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Truncated Singular Value Decomposition Method for Mitigating Unwanted Enhancement in Active Noise Control Systems

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PURDUE MECHANICAL ENGINEERING

RAY W. HERRICK LABORATORIES

* This project is the work of Xuchen Wang, under supervision of Dr. Yangfan Liu and Dr. J. Stuart Bolton.

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Problem Introduction

Truncated SVD Method

Simulation Validation

Problem Introduction

Introduction

- MIMO Active Noise Control (ANC) Problem

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- Noise Control in Open Region

↓

- Application: Range Hood, Headrest etc.

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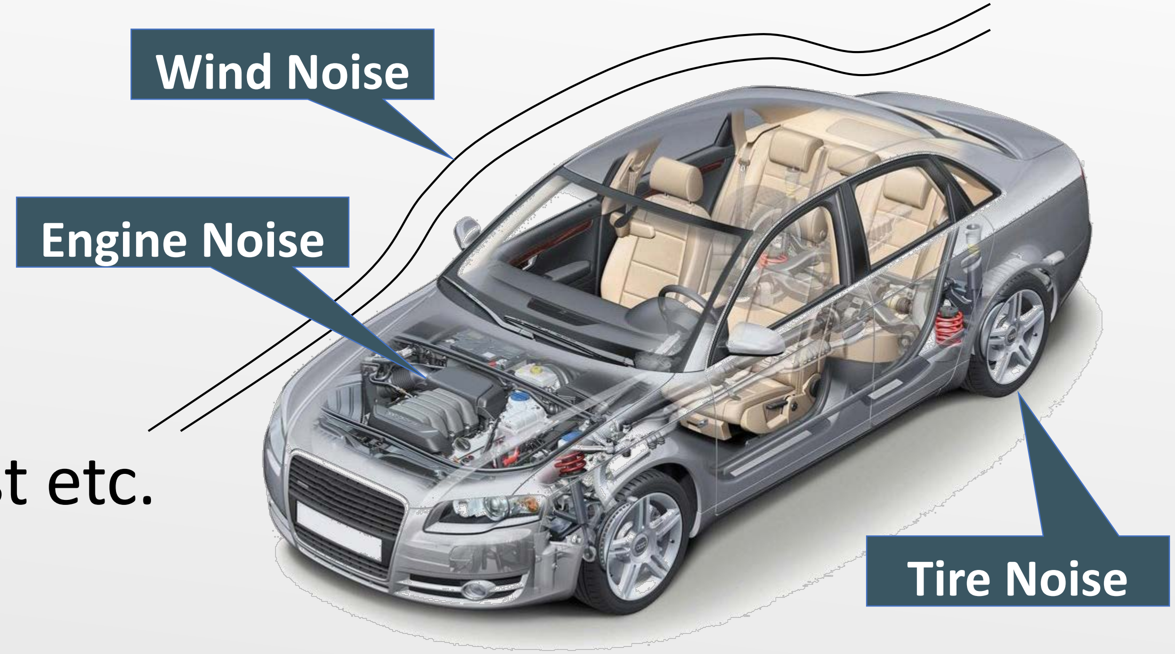


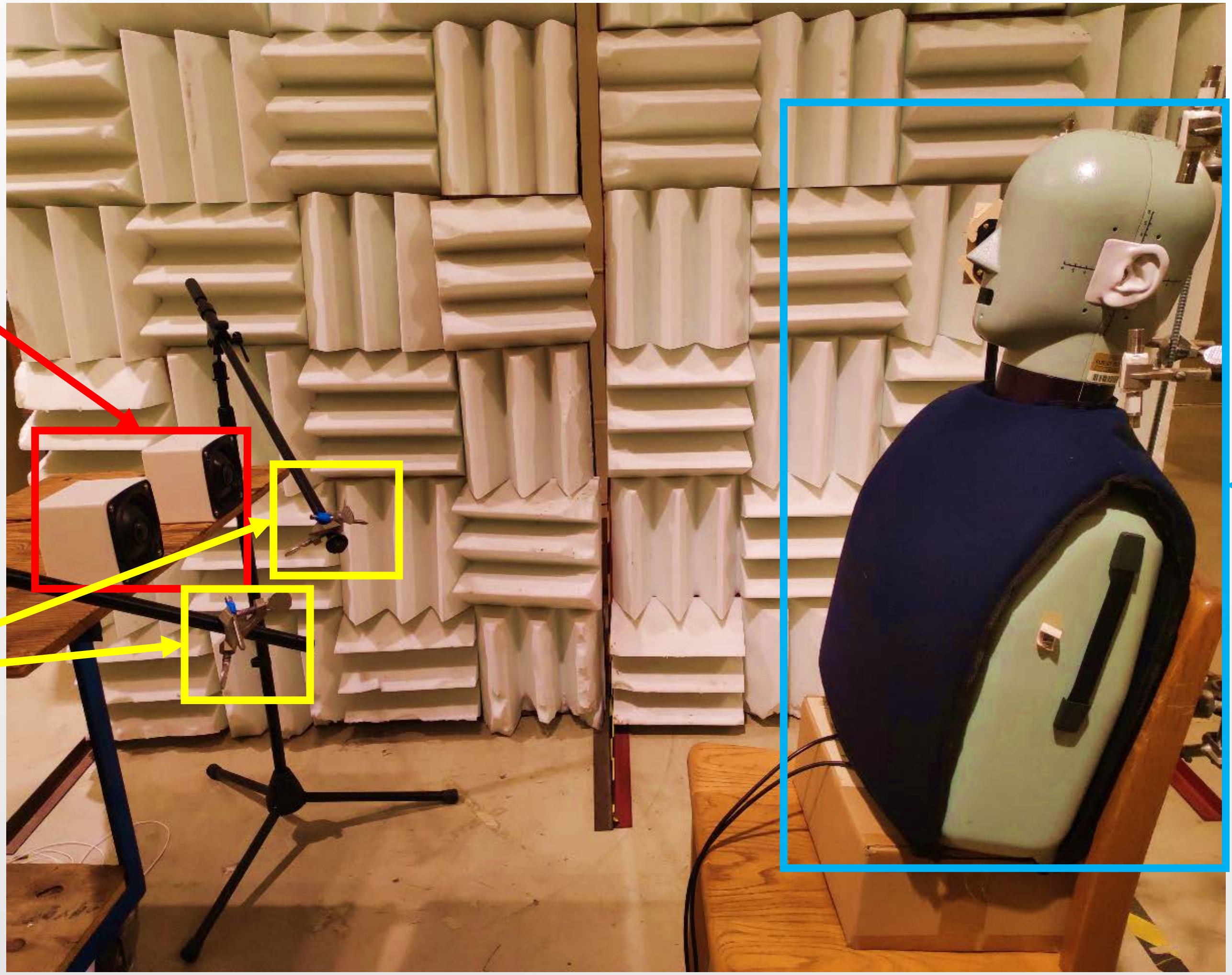
Enhancement Problem

- Possible Reasons:
  - System Delay
  - Feedback Path Cancellation
  - Correlated Reference Signals
  - …

- Focus:
  - Correlated Reference Signals Problem in MIMO Feed-forward Non-adaptive Active Noise Control System

