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Modification of Simulated Far-field Engine Noise by Changing Near Field Measurement Singular Values

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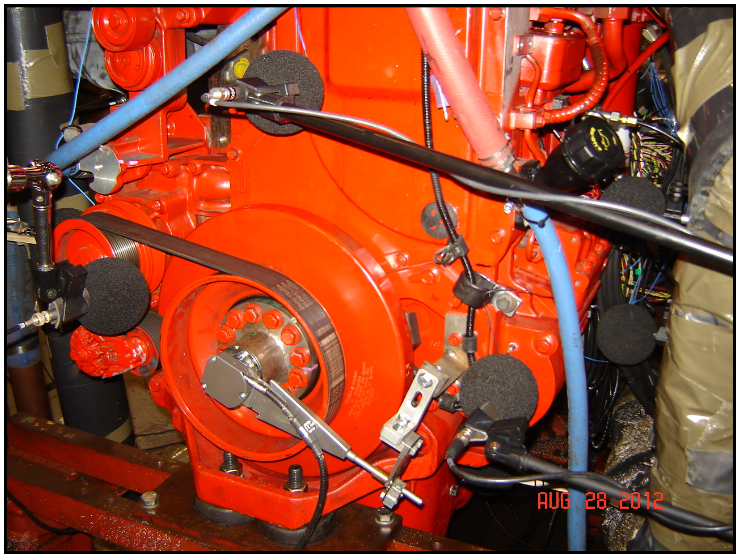
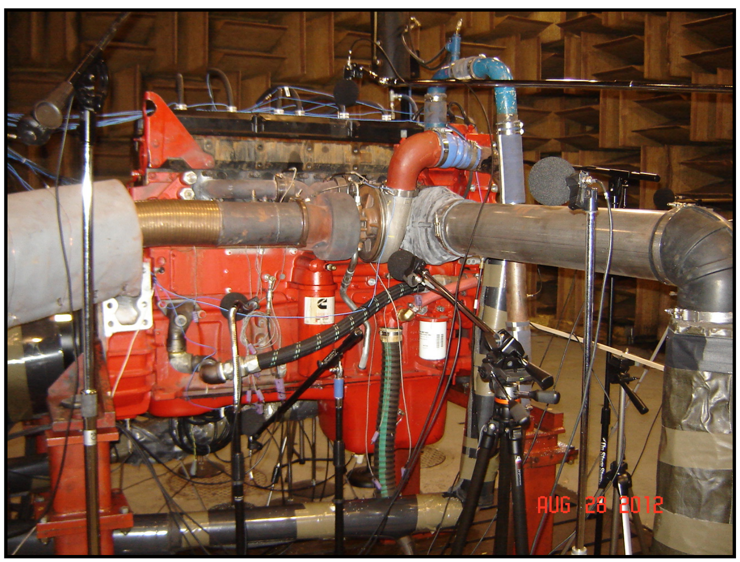
  - Paul Riehle and Randall Furnas of Roush Industries for their assistance in testing

