ACTIVE NOISE CONTROL OVER MULTIPLE REGIONS: PERFORMANCE ANALYSIS

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Outline

ANC, Spatial ANC and multizone ANC

- Active noise control (ANC)
- ANC over region (Spatial ANC) $\longrightarrow$ multi-channel ANC
  - Multi-point approach: cancel the noise at error sensors as well as their close surroundings
  - Wave domain approach: the noisefield over an entire region is targeted to be cancelled directly

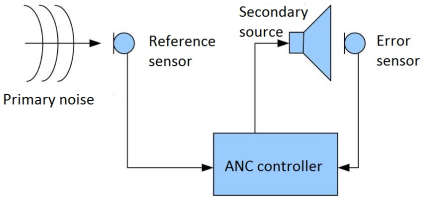


Figure: Basic ANC system structure.

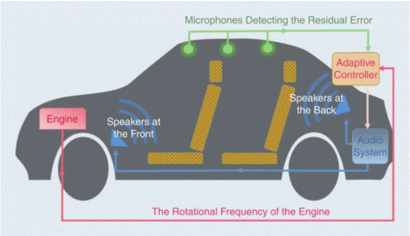


Figure: ANC inside an automobile cabin. [1]

Spatial ANC and Multizone spatial ANC

Noise cancellation over multiple regions (Multizone spatial ANC)$\longrightarrow$ control multiple regions of the interest simultaneously using a single secondary loudspeaker array

- Multizone sound field reproduction in the wave domain
- Multizone noise reduction (NR) performance analysis
  - Chen's work: characterizing the noise pattern and averaging noise energy over multiple regions
  - *This work: investigate the fundamental limitation of NR over multiple regions for a given single secondary loudspeaker array*

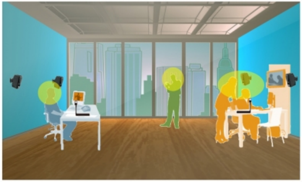


Figure: An example of a shared space with multiple zones for each individual [2]

NR performance analysis

In this work:

- *Evaluation over the multiple zones using wave-domain method*
- *Extract the subspace of the wave-domain coefficients of the secondary path, and investigate the maximum NR performance for each individual region by projecting the primary sound field into this subspace*

Outline

Multizone ANC system in a 3-D room

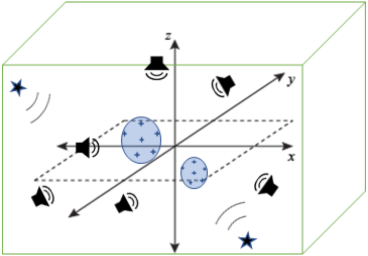


Figure: ANC system in a 3-D room.
Black stars: primary sources
loudspeakers: secondary sources
blue spheres: the regions of interest
dark blue stars: error microphones

- Regions of interest: Z spherical regions with radius $[R_1, R_2, \cdots, R_Z]$
- Error microphones: spherical microphone arrays on the boundary of the control regions
- Primary sources, secondary sources (L): outside all the regions

Representation of the primary noise field

- Within the z^{th} region of interest $r \leq R_z$, based on the spherical harmonics decomposition, we can use a finite number of modes to approximate the primary noise field

$$v^{(z)}(\boldsymbol{x}, k) \approx \sum_{n=0}^{N_z} \sum_{m=-n}^{n} \beta_{nm}^{(z)}(k) j_n(kr) Y_{nm}(\phi_{\boldsymbol{x}}, \psi_{\boldsymbol{x}}), \tag{1}$$

$N_z = \lceil ekR_z/2 \rceil$.
The wave domain coefficients $\boldsymbol{\beta}(k) = [\beta_{0,0}^{(1)}(k), \ldots, \beta_{N_1,N_1}^{(1)}(k), \ldots, \beta_{0,0}^{(Z)}(k), \ldots, \beta_{N_Z,N_Z}^{(Z)}(k)]^T$ represent the primary noise field in all the regions of interest.

