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Amplitude Matching for Multizone Sound Field Control

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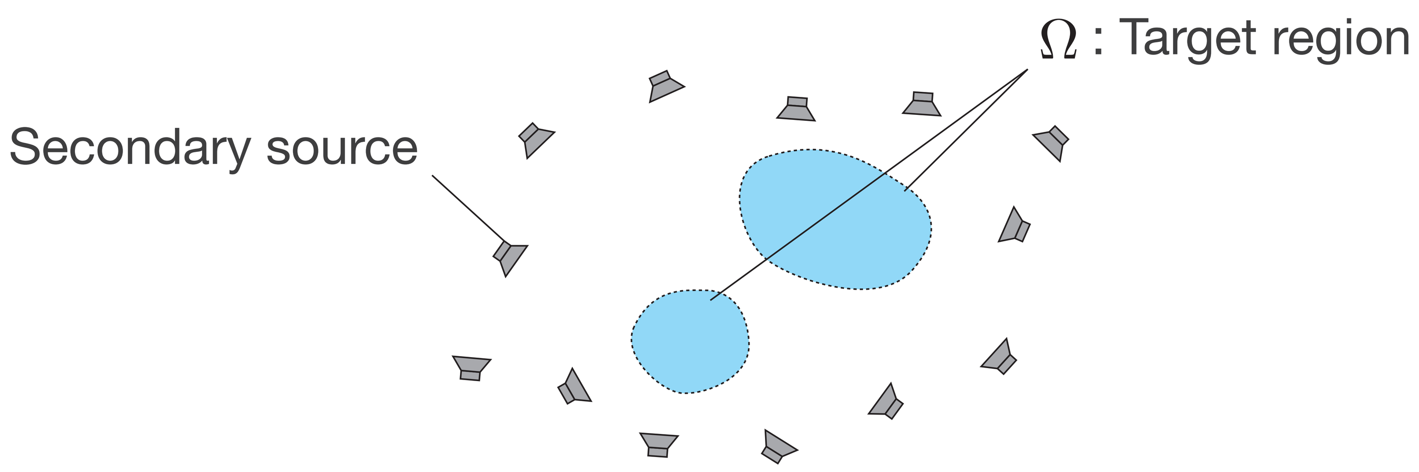
Abstract

▶ **Mutizone sound field control method based on amplitude matching**

- Generating independent sound zones using multiple loudspeakers for personal audio systems
- Amplitude matching aims to synthesize amplitude (or magnitude) distribution over target region, leaving phase distribution arbitrary
- Differential-norm penalty for inducing continuities of phase between frequency bins for time-domain filter design
- Algorithm based on algternating direction method of multipliers (ADMM) is derived
- Desired amplitude distribution is accurately and efficiently synthesized, compared with current methods

Problem Statement and Prior Work



Synthesizing desired sound field $u_{\mathrm{des}}(\boldsymbol{r},\omega)$ inside Ω with L secondary sources (loudspeakers)

$$\underset{\{d_l\}_{l=1}^{L}}{\text{minimize}}\ J := \int_\Omega \left| \sum_{l=1}^{L} d_l g_l(\boldsymbol{r}) - u_{\mathrm{des}}(\boldsymbol{r}) \right|^2 \mathrm{d}\boldsymbol{r}$$

l th driving signal; l th transfer function

▶ **Pressure Matching (PM)**

- Discretizing target region into control points
- Desired pressures (amplitude and phase) are synthesized at control points
- Closed-form solution by (regularized) least-squares

➡ Practical feasibility depends on the setting of desired phase distribution

▶ **Acoustic Contrast Control (ACC)**

- Aimed at generating regions of high- and low-acoustic potential energy
- Ratio of acoustic potential energy in one region to that in the other region is maximized
- Solved as generalized eigen value problem

➡ Power distribution inside the target region cannot be controlled, and flat amplitude response cannot be guaranteed

Amplitude Matching

Synthesizing desired amplitude (or magnitude) distribution inside target region, leaving the phase distribution arbitrary

- Setting M control points over Ω
- Cost function for PM

$$\underset{\boldsymbol{d}\in\mathbb{C}^L}{\text{minimize}}\ \|\boldsymbol{G}\boldsymbol{d} - \boldsymbol{u}^{\mathrm{des}}\|^2 + \gamma\|\boldsymbol{d}\|^2 \quad \Rightarrow \quad \hat{\boldsymbol{d}} = \left(\boldsymbol{G}^{\mathsf{H}}\boldsymbol{G} + \gamma\boldsymbol{I}\right)^{-1}\boldsymbol{G}^{\mathsf{H}}\boldsymbol{u}^{\mathrm{des}}$$