Motivations

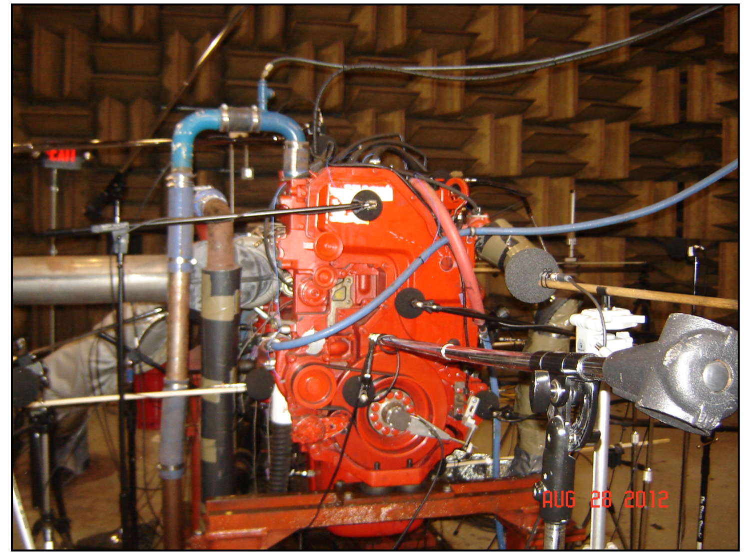


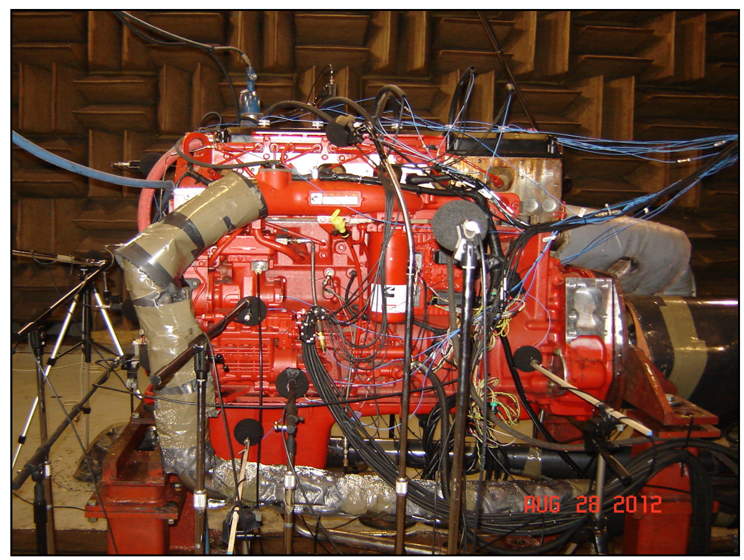


- Acoustical testing of diesel engines often requires a combination of fired and motored tests.
- Motored testing is a time-consuming and often expensive task.
- Reducing the needed amount of motored testing might:
  - Reduce financial costs.
  - Increase availability of testing resources (e.g., the semi-anechoic chamber and technical support).

Introduction

- Method demonstrates how a physical modification to an engine can be simulated by changing 'virtual sources' to simulate far-field noise.
- With an understanding of dominant noise-generating mechanisms, method would allow for a simulation of an attenuation of the dominant source.
- The method shown was validated using two separate tests in which only one engine component (Component A) was removed between the tests.





Literature Review

- Relationship between physical sources and near-field measurements can be determined using singular value decomposition and singular value contribution plots (Leclère *et al*., 2005; Hayward *et al*., 2012).

- Relationship between the near-field measurements and the far-field measurements can be estimated by solving a cross-spectral matrix problem (Kompella, 1992; Hayward *et al*., 2013).