Experiment Setup

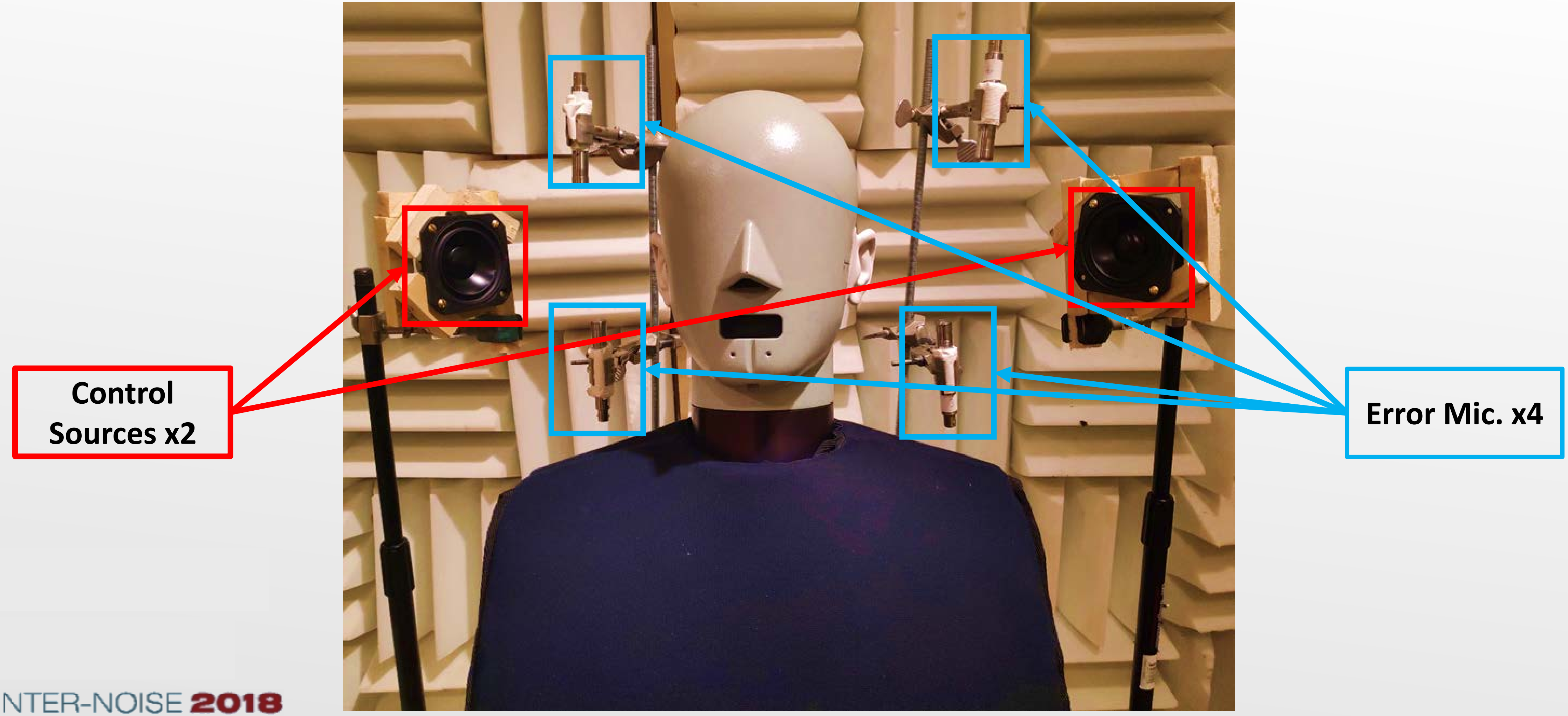
Noise Sources x2



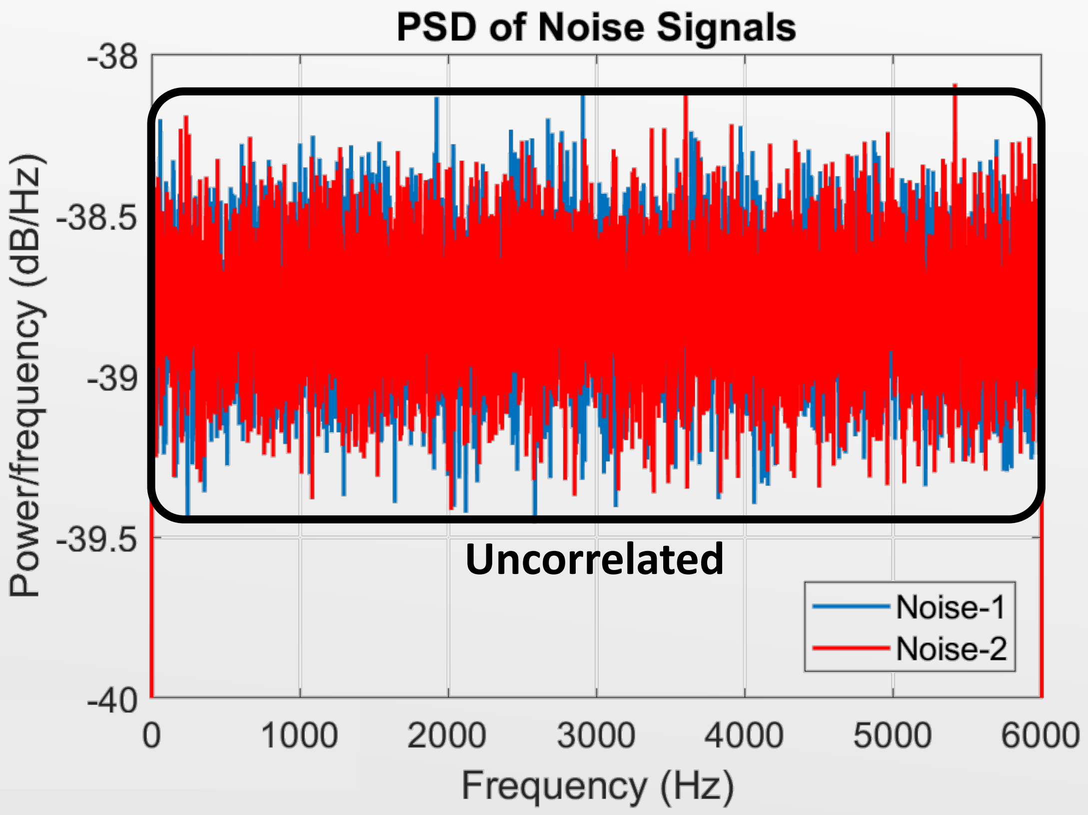
Dummy x1

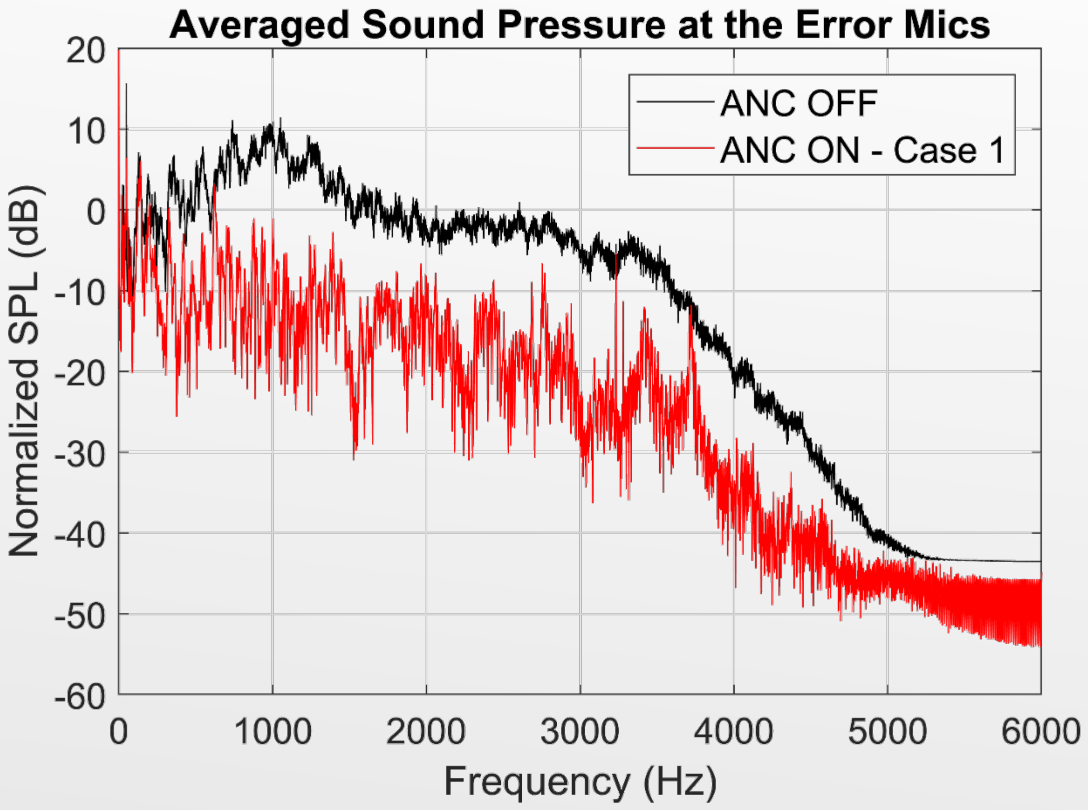
Reference Mic. x2

Experiment Setup

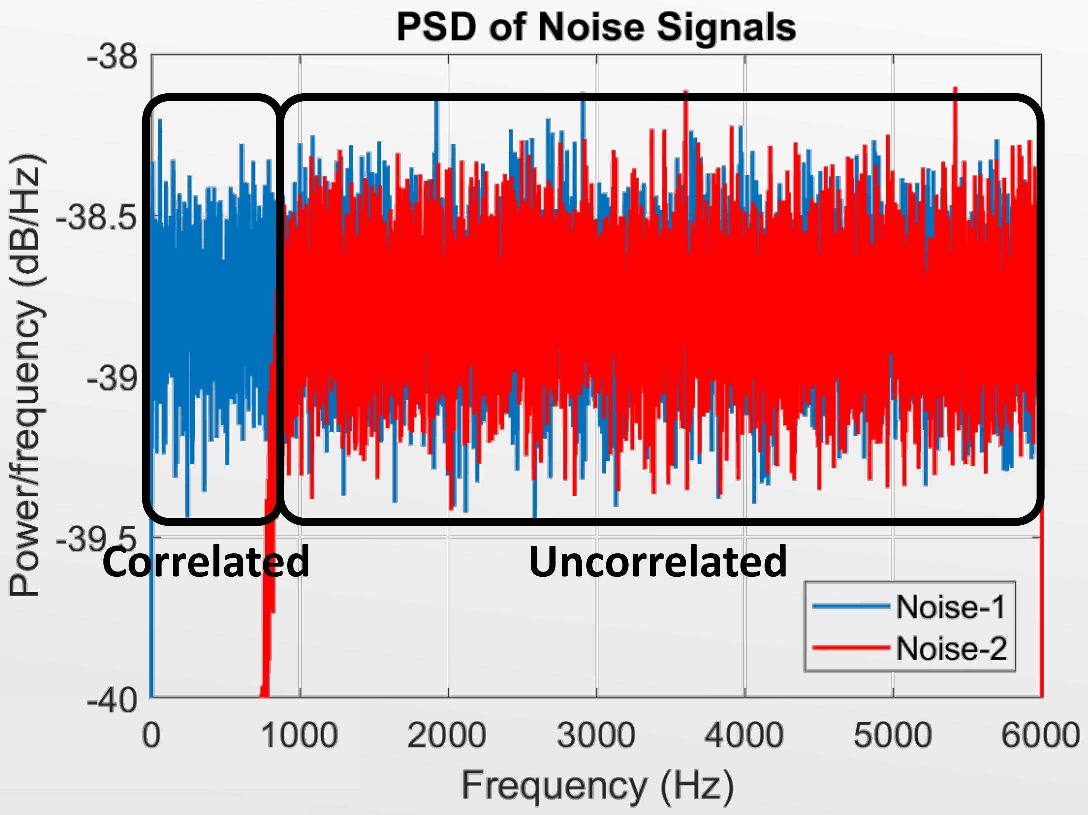


Case 1

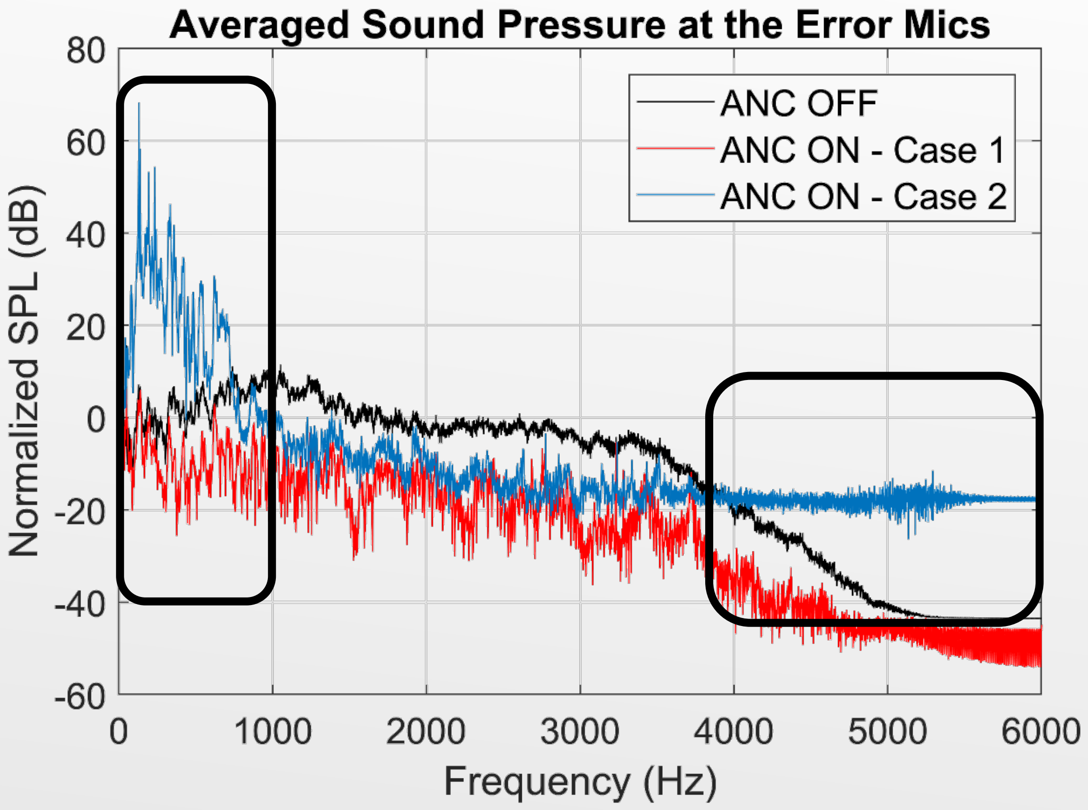

PSD of Noise Signals
-38
-38.5
-39
-39.5
-40
Power/frequency (dB/Hz)
0
1000
2000
3000
4000
5000
6000
Frequency (Hz)
Uncorrelated
Noise-1
Noise-2


Averaged Sound Pressure at the Error Mics
20
10
0
-10
-20
-30
-40
-50
-60
Normalized SPL (dB)
0
1000
2000
3000
4000
5000
6000
Frequency (Hz)
ANC OFF
ANC ON - Case 1