Least-squares solution

- Cost function for **Amplitude Matching**

$$\underset{\boldsymbol{d}\in\mathbb{C}^L}{\text{minimize}}\ \||\boldsymbol{G}\boldsymbol{d}| - |\boldsymbol{u}^{\mathrm{des}}|\|^2 + \lambda\|\boldsymbol{d}\|^2$$

Desired magnitude is synthesized at control points

Element-wise absolute value

➡ No closed-form solution owing to nonconvexity and indifferentiability

▶ **Algorithm**

- Gradient methods, e.g., gradient descent and (quasi-)Newton's method
- Majorization-minimization (MM) algorithm [Koyama+ ICASSP 2021]
- **Alternating direction method of multipliers (ADMM)**

Differential-Norm Penalty for Time-Domain Filter Design

▶ **Broadband cost function with ℓ_2-norm penalty**

$$\underset{\{\boldsymbol{d}_k\}_{k=1}^{K}}{\text{minimize}} \sum_{k=1}^{K} \||\boldsymbol{G}_k\boldsymbol{d}_k| - |\boldsymbol{u}^{\mathrm{des}}|\|^2 + \lambda\sum_{k=1}^{K}\|\boldsymbol{d}_k\|^2$$

K: # of frequency bins

➡ Discontinuities between frequency bins

▶ **Broadband cost function with differential-norm penalty**

$$\underset{\{\boldsymbol{d}_k\}_{k=1}^{K}}{\text{minimize}} \sum_{k=1}^{K} \||\boldsymbol{G}_k\boldsymbol{d}_k| - |\boldsymbol{u}^{\mathrm{des}}|\|^2 + \lambda D(\boldsymbol{d}_k)$$

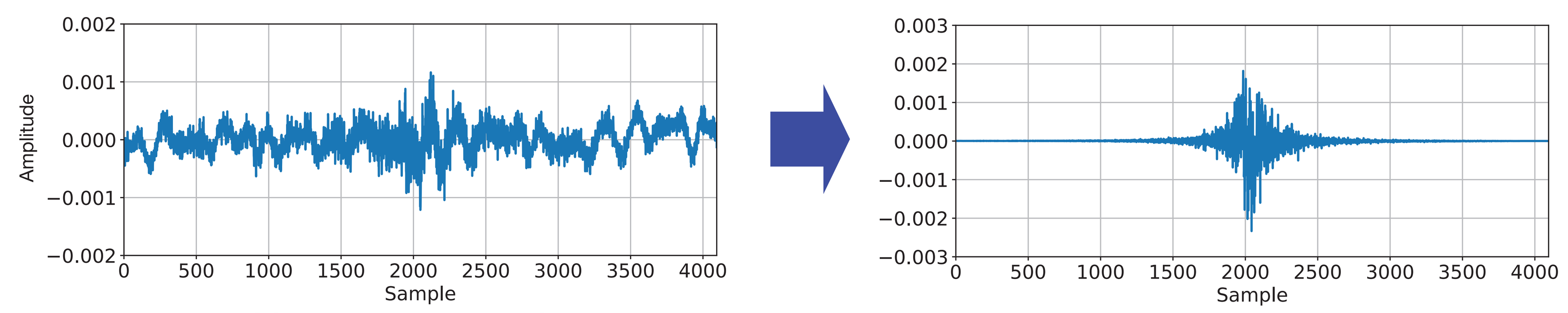
$$D(\boldsymbol{d}_k) := \sum_{k=2}^{K}\|\boldsymbol{d}_k - \boldsymbol{d}_{k-1}\|^2$$

Differential-norm penalty to induce smoothness between frequency bins

- ADMM is still applicable to solve this optimization problem
- Computational complexities can be reduced by using the properties of block tridiagonal matrix
- AM in broadband can be achieved by relatively short time-domain filter

▶ **Example**

- Impulse responses measured in real environment (MeshRIR [Koyama+ WASPAA 2021]) is used