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Outline

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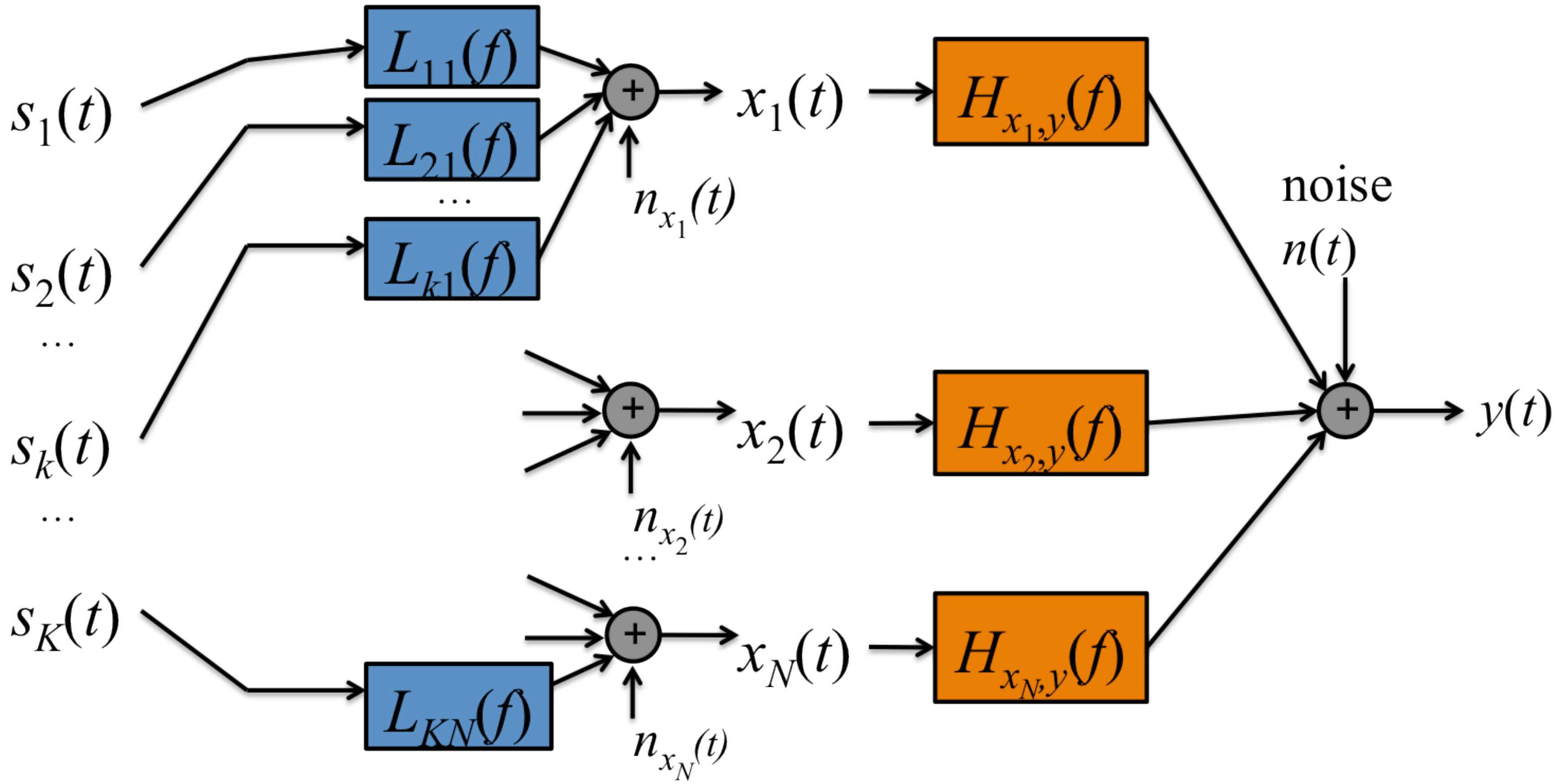
Validation
Application of process to real, motored test data