Case 2



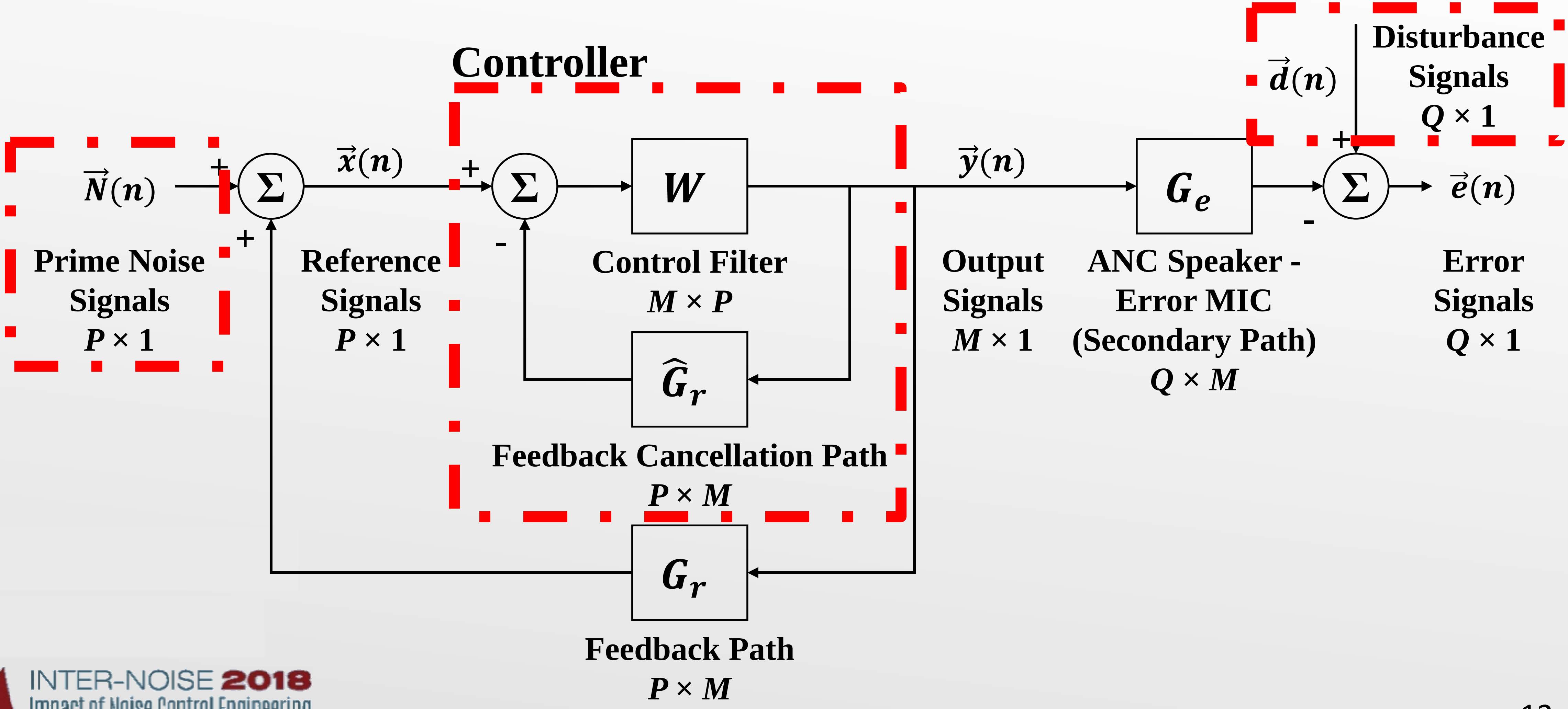
PSD of Noise Signals
Power/frequency (dB/Hz)
-38
-38.5
-39
-39.5
-40
0
1000
2000
3000
4000
5000
6000
Frequency (Hz)
Correlated
Uncorrelated
Noise-1
Noise-2



Averaged Sound Pressure at the Error Mics
Normalized SPL (dB)
80
60
40
20
0
-20
-40
-60
0
1000
2000
3000
4000
5000
6000
Frequency (Hz)
ANC OFF
ANC ON - Case 1
ANC ON - Case 2

Truncated SVD Method

Feed-forward Active Noise Control System



Coefficients of Controller

*S. J. Elliott, *Signal processing for active control*, Elsevier, (2000).

$$\boldsymbol{J} = \boldsymbol{E}[\vec{\boldsymbol{e}}^T(n) \cdot \vec{\boldsymbol{e}}(n)] = \vec{\boldsymbol{w}}^T \boldsymbol{A} \vec{\boldsymbol{w}} + 2\vec{\boldsymbol{w}}^{\boldsymbol{T}} \vec{\boldsymbol{b}} + c$$

$$\vec{\boldsymbol{w}}_{opt} = -\boldsymbol{A}^{-1} \vec{\boldsymbol{b}}$$

$\boldsymbol{A}$ – Autocorrelation function of the filtered reference signals

$\vec{\boldsymbol{b}}$ – Cross-correlation function between the filtered reference signals and the disturbance signals

c – Autocorrelation function of the disturbance signals

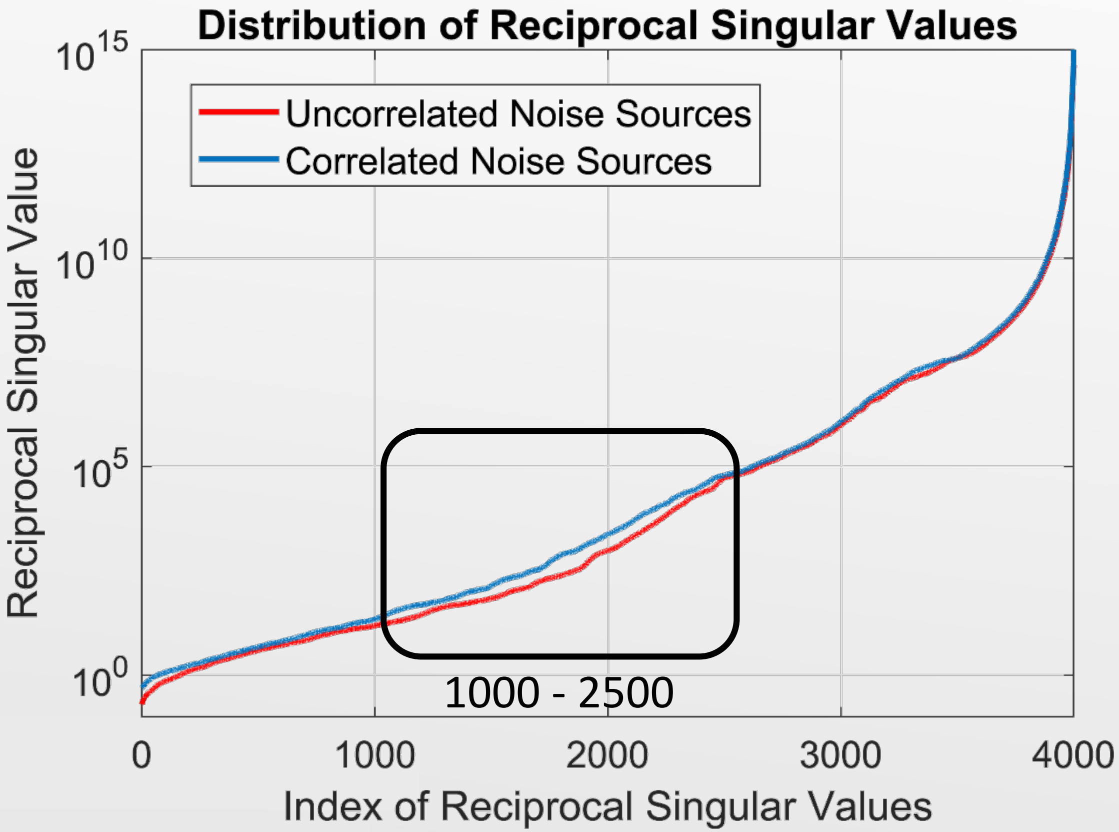
Singular Value Decomposition Analysis

SVD is used to analysis the autocorrelation function of the filtered reference signals.

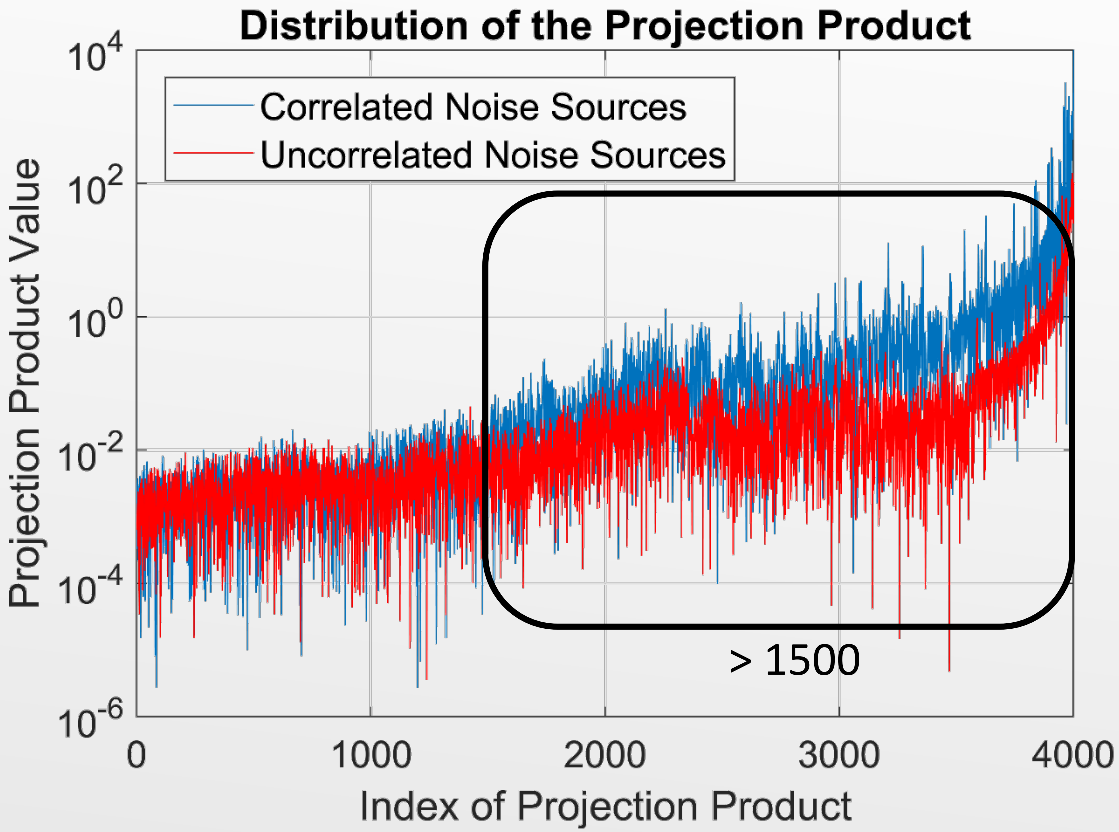
$$\boldsymbol{A} = \boldsymbol{U\Sigma U}^T = [\vec{\boldsymbol{u}}_1 \cdots \vec{\boldsymbol{u}}_N] \begin{bmatrix} \sigma_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_N \end{bmatrix} \begin{bmatrix} \vec{\boldsymbol{u}}_1 \\ \vdots \\ \vec{\boldsymbol{u}}_N \end{bmatrix}$$

