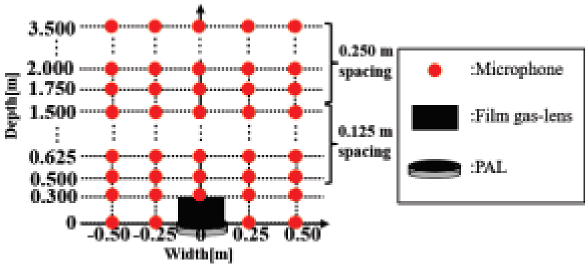


Figure 5 – Experimental environment for measuring the sound pressure distributions.

point at which the SPL of the demodulated audible sound is attenuated by 6 dB in the lateral direction based on a point 1.00 m from the front of the PAL.

## 4.2 Experimental Results

As the results of this experiment, Fig. 6 shows the ADE between the D-MDD $l$ and the O-MDD $x'_{\max}$ in each condition. In Fig. 6, the horizontal axis shows the error between the D-MDD $l$ and the O-MDD $x'_{\max}$ and the vertical axis shows the D-MDD $l$. From Fig. 6, we confirmed that the proposed method can control the MDD with an error within 0.047 m on average. We also confirmed that the variance was 0 and it is reproducible. Figure 7 shows the estimated MDD of the conventional and proposed methods. In Fig. 7, the horizontal axis shows the MDD and the vertical axis shows the D-MDD $l$. The average error between estimated MDD and O-MDD $x'_{\max}$ was 0.432 m in the conventional method and 0.047 m in the proposed method. From these results, we confirmed that the proposed method can control the MDD more accurately than the conventional method.

Figure 8 shows the sound pressure distributions in each condition. As shown in Fig. 8, we confirmed that the high SPL was obtained near the D-MDD $l$ in each condition. Table 7 shows the radiation angles in each condition. As shown in Table 7, in the case of enclosing $CO_2$ or $SF_6$, gases whose density is higher than air, we confirmed that the radiation angle spread compared to the one in the case of the AM wave transmits through only the air. Besides, we confirmed that the radiation angle in the case of enclosing $SF_6$ spread larger than that in the case of enclosing $CO_2$. This is because $SF_6$ has a larger density difference with air than $CO_2$. However, this spread of the radiation angle barely affects the performance of the PAL in practical use. Furthermore, we confirmed that the radiation angle spread with the increase of the film gas-lens depth $w$ in the case of enclosing $CO_2$ and $SF_6$. Similarly, the radiation angle narrowed down with the increase of the film gas-lens depth $w$ in the case of enclosing He. From these results, we confirmed that the influence of the gas increased with the increase of the film gas-lens depth $w$. Thus, we confirmed that the proposed method can control the MDD to be equal to any listener’s positions.

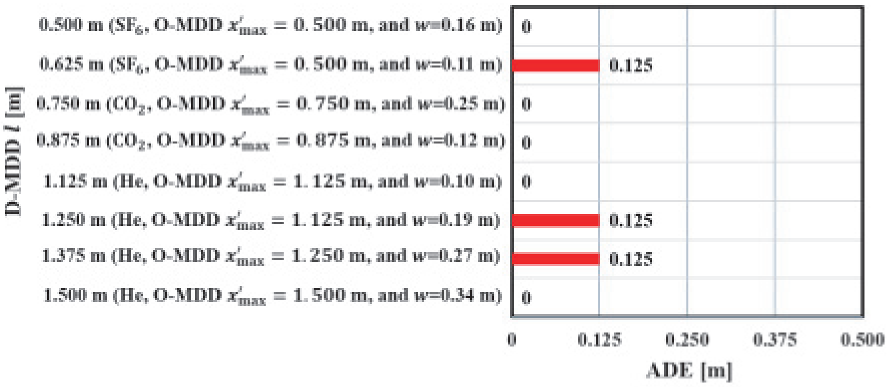


Figure 6 – Experimental results for ADE between the D-MDD $l$ and the O-MDD $x'_{\max}$ in each condition.

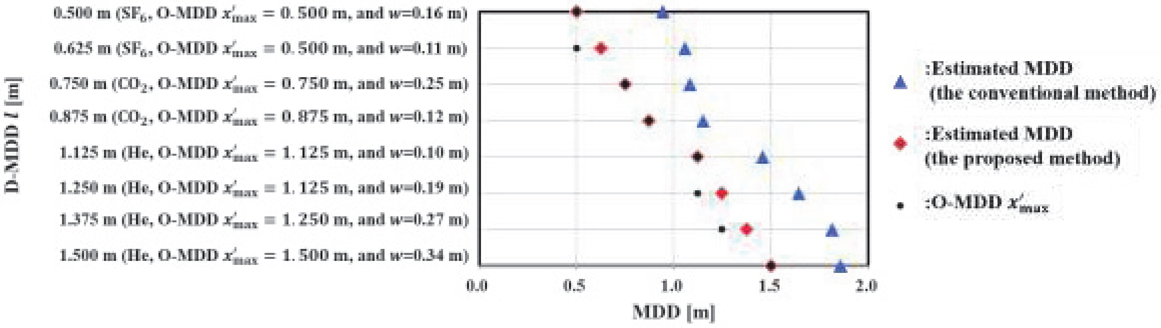
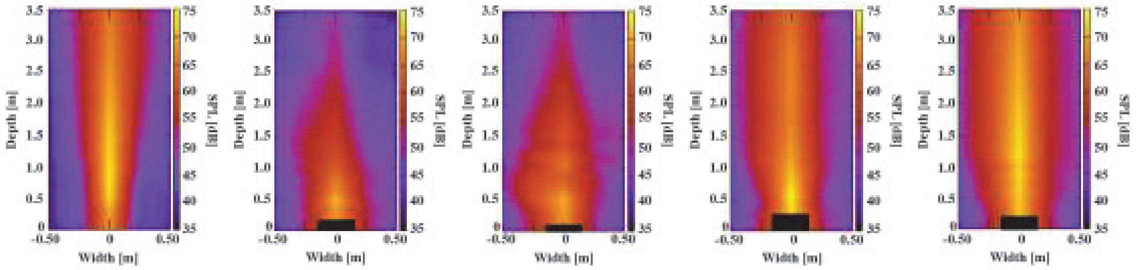


