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Spatial Active Noise Control Method Based on Sound Field Interpolation From Reference Microphone Signals

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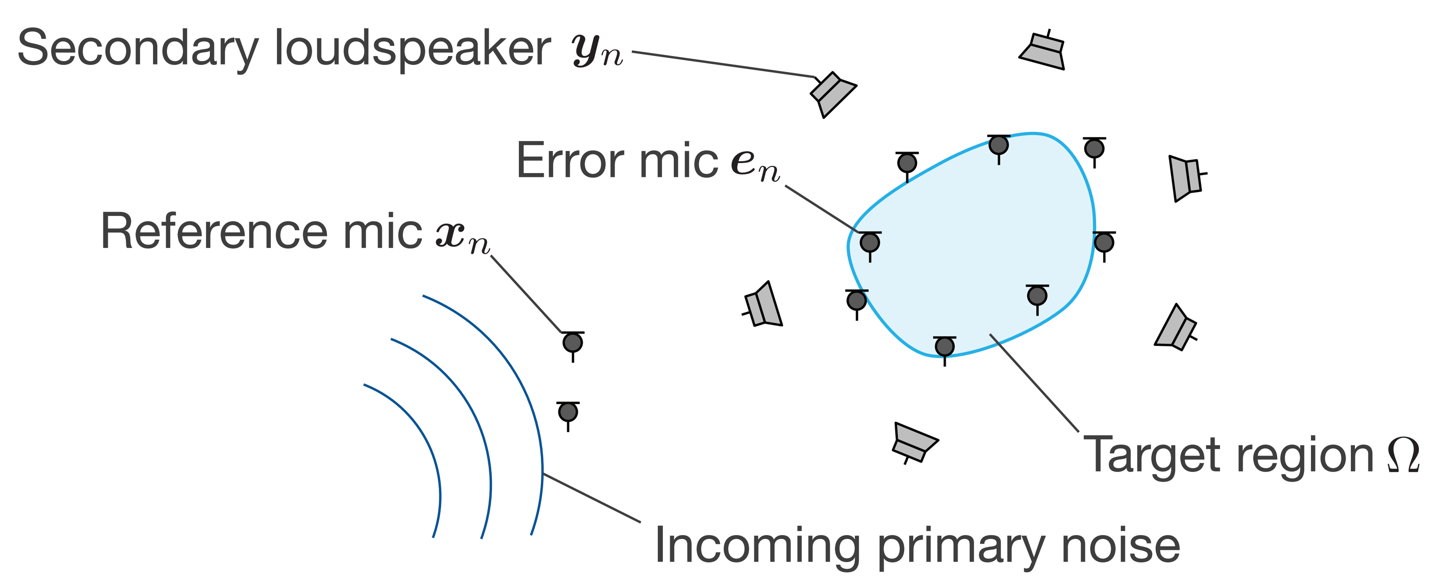
Abstract

▸ **Spatial ANC based on kernel interpolation of sound field from reference mics**

- Most current spatial ANC methods are based on sound field estimation from error mics, but small number of error mics is preferable to keep a spce for ANC users
- The proposed method is based on sound field interpolation from reference mics, which are normally placed outside the target region
- Two approaches:
  1. Fixed filter minimizing potential energy of estimated sound field
  2. NLMS algorithm for transitioning from fixed filter to control filter of multichannel NLMS
- Achieved large noise reduction over target region by NLMS with fixed filter, compared with conventional NLMS

Problem Statement and Prior Work



Cost function in conventional ANC

$$J_{\mathrm{e}} = \mathbb{E}\left[\|\boldsymbol{e}_n\|_2^2\right]$$: Power of error mics

Cost function in spatial ANC

$$J_{\mathrm{PE}} = \mathbb{E}\left[\int_\Omega |u_{\mathrm{e}}(\boldsymbol{r},n)|^2 \mathrm{d}\boldsymbol{r}\right]$$: Regional noise power