$$\vec{\boldsymbol{w}}_{opt} = -[\vec{\boldsymbol{u}}_1 \cdots \vec{\boldsymbol{u}}_N] \begin{bmatrix} \sigma_1^{-1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_N^{-1} \end{bmatrix} \begin{bmatrix} \vec{\boldsymbol{u}}_1 \\ \vdots \\ \vec{\boldsymbol{u}}_N \end{bmatrix} \vec{\boldsymbol{b}} = -\sum_{n=1}^{N} \sigma_n^{-1} \langle \vec{\boldsymbol{u}}_n, \vec{\boldsymbol{b}} \rangle \vec{\boldsymbol{u}}_n$$

Singular Values & Projection Product



σ_n



$\langle \vec{u}_n, \vec{b} \rangle$

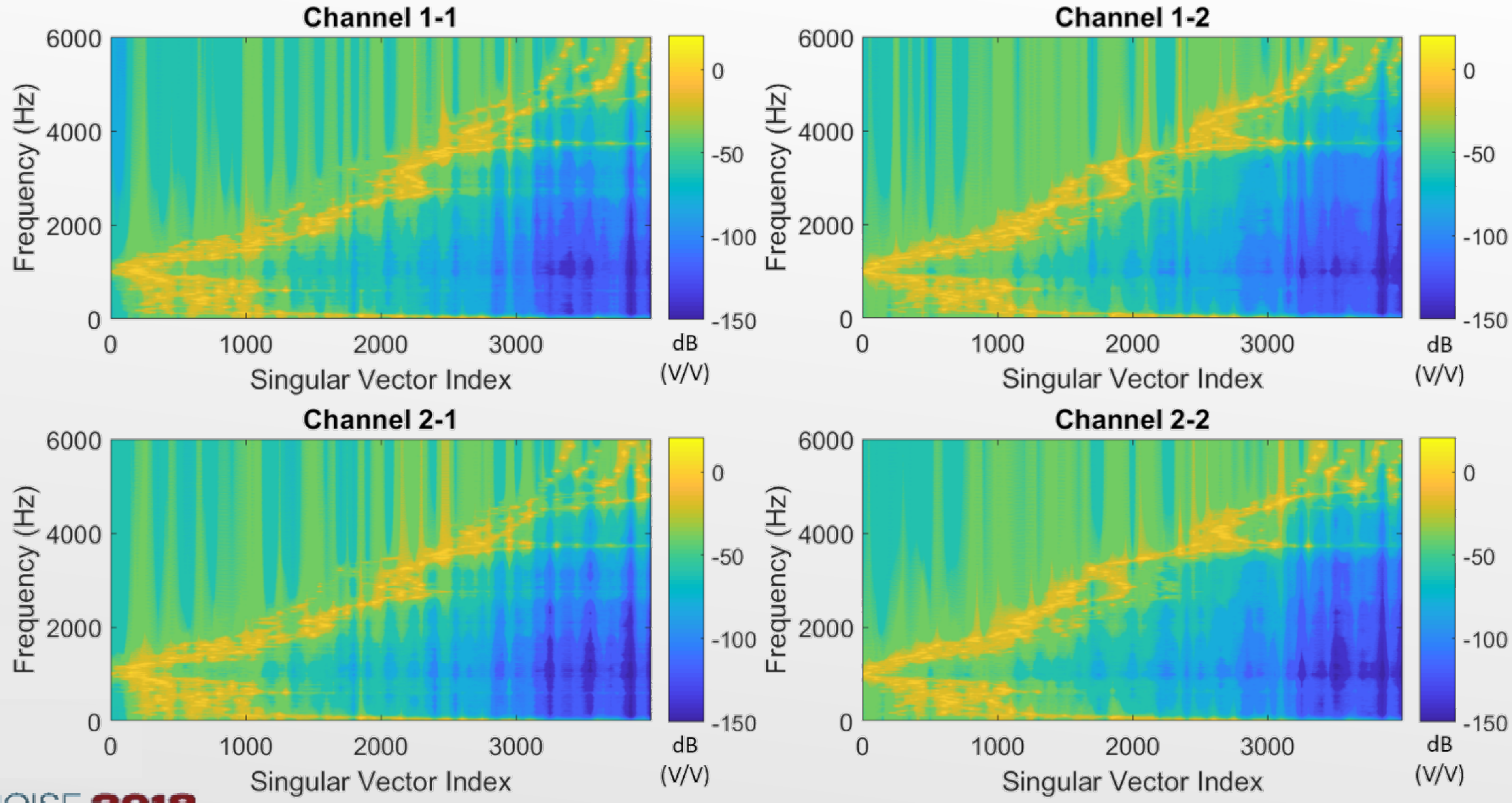
Singular Value Decomposition Analysis

SVD is used to analysis the autocorrelation function of the filtered reference signals.

