AUD-37.2

Spatial Active Noise Control Based on Individual Kernel Interpolation of Primary and Secondary Sound Fields

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Abstract

Spatial ANC

- Approach to reduce noise in space
- Conventional ANC aims at reducing noise at discrete points, while Spatial ANC aims at reducing noise in continuous target region

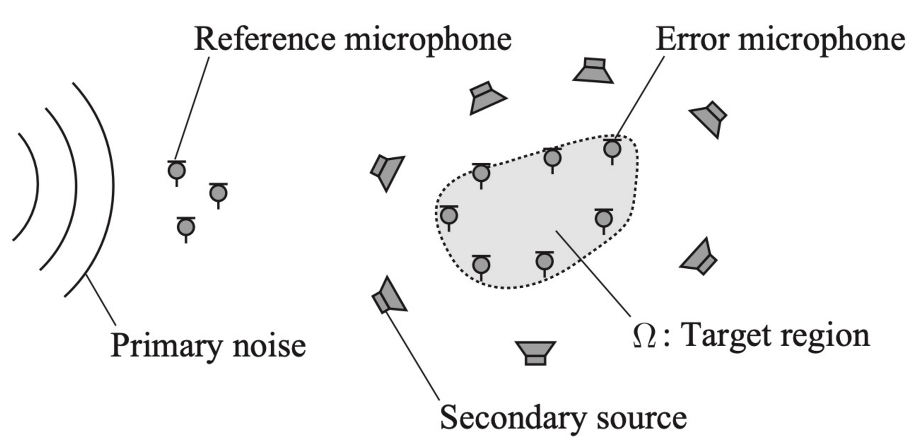
Spatial ANC based on kernel interpolation [1 - 3]

- Interpolate sound field from error mic signals using kernel ridge regression, and define cost function as regional square integral of sound field
- Apply a single kernel function to interpolate superposition of primary and secondary sound fields

This paper

- Primary and secondary sound fields are interpolated individually
- Interpolation accuracy can be improved by using kernel functions weighted on directions of primary noise and each loudspeaker
- NLMS algorithm based on individual kernel interpolation is derived, and numerical experiments verified that better noise reduction is achieved than previous methods

Problem Formulation of Spatial ANC in freq domain



Error mic signals:

$$\boldsymbol{e} = \boldsymbol{d} + \boldsymbol{G}\boldsymbol{y}$$

Noise signals — Transfer func matrix

Loudspeaker signals:

$$\boldsymbol{y} = \boldsymbol{W}\boldsymbol{x}$$

Adaptive filter matrix — Ref mic signals

Update adaptive filter using gradient method (LMS algorithm)

$$\boldsymbol{W}(n+1) = \boldsymbol{W}(n) - \mu \frac{\partial}{\partial \boldsymbol{W}^*(n)} J(n) \qquad (1)$$

Iteration step — Cost function for ANC

Kernel interpolation of sound field

- Estimate sound field by kernel ridge regression:

$$u_e(\boldsymbol{r}) = \left[\left((\boldsymbol{K} + \lambda \boldsymbol{I}_M)^{-1} \right)^{\top} \boldsymbol{\kappa}(\boldsymbol{r}) \right]^{\top} \boldsymbol{e} = \boldsymbol{z}_e(\boldsymbol{r})^{\top} \boldsymbol{e}$$

$$\left[(\boldsymbol{K})_{mm'} = \kappa(\boldsymbol{r}_m, \boldsymbol{r}_{m'}), (\boldsymbol{\kappa}(\boldsymbol{r}))_m = \kappa(\boldsymbol{r}, \boldsymbol{r}_m) \right]$$

Kernel function with directional weighting [2]

- Kernel function to estimate sound field is defined as:

$$\kappa(\boldsymbol{r}, \boldsymbol{r}') = j_0 \left(\sqrt{(\mathrm{j}\beta\boldsymbol{\eta} - k(\boldsymbol{r}' - \boldsymbol{r}))^{\top} (\mathrm{j}\beta\boldsymbol{\eta} - k(\boldsymbol{r}' - \boldsymbol{r}))} \right)$$

Wave number — Sharpness parameter — Arrival direction of noise

- By using this kernel function, interpolated sound field $u_e(\boldsymbol{r})$ is guaranteed to satisfy Helmholtz equation
- If noise source direction is known in advance, by appropriately setting parameter β, interpolation accuracy can be improved compared to using no directional weighting ($\beta = 0$)