Pressure field in Ω

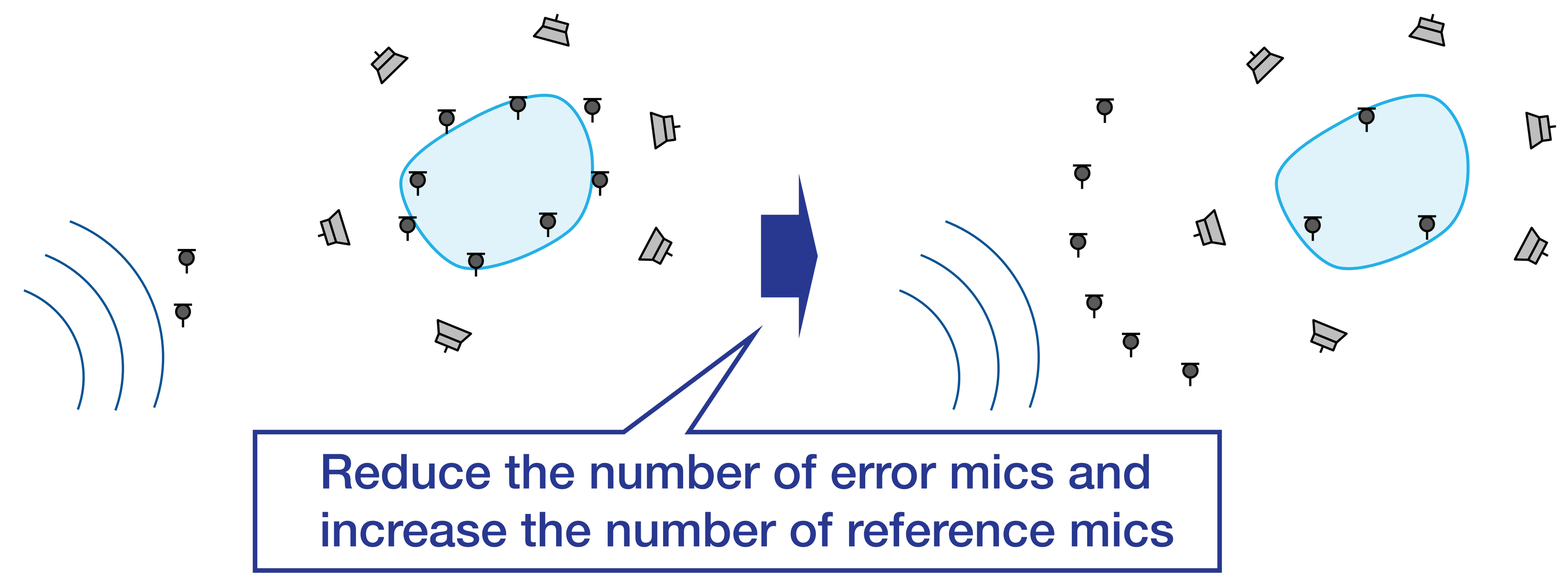
▸ **Kernel-interpolation-based spatial ANC** [Ito+ 2019, Koyama+ 2021]

- Cost function of regional noise power is estimated by kernel interpolation of sound field to obtain optimal filter $\boldsymbol{W}_n$ ($\boldsymbol{y}_n = \boldsymbol{W}_n \boldsymbol{x}_n$)
- Higher level of regional noise reduction than conventional multichannel ANC

Spatial ANC Based on Interpolation From Reference Mics

How can we reduce error mics to keep a space in target region?