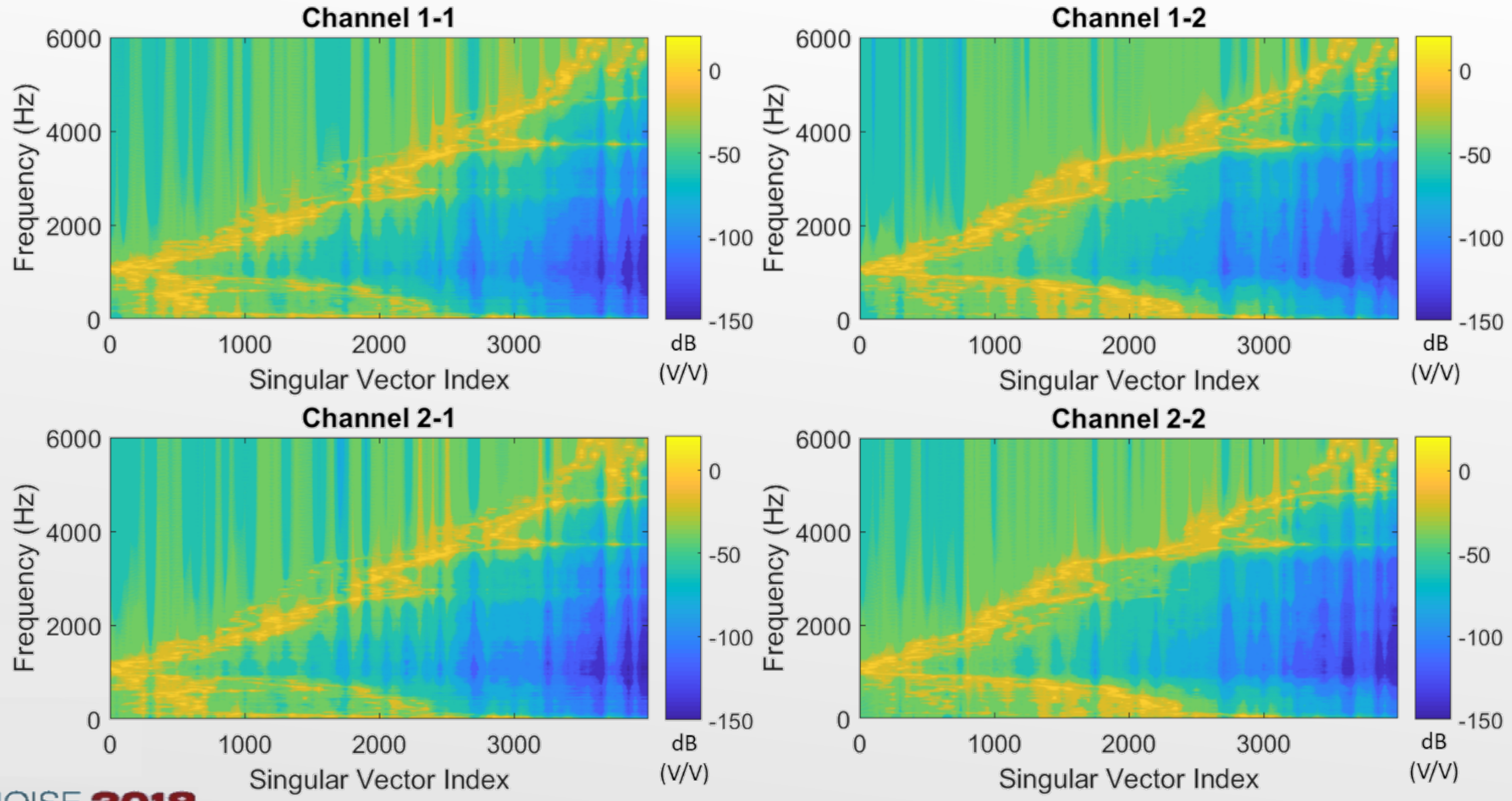
$$\boldsymbol{A} = \boldsymbol{U\Sigma U}^T = [\vec{\boldsymbol{u}}_1 \cdots \vec{\boldsymbol{u}}_N] \begin{bmatrix} \sigma_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_N \end{bmatrix} \begin{bmatrix} \vec{\boldsymbol{u}}_1 \\ \vdots \\ \vec{\boldsymbol{u}}_N \end{bmatrix}$$

$$\vec{\boldsymbol{w}}_{opt} = -[\vec{\boldsymbol{u}}_1 \cdots \vec{\boldsymbol{u}}_N] \begin{bmatrix} \sigma_1^{-1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_N^{-1} \end{bmatrix} \begin{bmatrix} \vec{\boldsymbol{u}}_1 \\ \vdots \\ \vec{\boldsymbol{u}}_N \end{bmatrix} \vec{\boldsymbol{b}} = -\sum_{n=1}^{N} \sigma_n^{-1} \langle \vec{\boldsymbol{u}}_n, \vec{\boldsymbol{b}} \rangle \vec{\boldsymbol{u}}_n$$

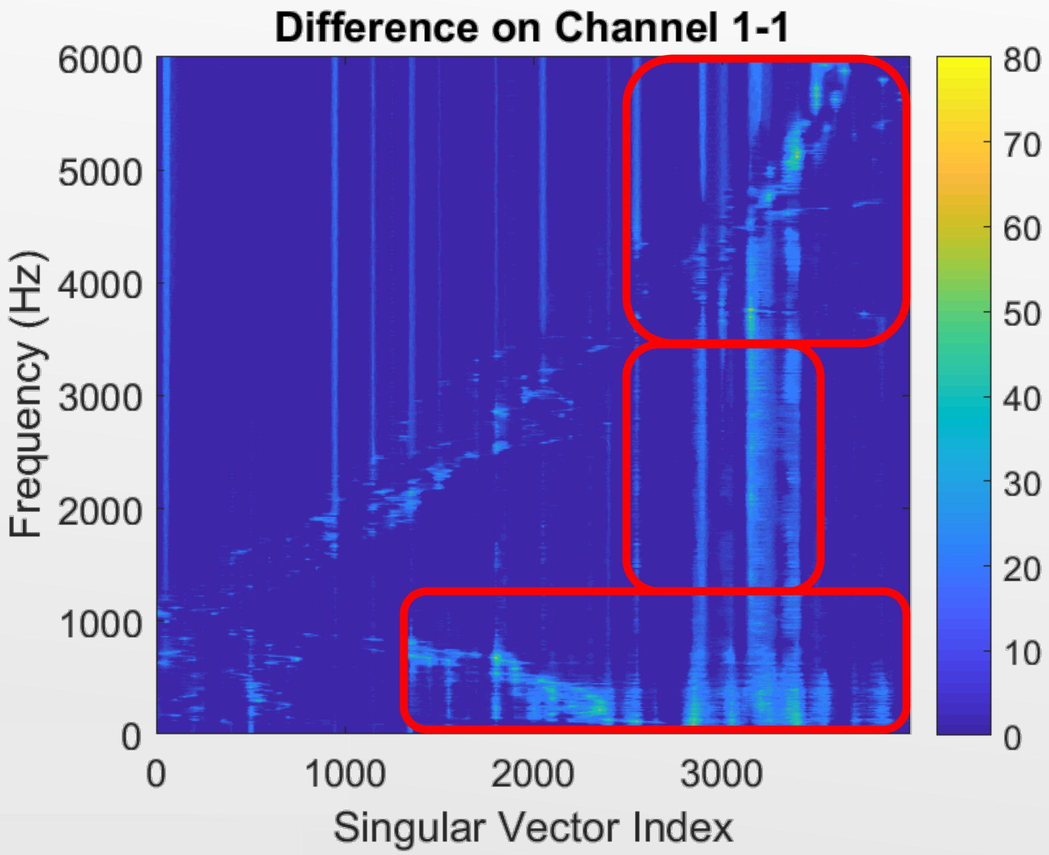
Uncorrelated Noise Sources Case

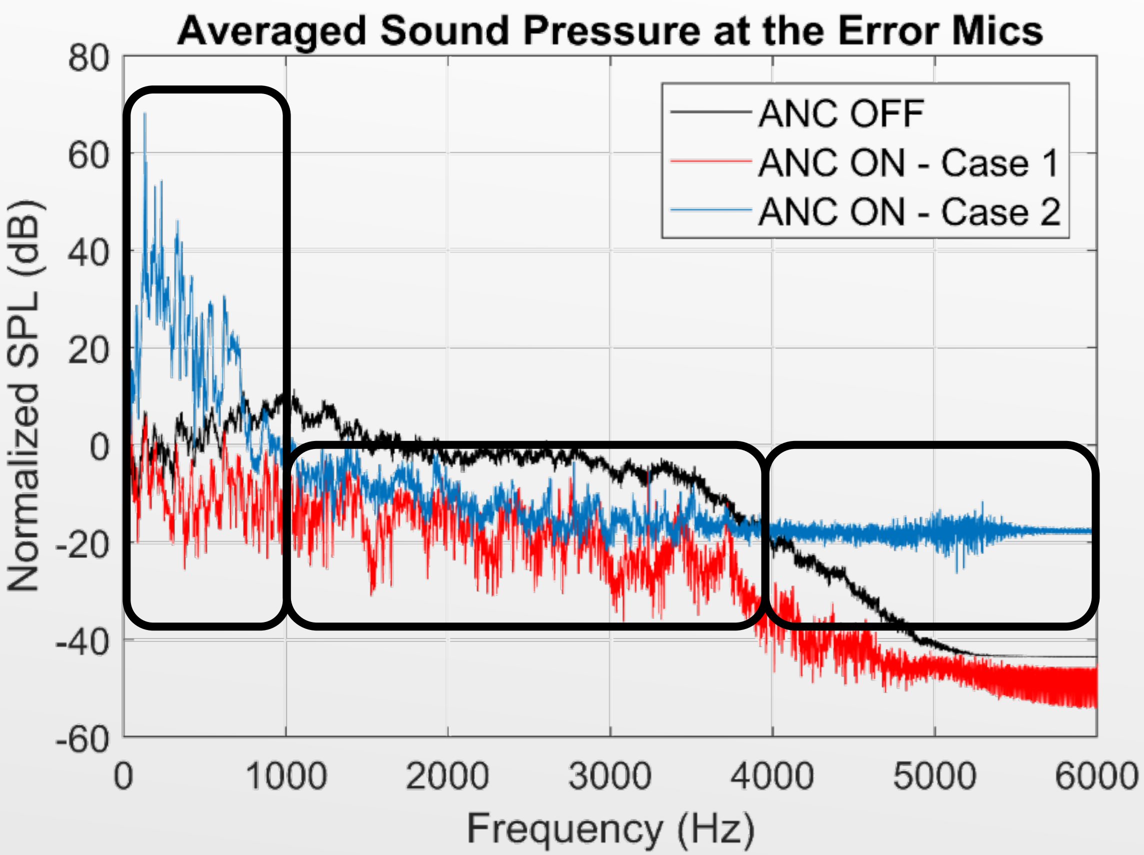


Correlated Noise Sources Case



Comparison of Two Cases





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Truncated Singular Value Decomposition Method