Spatial ANC based on Individual kernel interpolation

Issue of directional weighting on noise source direction

- Sound field in target region $u_e(\boldsymbol{r})$ is superposition of primary noise field $u_p(\boldsymbol{r})$ and secondary source field $u_s(\boldsymbol{r})$

$$\hat{u}_e(\boldsymbol{r}) = \boldsymbol{z}_e(\boldsymbol{r})^{\top} \boldsymbol{e}$$
$$= \underbrace{\boldsymbol{z}_e(\boldsymbol{r})^{\top} \boldsymbol{d}}_{u_p(\boldsymbol{r})} + \underbrace{\boldsymbol{z}_e(\boldsymbol{r})^{\top} \boldsymbol{G}\boldsymbol{y}}_{u_s(\boldsymbol{r})}$$

Weighted on primary noise direction

- Secondary source field is interpolated with directional weighting on primary noise direction, which limits interpolation accuracy

Individual kernel interpolation

(Step 1) Estimate primary noise component from error mic signals

$$\hat{\boldsymbol{d}} = \boldsymbol{e} - \boldsymbol{G}\boldsymbol{y}$$

(Step 2) Interpolate primary noise and secondary source fields individually using directionally weighted kernel func

$$u_p(\boldsymbol{r}) = \boldsymbol{z}_d(\boldsymbol{r})^{\top} \hat{\boldsymbol{d}}$$

$$u_s(\boldsymbol{r}) = \sum_{l=1}^{L} \boldsymbol{z}_{y,l}(\boldsymbol{r})^{\top} \boldsymbol{G}_l y_l = \boldsymbol{\zeta}_y(\boldsymbol{r})^{\top} \boldsymbol{y}$$

Apply kernel functions weighted on primary noise/each loudspeaker directions

NLMS algorithm based on individual kernel interpolation

- Define cost function and derive the gradient w.r.t. filter matrix

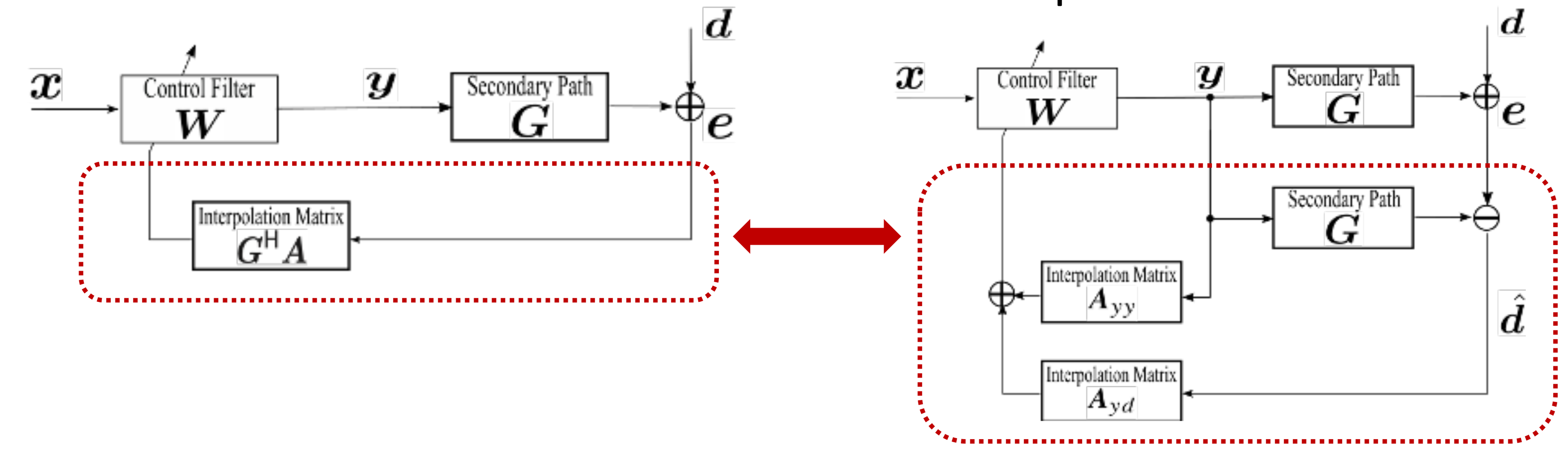
$$J(n) := \int_{\Omega} |u_e(\boldsymbol{r})|^2 \, d\boldsymbol{r}$$