➡ **Kernel interpolation of sound field from reference mics instead of error mics**



▸ **Fixed filter based on kernel interpolation**

- Sound field is estimated as

$$u_{\mathrm{e}}(\boldsymbol{r},n) = u_{\mathrm{p}}(\boldsymbol{r},n) + u_{\mathrm{s}}(\boldsymbol{r},n)$$
$$= \boldsymbol{\kappa}(\boldsymbol{r})^{\mathsf{T}}\left[(\boldsymbol{K}+\lambda\boldsymbol{I})^{-1}\right]\boldsymbol{x}_n + \left[G(\boldsymbol{r},\boldsymbol{r}_1)\dots,G(\boldsymbol{r},\boldsymbol{r}_L)\right]\boldsymbol{y}_n$$

$\boldsymbol{z}_x(\boldsymbol{r})^{\mathsf{T}}$: Kernel interpolation filter $\boldsymbol{\zeta}_y(\boldsymbol{r})^{\mathsf{T}}$: Free-field Green's functions

Here, $\boldsymbol{\kappa}(\boldsymbol{r})$ and $\boldsymbol{K}$ are vector and matrix consisting of kernel functions that constrain the interpolated function with the solution of Helmholtz eq [Ueno+ 2018, 2021]

- Fixed filter minimizing the cost function is obtained as

$$\frac{J_{\mathrm{PE}}}{\partial \boldsymbol{W}_n} \simeq (\boldsymbol{A}_{yy}\boldsymbol{W}_n + \boldsymbol{A}_{yx})\boldsymbol{x}_n\boldsymbol{x}_n^{\mathsf{H}}$$

$$\left(\begin{aligned}\boldsymbol{A}_{yy} &:= \int_\Omega \boldsymbol{\zeta}_y(\boldsymbol{r})^*\boldsymbol{\zeta}_y(\boldsymbol{r})^{\mathsf{T}}\mathrm{d}\boldsymbol{r}\\ \boldsymbol{A}_{yx} &:= \int_\Omega \boldsymbol{\zeta}_y(\boldsymbol{r})^*\boldsymbol{z}_x(\boldsymbol{r})^{\mathsf{T}}\mathrm{d}\boldsymbol{r}\end{aligned}\right)$$

➡ $$\boldsymbol{W}_{\mathrm{fixed}} = -\boldsymbol{A}_{yy}^{-1}\boldsymbol{A}_{yx}$$

Error mics are not necessary

▸ **NLMS algorithm transitioning from fixed filter**

- Cost function of time-varying weighted sum of J_{PE} and J_{e} to compensate the estimation error of sound field

$$J_{\mathrm{trans},n} = \gamma^n J_{\mathrm{PE}} + \|\boldsymbol{e}_n\|_2^2$$

Forgetting factor $\gamma \in (0,1)$

- NLMS algorithm transitioning from fixed filter is obtained as

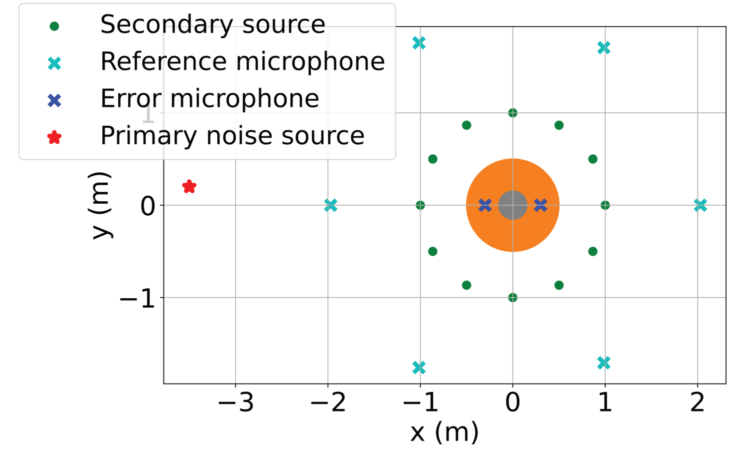
$$\boldsymbol{W}_{n+1} = \boldsymbol{W}_n - \mu_n \frac{\partial J_{\mathrm{trans},n}}{\partial \boldsymbol{W}_n^*}$$
$$= \boldsymbol{W}_n - \mu_n\left[\gamma^n(\boldsymbol{A}_{yy}\boldsymbol{y}_n + \boldsymbol{A}_{yx}\boldsymbol{x}_n) + \boldsymbol{G}^{\mathsf{H}}\boldsymbol{e}_n\right]\boldsymbol{x}_n^{\mathsf{H}}$$