Representation of secondary sources

- The secondary sound field generated by a discrete loudspeaker array with L loudspeakers

$$s(\boldsymbol{x},k) = \sum_{l=1}^{L} d_l(k) G(\boldsymbol{x}|\boldsymbol{y}_l,k), \tag{2}$$

$d_l(k)$ – the driving signal for the l^{th} loudspeaker, $\boldsymbol{y}_l$ – the location of the l^{th} loudspeaker, $G(\boldsymbol{x}|\boldsymbol{y}_l,k)$ – the acoustic transfer function (ATF)

- Using the spherical harmonic expansion, similar to the primary noise field, inside the z^{th} region of interest with the radius of R_z,

$$G(\boldsymbol{x}|\boldsymbol{y}_l,k) \approx \sum_{n=0}^{N_z} \sum_{m=-n}^{n} \eta_{nm}^{(zl)}(k) j_n(kr) Y_{nm}(\phi_{\boldsymbol{x}}, \psi_{\boldsymbol{x}}), \tag{3}$$

$$s^{(z)}(\boldsymbol{x},k) \approx \sum_{n=0}^{N_z} \sum_{m=-n}^{n} \gamma_{nm}^{(z)}(k) j_n(kr) Y_{nm}(\phi_{\boldsymbol{x}}, \psi_{\boldsymbol{x}}). \tag{4}$$

Problem to be solved

- For a given ANC system setup in a given environment, the secondary-path coefficient $\boldsymbol{\eta}(k)$ can be estimated

$$\boldsymbol{\eta}(k) = \begin{bmatrix} \boldsymbol{\eta}^{(1)}(k) & \boldsymbol{\eta}^{(2)}(k) & \cdots & \boldsymbol{\eta}^{(L)}(k) \end{bmatrix}, \qquad (5)$$

  with the dimension of $\sum_{z=1}^{Z} (N_z + 1)^2 \times L$
  For the l^{th} loudspeaker, $\boldsymbol{\eta}^{(l)}(k) =$
  $[\eta_{00}^{(1l)}(k), \cdots, \eta_{N_1 N_1}^{(1l)}(k), \cdots, \eta_{00}^{(Zl)}(k), \cdots, \eta_{N_Z N_Z}^{(Zl)}(k)]^T$.
- Based on the primary noise field coefficients $\boldsymbol{\beta}(k)$ and the secondary-path information $\boldsymbol{\eta}(k)$
  - Investigate the maximum achievable ANC performance
  - Derive loudspeaker driving signals to achieve the maximum NR performance over the multiple regions

  Main idea: Extract the subspace spanned by $\boldsymbol{\eta}(k)$, and only cancel the primary noise projected into this subspace.

Outline

Principal component analysis of secondary path

- 1. To obtain an orthonormal eigen-basis for the space of the secondary path in the wave domain, we perform the principal component analysis (PCA) of the correlation matrix $E\{\boldsymbol{\eta}^H(k)\boldsymbol{\eta}(k)\}$

$$E\{\boldsymbol{\eta}^H\boldsymbol{\eta}\} = \boldsymbol{U}\boldsymbol{\Lambda}\boldsymbol{V} \tag{6}$$

- 2. Depending on the acoustic environment and the loudspeaker placement, the first B components contain the most useful information of the loudspeaker, $\boldsymbol{U}^\diamond$

Extract the subspace spanned by $\boldsymbol{\eta}$

- 3. Generate the subspace $\boldsymbol{O}$ spanned by $\boldsymbol{\eta}$

$$\boldsymbol{O} = \boldsymbol{\eta}\boldsymbol{U}^{\diamond}. \tag{7}$$

Orthonormal vectors $\boldsymbol{o}_1, \ldots, \boldsymbol{o}_B$ generate a subspace, which represents the loudspeaker array and the acoustic environment.

- 4. Represent the average ATF coefficients

$$\bar{\boldsymbol{\eta}}^{(l)} = \boldsymbol{O}\boldsymbol{\kappa}^{(l)}, \tag{8}$$

$\boldsymbol{\kappa} = \{\kappa^{(1)}, \ldots, \kappa^{(L)}\}$ **is the secondary-path coefficients in the subspace $\boldsymbol{O}$, dimension:** $B \times L$.

Projection of the Primary Noise Field into the Subspace

- 5. Project a new primary noise field $\boldsymbol{\beta}$ into subspace $\boldsymbol{O}$

$$\text{Proj}_{\boldsymbol{O}}\boldsymbol{\beta} = \sum_{b=1}^{B} < \boldsymbol{\beta}, \boldsymbol{o}_b > \boldsymbol{o}_b = \boldsymbol{O}\boldsymbol{y}, \tag{9}$$

$\boldsymbol{y} = \{y_1, y_2, \ldots, y_B\}^T$ – the primary noise field coefficients in the subspace, $y_b = < \boldsymbol{\beta}, \boldsymbol{o}_b >$.