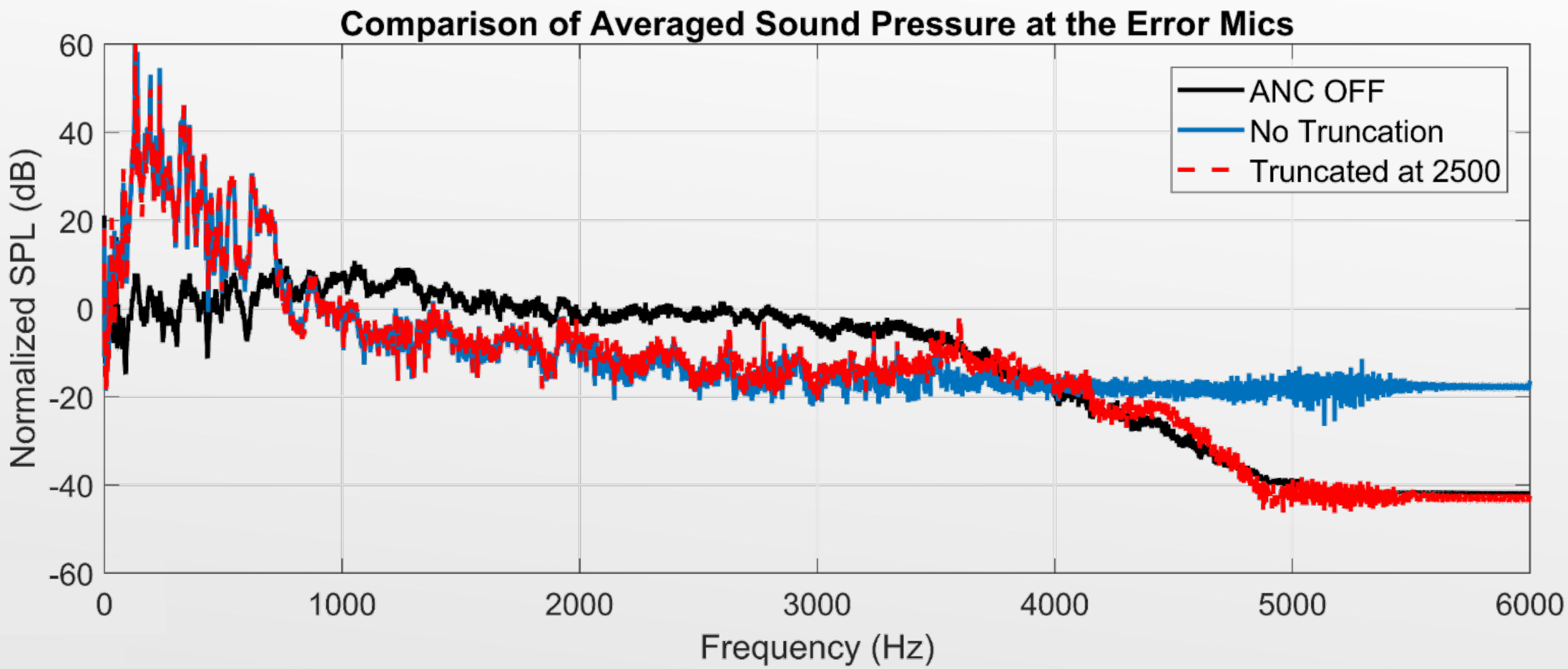
l : Truncation Point

$$\vec{\boldsymbol{w}}_{opt} = -[\vec{\boldsymbol{u}}_1 \cdots \vec{\boldsymbol{u}}_N] \begin{bmatrix} \sigma_1^{-1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_N^{-1} \end{bmatrix} \begin{bmatrix} \vec{\boldsymbol{u}}_1 \\ \vdots \\ \vec{\boldsymbol{u}}_N \end{bmatrix} \vec{\boldsymbol{b}} = -\sum_{n=1}^{N} \sigma_n^{-1} \ \langle \vec{\boldsymbol{u}}_n, \vec{\boldsymbol{b}} \rangle \, \vec{\boldsymbol{u}}_n$$

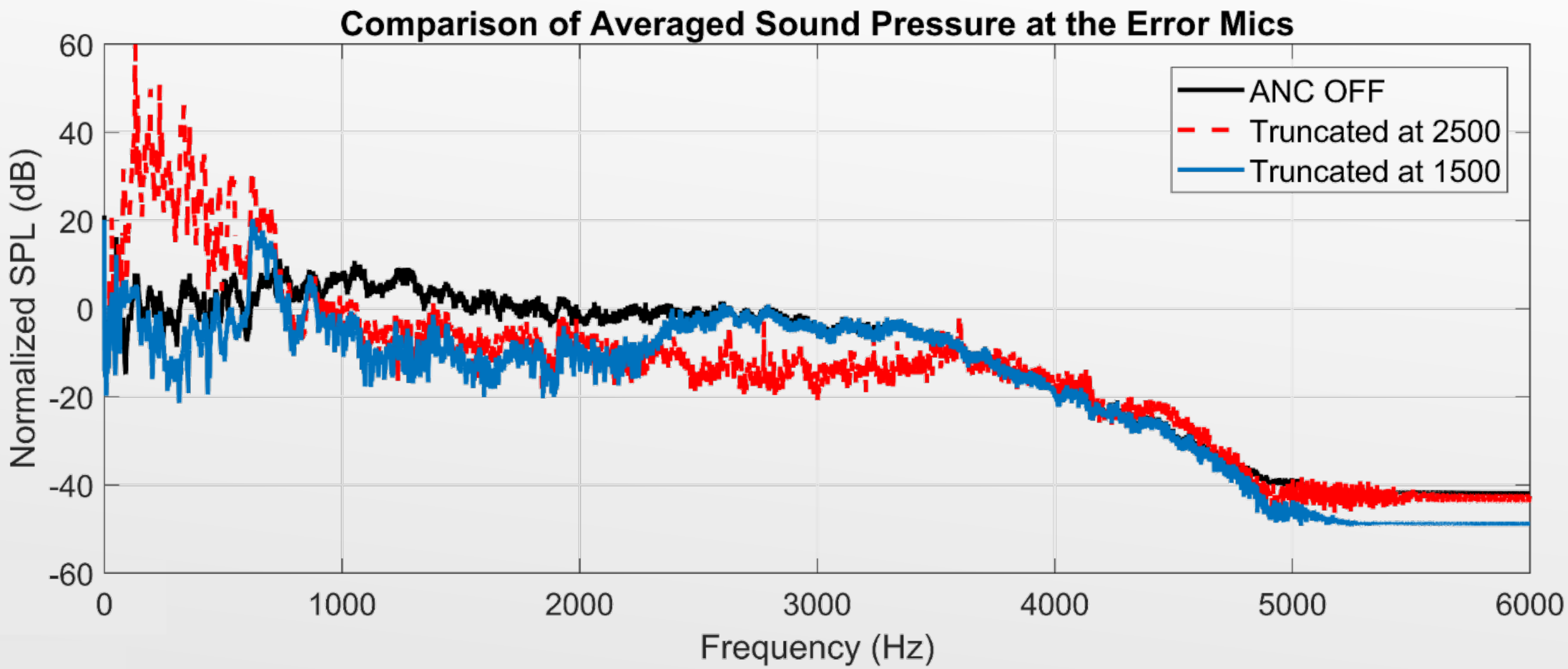
$$\vec{\boldsymbol{w}}^{*}{}_{opt} = -[\vec{\boldsymbol{u}}_1 \cdots \vec{\boldsymbol{u}}_l] \begin{bmatrix} \sigma_1^{-1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_l^{-1} \end{bmatrix} \begin{bmatrix} \vec{\boldsymbol{u}}_1 \\ \vdots \\ \vec{\boldsymbol{u}}_l \end{bmatrix} \vec{\boldsymbol{b}} = -\sum_{n=1}^{l} \sigma_n^{-1} \ \langle \vec{\boldsymbol{u}}_n, \vec{\boldsymbol{b}} \rangle \, \vec{\boldsymbol{u}}_n$$