Transitioning from $\boldsymbol{W}_{\mathrm{fixed}}$ to control filter of multichannel NLMS

Experiments

▸ **2D free field simulation**

- Circular target region of radius 0.5 m
- Rigid circular object of radius 0.15 m
- 12 secondary loudspeakers
- 2 error mics
- 6 reference mics

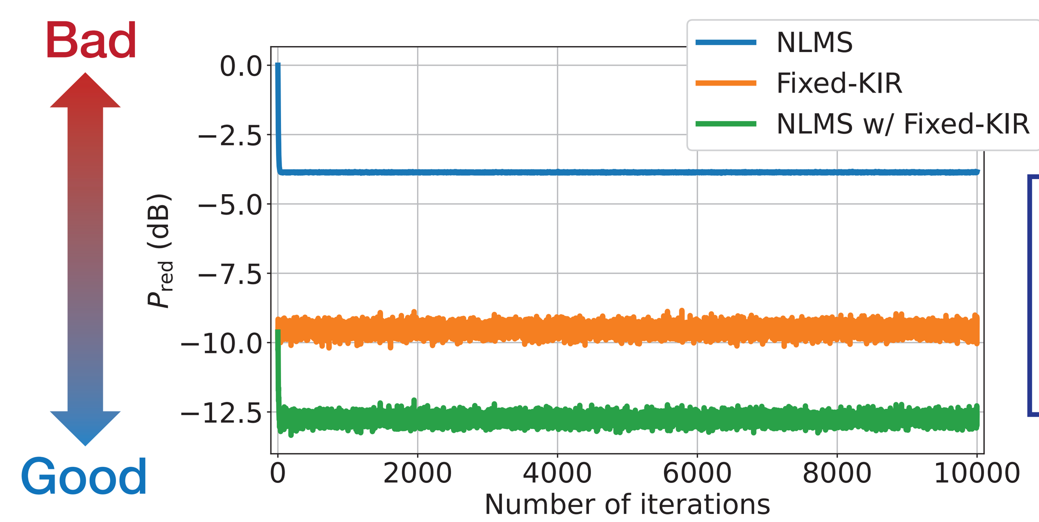


- Comparison
  - Conventional NLMS (**NLMS**)
  - Proposed fixed filter (**Fixed-KIR**)
  - Proposed NLMS transitioning from Fixed-KIR (**NLMS w/ Fixed-KIR**)
- Evaluation measure
  - Regional noise reduction over target region