- $\boldsymbol{\beta}$ can be separated by two parts:

$$\boldsymbol{\beta} = \text{Proj}_{\boldsymbol{O}}\boldsymbol{\beta} + R(\boldsymbol{\beta}) \tag{10}$$

Projected part and orthogonal complement

- The projected part indicates the primary noise field which can be cancelled in this system setup, and
- The orthogonal complement indicates the primary noise field which can not be cancelled in this system.
  - If $R(\beta) = 0$, β lies in the subspace, then the primary noise field over the regions of interest can be completely cancelled by the loudspeaker array.
  - If $R(\beta) \neq 0$, $R(\beta)$ indicates the limitation of noise cancellation over all the regions, under the particular loudspeaker placement and acoustic environment.

Driving signal design in the subspace

- 6. In the subspace, matching the secondary sound field coefficients to the projected primary noise field coefficients,

$$\gamma = -\mathrm{Proj}_{\boldsymbol{O}}\boldsymbol{\beta} = \boldsymbol{O}\boldsymbol{\kappa}\boldsymbol{d}. \tag{11}$$

- Design the loudspeaker driving signals $\boldsymbol{d}$ based on secondary-path information in the subspace $\boldsymbol{\kappa}$ and the primary noise field coefficients in the subspace $\boldsymbol{y}$

$$\boldsymbol{d} = -(\boldsymbol{\kappa})^{\dagger}\boldsymbol{y}. \tag{12}$$

Outline

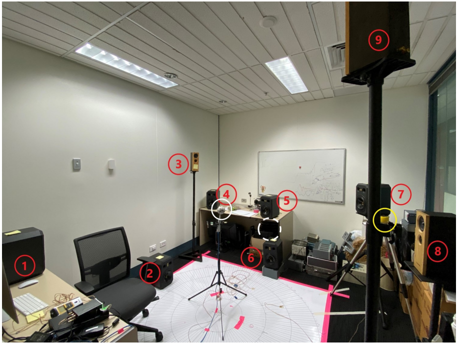


Figure: Experimental setup in a reverberant room for an ANC system, with single noise source (yellow circle), 9 secondary loudspeakers (red circles) and an Eigenmike (white circle).

- Spherical regions of interest: $r_1 = 0.042$ m; $r_2 = 0.042$ m
- Microphone array: Eigenmike
- Single primary source: position 1 (SP1): [1.43,3.78,1.00] m; position 2 (SP2): [0.61,1.10,1.00] m
- Primary noise signal: white Gaussian noise
- Secondary sources: loudspeaker [1:9]
- Frequency range: $f = [100, 500]$ Hz

Evaluation variables

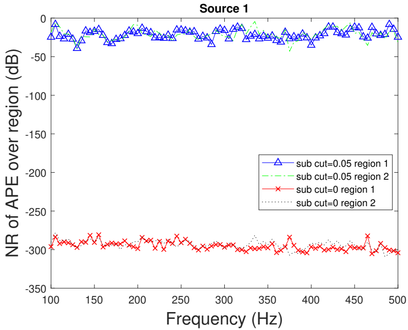
- To analyse the spatial ANC performance over multiple regions, we define the NR over the z^{th} region as

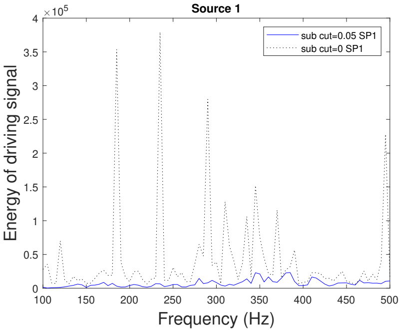
$$N_{\mathrm{r}}^{(\mathrm{z})} \triangleq 10 \log_{10} \frac{\sum_{nm} w_n^{(z)} |\alpha_{nm}^{(\mathrm{z})}|^2}{\sum_{nm} w_n^{(z)} |\beta_{nm}^{(\mathrm{z})}|^2}. \tag{13}$$