$$u_e(\boldsymbol{r}) = \boldsymbol{z}_d(\boldsymbol{r})^{\top} \hat{\boldsymbol{d}} + \boldsymbol{\zeta}_y(\boldsymbol{r})^{\top} \boldsymbol{y}$$

$$\boldsymbol{A}_{yd} := \int_{\Omega} \boldsymbol{\zeta}_y^*(\boldsymbol{r}) \boldsymbol{z}_d^{\top}(\boldsymbol{r}) \, d\boldsymbol{r} \qquad \boldsymbol{A}_{yy} := \int_{\Omega} \boldsymbol{\zeta}_y^*(\boldsymbol{r}) \boldsymbol{\zeta}_y^{\top}(\boldsymbol{r}) \, d\boldsymbol{r}$$

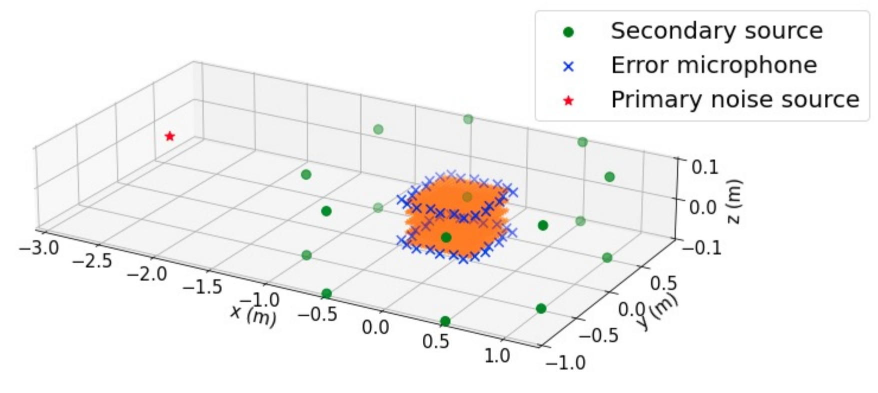
$$\frac{\partial}{\partial \boldsymbol{W}^*(n)} J(n) = \boldsymbol{A}_{yd} \boldsymbol{e}(n) \boldsymbol{x}(n)^{\mathsf{H}} + (\boldsymbol{A}_{yy} - \boldsymbol{A}_{yd}\boldsymbol{G}) \boldsymbol{y}(n) \boldsymbol{x}(n)^{\mathsf{H}}$$

Comparison of block diagrams



Numerical experiments

3D free field simulation setting



Target region: 0.6 m x 0.6 m x 0.2 m
\# of error mics: 48
\# of loudspeakers: 16
\# of noise sources: 1

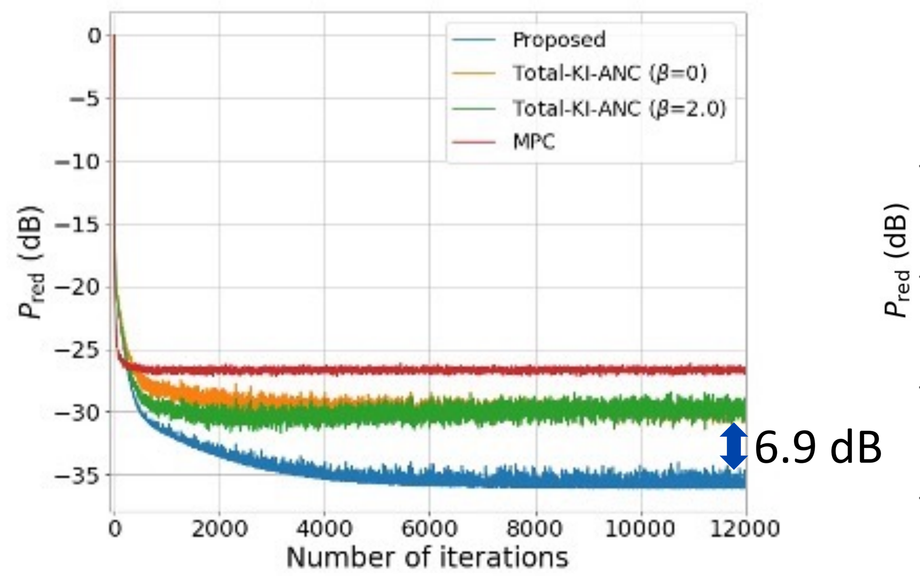
Performance measure:

$$P_{\mathrm{red}}(n) = 10 \log_{10} \frac{\sum_j |u_e^{(n)}(\boldsymbol{r}_j)|^2}{\sum_j |u_p^{(n)}(\boldsymbol{r}_j)|^2}$$