Simulation Validation

Simulation Validation



Simulation Validation



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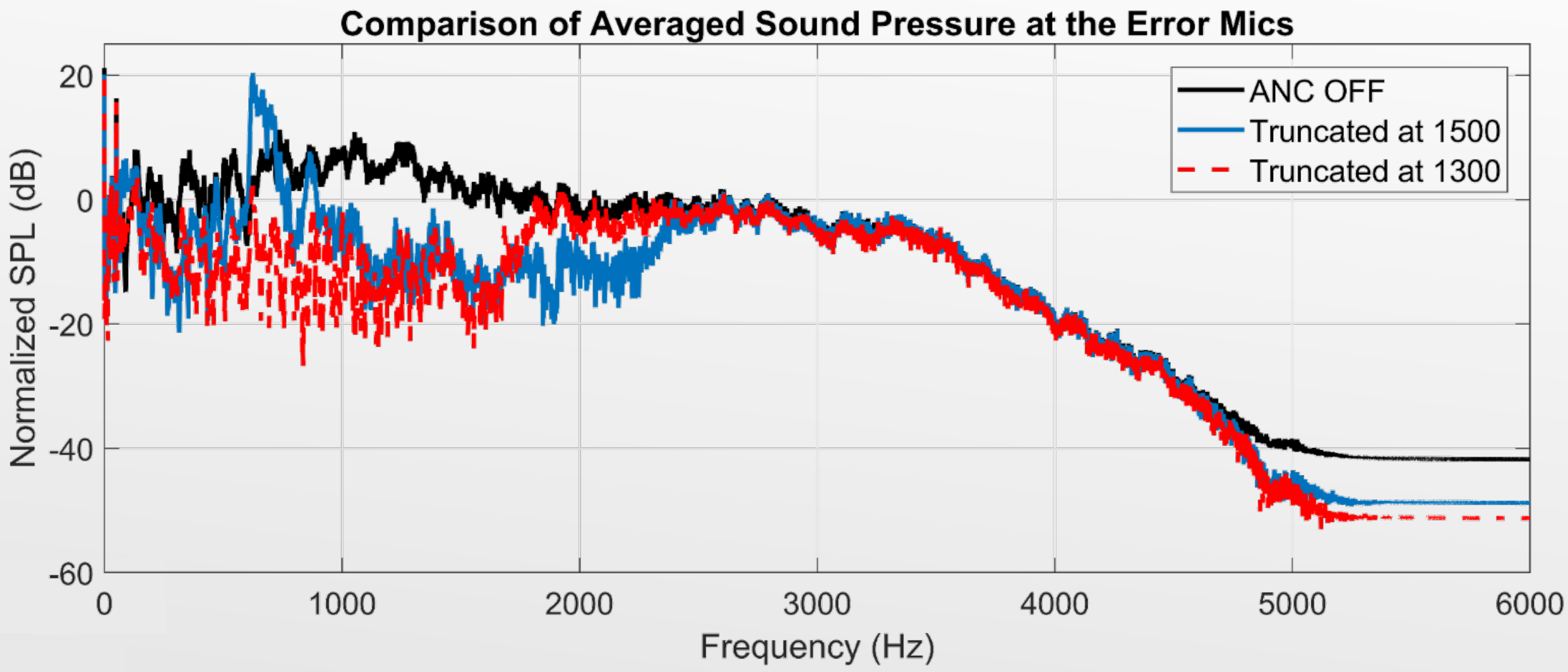
Simulation Validation



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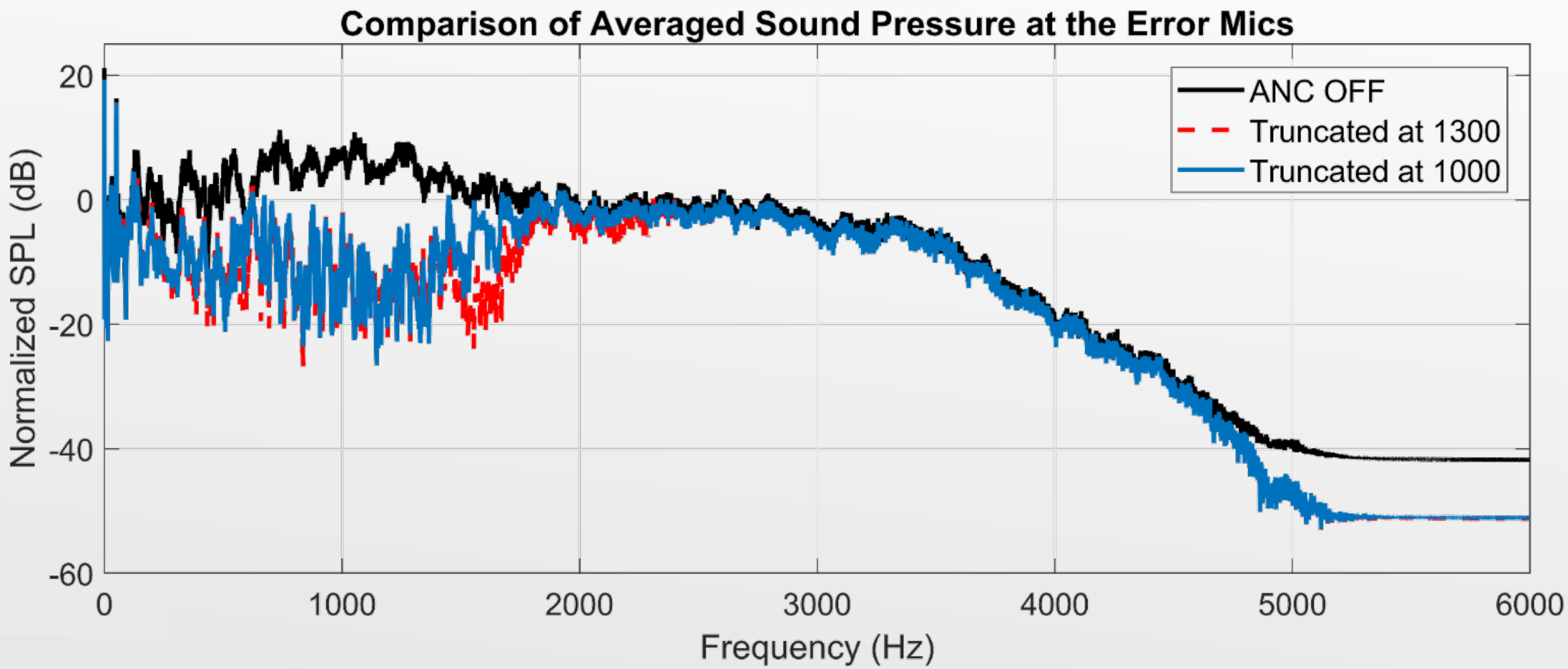

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Conclusions

- The large reciprocal of singular values σ_n^{-1} and the projection product of $\langle \vec{\boldsymbol{u}}_n, \vec{\boldsymbol{b}} \rangle$ are two causes of the noise enhancement.
- The singular vectors of some indices contribute to both noise enhancement and noise cancellation.
- Still need more tries to find the best index for truncation point to improve the performance or mitigate the unwanted enhancement.

Thank you!