Multiple Input/Multiple Output System



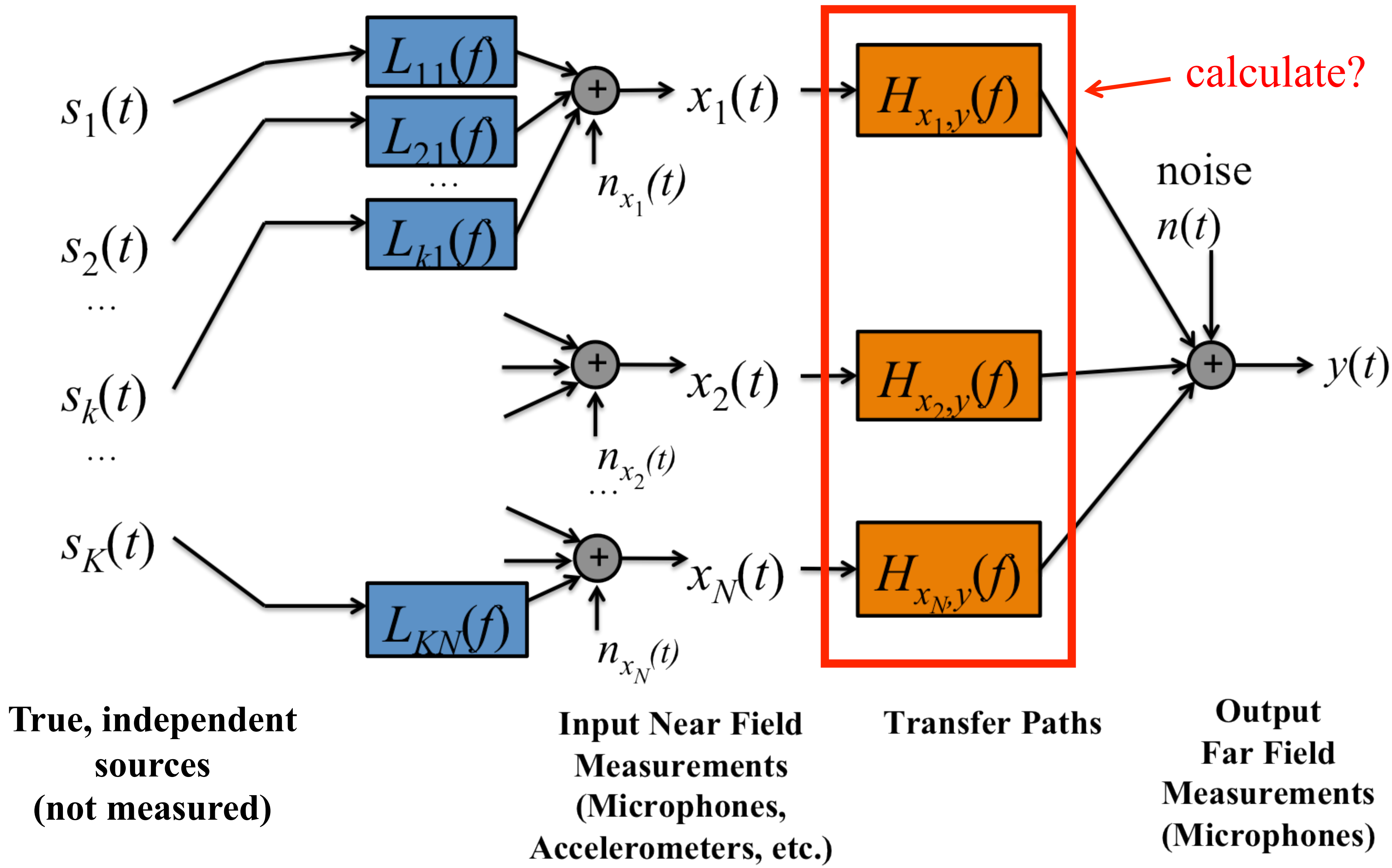
True, independent sources (not measured)

Input Near Field Measurements (Microphones, Accelerometers, etc.)

Transfer Paths

Output Far Field Measurements (Microphones)

Multiple Input/Multiple Output System



Transfer Path/Far-Field Estimation

- Far field measurement, $y(t)$, can be expressed as

$$y(t) = \sum_{j=1}^{N} \int_{-\infty}^{\infty} x_j(\tau) h_{x_j y}(t-\tau) d\tau.$$