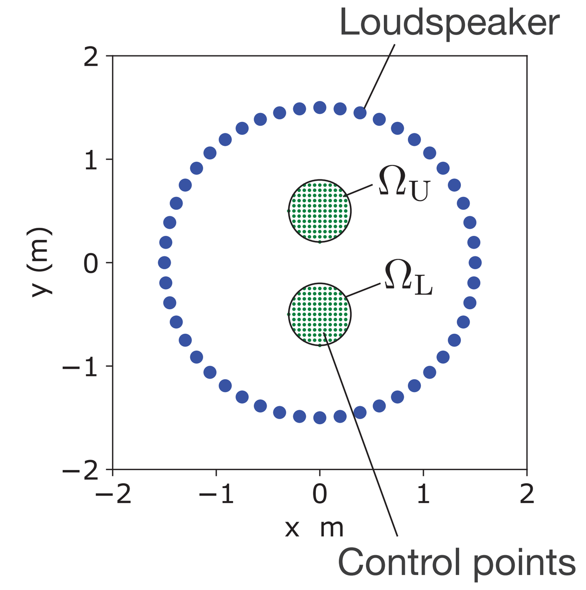


l2-norm penalty   Diff.-norm penalty

Experiments

▶ **2D free field simulation**

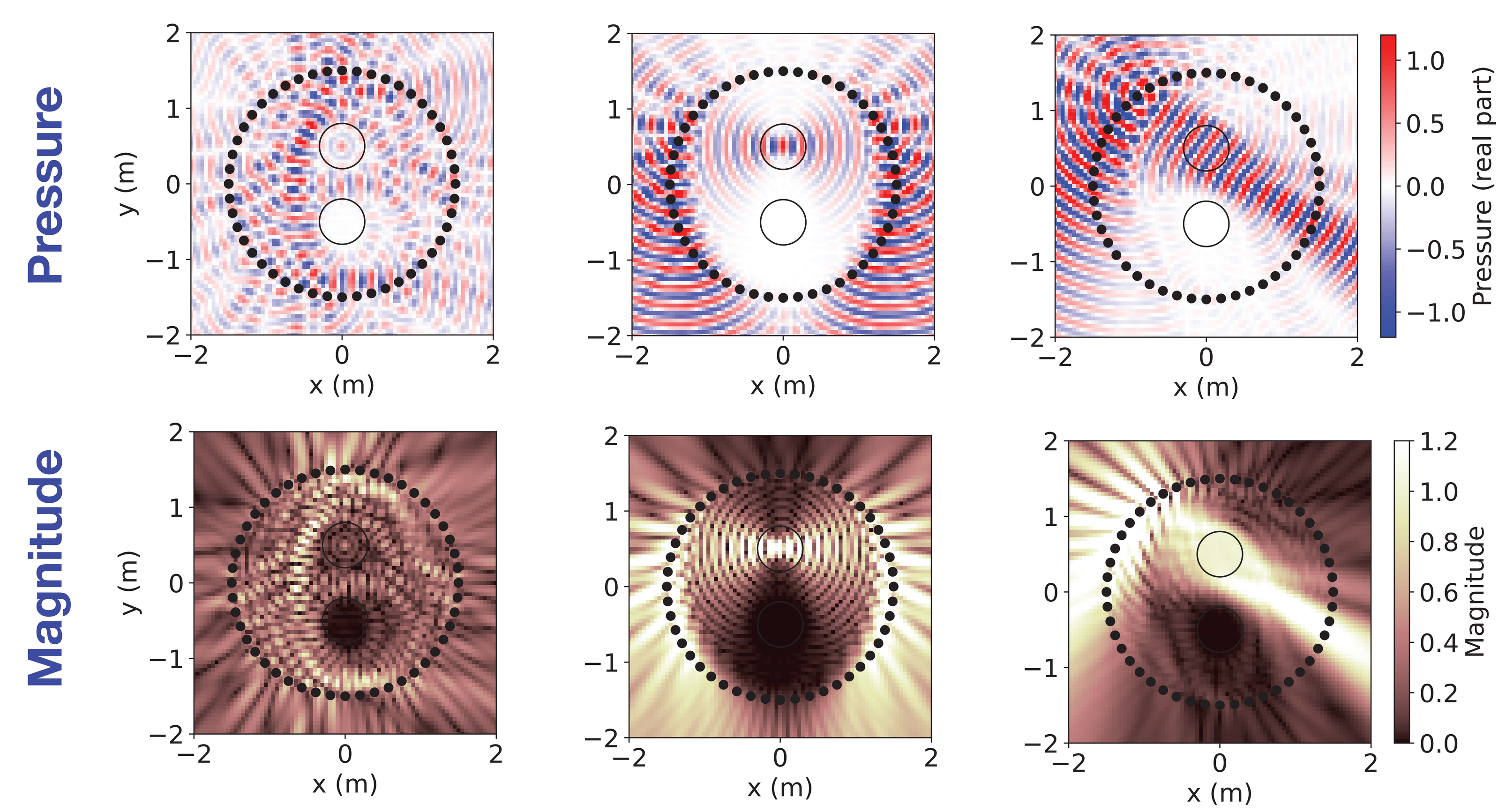
- Circular array of 48 loudspeakers
- Two circular target regions with 111 control points
- Desired amplitude is 1 in Ω_{U} (Bright zone) and 0 in Ω_{L} (Dark zone)
- Frequency: 1400 Hz
- Evaluation measure:



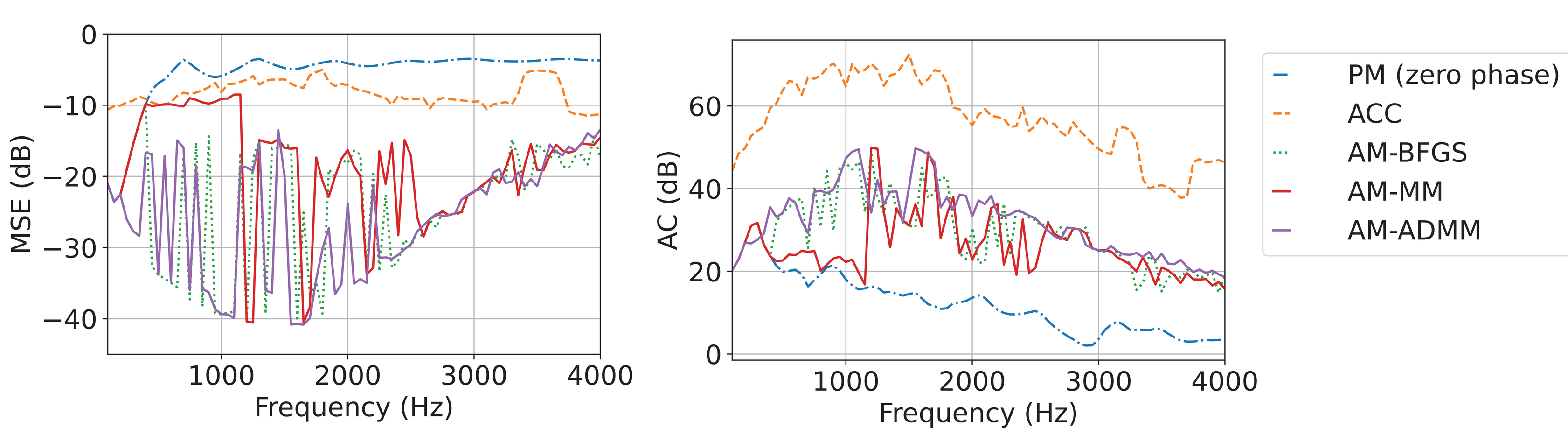
$$\mathrm{MSE}(\omega) = 10\log_{10}\left(\frac{1}{M}\||\boldsymbol{u}^{\mathrm{syn}}(\omega)| - |\boldsymbol{u}^{\mathrm{des}}(\omega)|\|^2\right)$$

$$\mathrm{AC}(\omega) = 10\log_{10}\frac{\|\boldsymbol{u}^{\mathrm{syn}}_{\Omega_{\mathrm{U}}}(\omega)\|^2}{\|\boldsymbol{u}^{\mathrm{syn}}_{\Omega_{\mathrm{L}}}(\omega)\|^2}$$

Synthesized pressure at control points



PM (zero phase)	ACC	AM-ADMM
MSE: -4.2 dB	MSE: -6.4 dB	MSE: -36.4 dB
AC: 14.5 dB	AC: 67.9 dB	AC: 39.3 dB



Paper **Code** **Demo**

T. Abe, S. Koyama, N. Ueno, and H. Saruwatari, "Amplitude Matching for Multizone Sound Field Control," *IEEE/ACM Trans. Audio, Speech, and Language Processing*, vol. 31, 2023.