Figure 7 – Estimated MDD of the conventional and proposed methods.



(a) Air

($x_{\text{air}}$=1.000 m)

(b) SF$_6$

(D-MDD $l$=0.500 m, O-MDD $x'_{\max}$=0.500 m, and $w$=0.16 m)

(c) SF$_6$

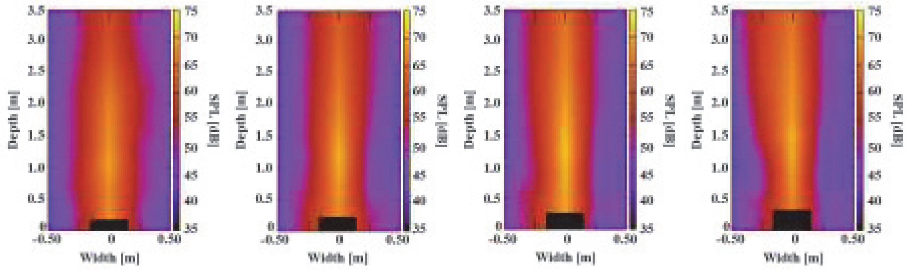
(D-MDD $l$=0.625 m, O-MDD $x'_{\max}$=0.500 m, and $w$=0.11 m)

(d) CO$_2$

(D-MDD $l$=0.750 m, O-MDD $x'_{\max}$=0.750 m, and $w$=0.25 m)

(e) CO$_2$

(D-MDD $l$=0.875 m, O-MDD $x'_{\max}$=0.875 m, and $w$=0.12 m)



(f) He

(D-MDD $l$=1.125 m, O-MDD $x'_{\max}$=1.125 m, and $w$=0.10 m)

(g) He

(D-MDD $l$=1.250 m, O-MDD $x'_{\max}$=1.250 m, and $w$=0.19 m)

(h) He

(D-MDD $l$=1.375 m, O-MDD $x'_{\max}$=1.250 m, and $w$=0.27 m)

(i) He

(D-MDD $l$=1500 m, O-MDD $x'_{\max}$=1.500 m, and $w$=0.34 m)

Figure 8 – Experimental results for sound pressure distributions in each condition.

Table 7 – Experimental results for radiation angles in each condition.

| Gas | Radiation angle |
|---|---|
| Air ($x_{\text{air}}$=1.000 m) | 3.26 deg. |
| $SF_6$ (D-MDD $l$=0.500 m, O-MDD $x'_{\max}$=0.500 m, and $w$=0.16 m) | 9.92 deg. |
| $SF_6$ (D-MDD $l$=0.625 m, O-MDD $x'_{\max}$=0.500 m, and $w$=0.11 m) | 9.67 deg. |
| $CO_2$ (D-MDD $l$=0.750 m, O-MDD $x'_{\max}$=0.750 m, and $w$=0.25 m) | 6.39 deg. |
| $CO_2$ (D-MDD $l$=0.875 m, O-MDD $x'_{\max}$=0.875 m, and $w$=0.12 m) | 5.88 deg. |
| He (D-MDD $l$=1.125 m, O-MDD $x'_{\max}$=1.125 m, and $w$=0.10 m) | 4.87 deg. |
| He (D-MDD $l$=1.250 m, O-MDD $x'_{\max}$=1.250 m, and $w$=0.19 m) | 3.99 deg. |
| He (D-MDD $l$=1.375 m, O-MDD $x'_{\max}$=1.250 m, and $w$=0.27 m) | 3.73 deg. |
| He (D-MDD $l$=1500 m, O-MDD $x'_{\max}$=1.500 m, and $w$=0.34 m) | 3.62 deg. |

## 5. CONCLUSIONS

In this paper, we proposed a new MDD control based on an analytic model between the film gas-lens depth and the O-MDD for PAL. First, to design the analytic model, we investigate the O-MDD corresponding to the film gas-lens depth set at equal intervals and design a regression curve in each gas through the preliminary experiments. Next, to calculate the appropriate film gas-lens depth corresponding to the D-MDD, we design the analytic model as an inverse function of the regression curve. The analytic model can accurately adjust the film gas-lens depth to control the MDD. Thus, we can achieve the accurate MDD control for PAL by utilizing the analytic model. It becomes able to transmit the audible sound with maximum SPL to the listener at any points. As the results of the evaluation experiment, we confirmed the effectiveness of the proposed method and the proposed method can control the MDD more accurately than the conventional method. In future work, we will attempt to the MDD control by temperature or humidity.

## ACKNOWLEDGEMENTS

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