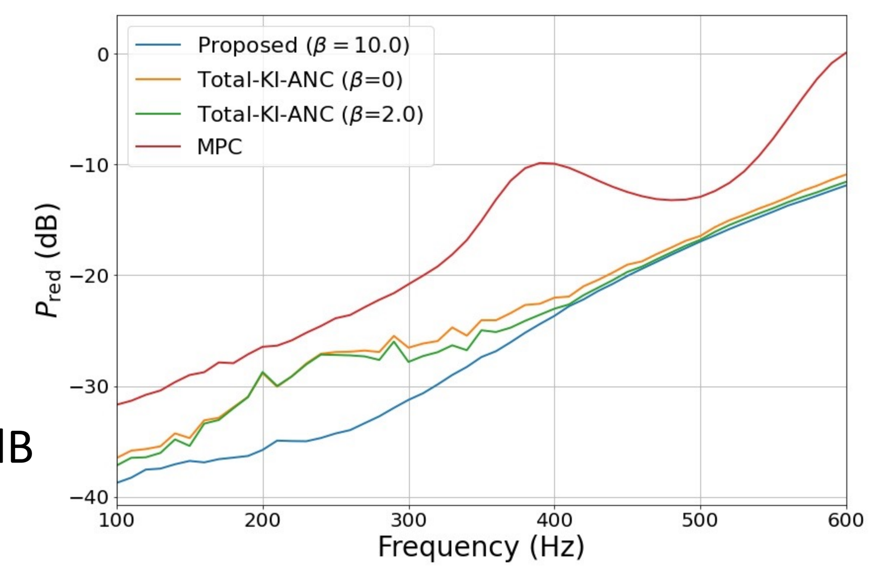
Results

Case1: Noise direction is exactly same as prior information

P_{red} for each iteration at 200Hz

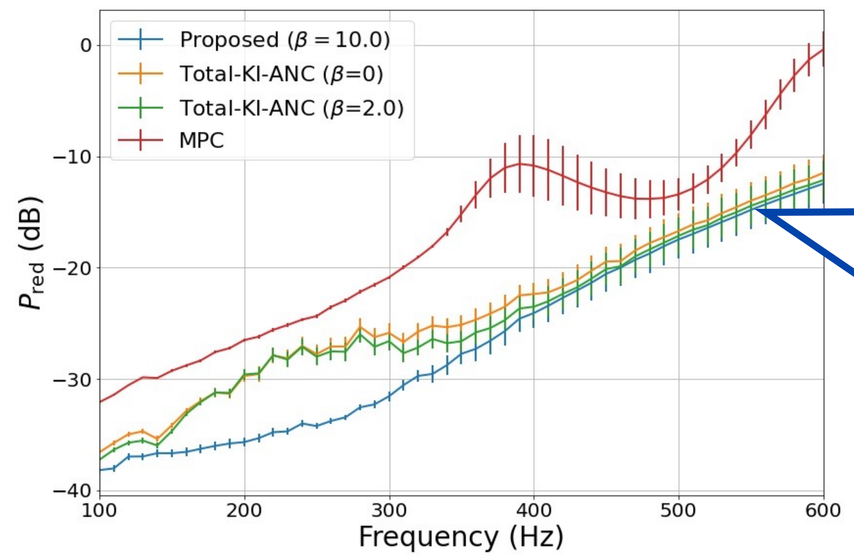


P_{red} after 12000 iterations at different frequencies



Case2: Noise direction is perturbed from prior information

- Perturbation is drawn from Gaussian distribution of standard deviations (0.05 m, 6°, 3°) in polar coordinates



- Proposed method achieves best performance on average
- Robustness to source perturbation is almost same as other methods

[1] Ito et.al., Proc. IEEE ICASSP, pp.511–515, 2019
[2] Ito et. al,IEEE ICASSP, pp.8399–8403, 2020.
[3] Koyama et.al., IEEE/ACM Trans. ASLP, vol.29, pp.3052–3063, 2021