  Here, we evaluate the APE within each spherical region:
  $E_p^{(z)}(k) = \frac{1}{4\rho c^2} \sum_{nm} w_n^{(z)} |\alpha_{nm}^{(\mathrm{z})}|^2$
  where $\alpha_{nm}^{(z)}$ – error coefficient $\alpha_{nm}^{(z)} = \beta_{nm}^{(z)} + \gamma_{nm}^{(z)}$
  $w_n^{(z)}$ – the APE weights $w_n^{(z)} = \int_0^{R_z} j_n(kr)^2 r^2 dr$.
- To evaluate the loudspeaker energy consumption, we use the total energy of all the loudspeakers

$$E_d = \boldsymbol{d}^T \boldsymbol{d} \tag{14}$$

Loudspeaker Number Meeting the Requirement [1:9]





- When we omit the less significant component in basis $\boldsymbol{u}$, N_r is lower than what it would be if all components of $\boldsymbol{u}$ were used
- While the high NR when we use all the information is not physically achievable

Loudspeaker Number Less Than the Requirement [1:6]

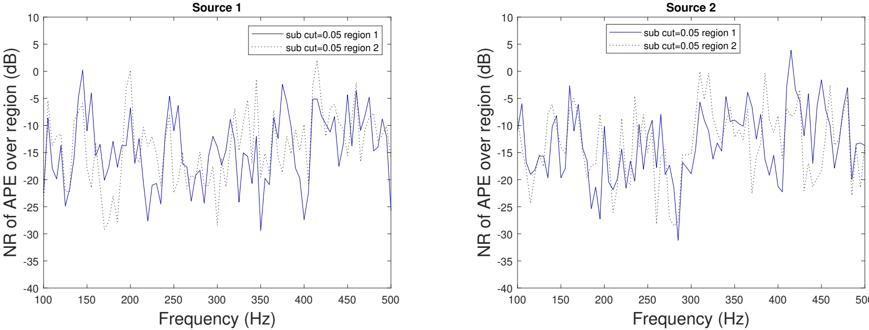
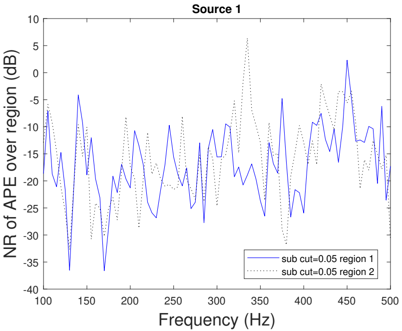
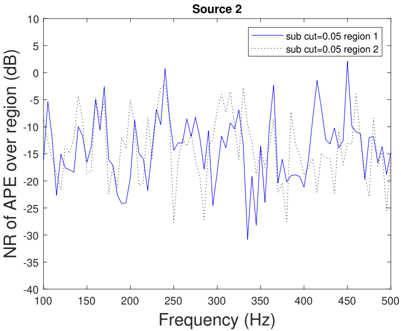


Figure: When secondary loudspeakers [1:6] are active, (a) N_r for source position 1, (b) N_r for source position 2.

Loudspeaker Number Less Than the Requirement [4:9]





- By evaluating the NR over each individual region, we can determine a better loudspeaker setup suitable for a particular noise field.

Outline

Concluding remarks

- An evaluation method for analysing the spatial active noise control performance over multiple regions
  - For a given loudspeaker array setup, we analysed maximum noise reduction over multiple regions with a feasible solution. (not overloading of the secondary sources)
  - For a given number of secondary loudspeakers, especially when the secondary sources have constraints on numbers and locations, we can analyse better locations to cancel a given primary sound field over multiple regions
- Future work: an investigation of spatial ANC performance over multiple regions by analysing sound acquisition capability of non- spherical microphone array

Thanks!

Questions?

P. N. Samarasinghe, W. Zhang, and T. D. Abhayapala, "Recent advances in active noise control inside automobile cabins: Toward quieter cars," *IEEE Signal Processing Magazine*, vol. 33, no. 6, pp. 61–73, 2016.

T. Betlehem, W. Zhang, M. A. Poletti, and T. D. Abhayapala, "Personal sound zones: Delivering interface-free audio to multiple listeners," *IEEE Signal Processing Magazine*, vol. 32, no. 2, pp. 81–91, 2015.