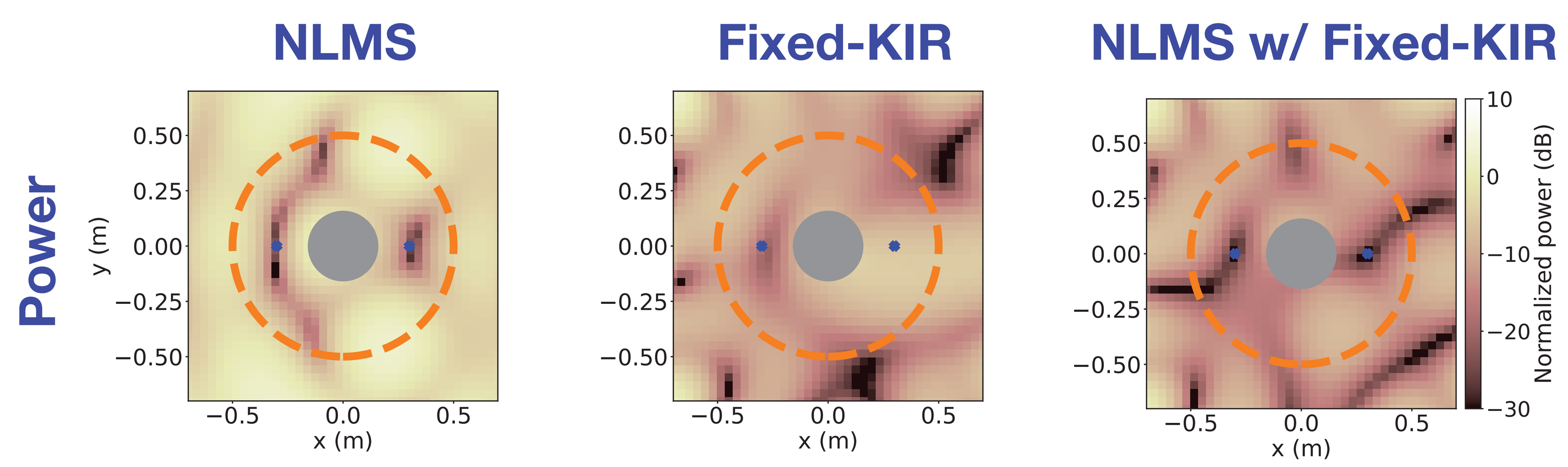
$$P_{\mathrm{red}}(n) := 10\log_{10}\frac{\sum_j |u_{\mathrm{e}}^{(n)}(\boldsymbol{r}_j)|^2}{\sum_j |u_{\mathrm{p}}^{(n)}(\boldsymbol{r}_j)|^2}$$

Primary noise field

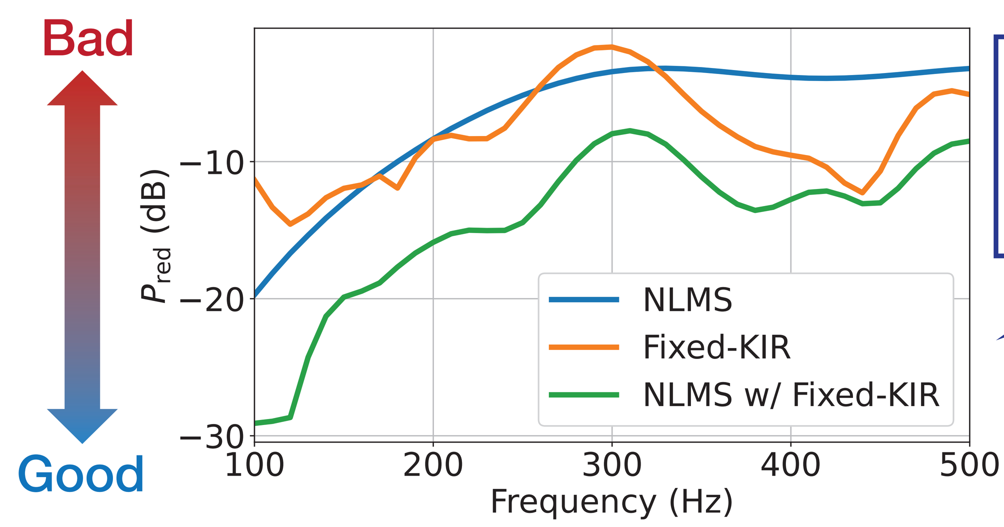
▸ **Regional noise power reduction at 400 Hz**



Noise reduction over the target region is achived by the proposed methods



▸ **Frequency vs. regional noise power reduction**



NLMS w/ Fixed-KIR achieved the largest noise reduction at all frequencies

S. Koyama, J. Brunnström, H. Ito, N. Ueno, and H. Saruwatari, "Spatial Active Noise Control Based on Kernel Interpolation of Sound Field," *IEEE/ACM Trans. Audio, Speech, and Language Processing*, vol. 29, 2021.