Impulse response of $H_{x_j y}$

- Cross-spectral density between the input, $x_i(t)$, and the output is

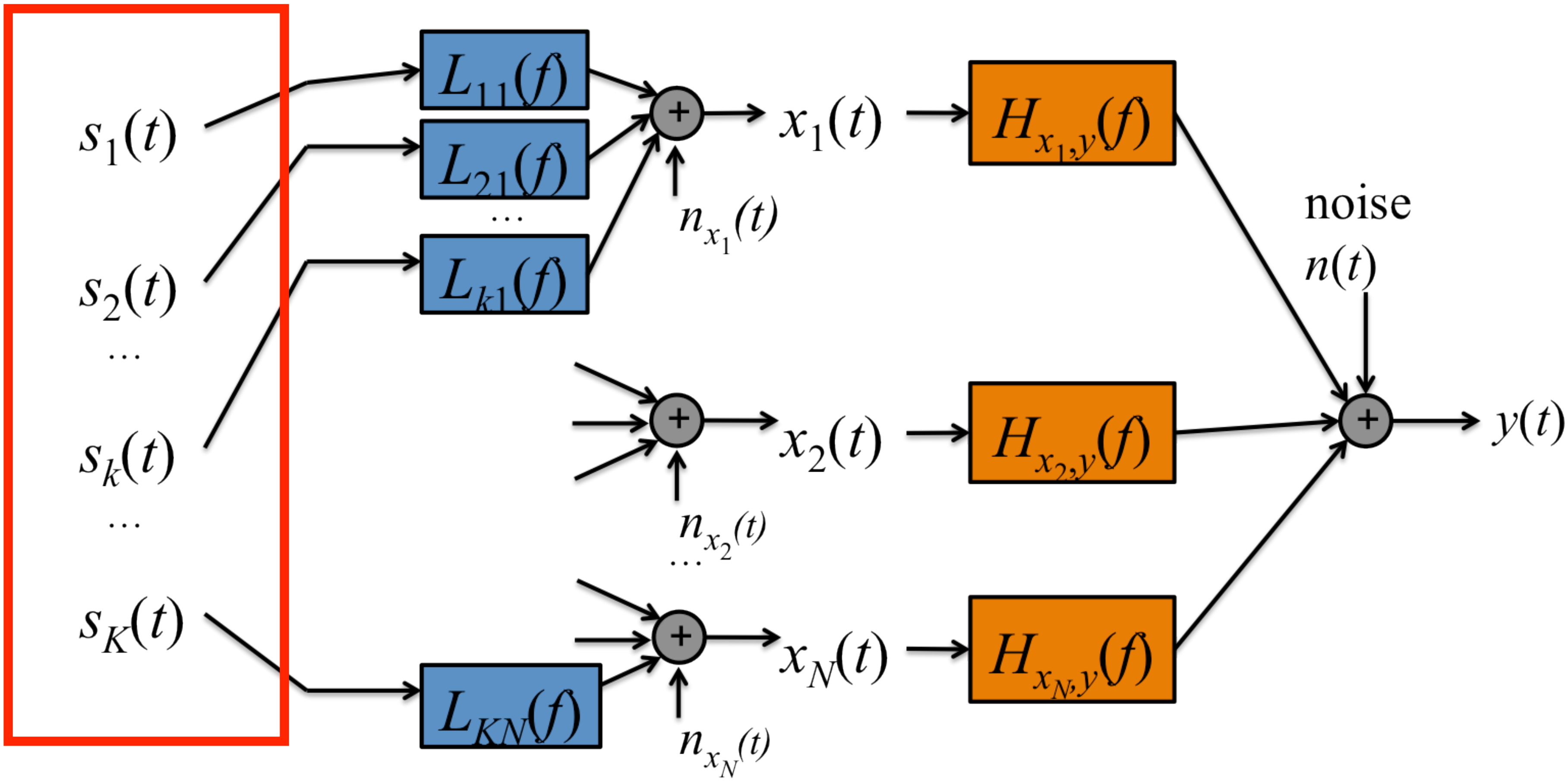
$$S_{x_i y}(f) = \sum_{j=1}^{N} H_{x_j y}(f) S_{x_i x_j}(f),$$

- which can be expressed in matrix form as

$$\left[\mathrm{S}_{\mathrm{xy}}\right] = \left[\mathrm{S}_{\mathrm{xx}}\right][\mathbf{H}]$$

H can be solved by using any robust matrix solution method

Multiple Input/Multiple Output System



True, independent sources (not measured)

Input Near Field Measurements (Microphones, Accelerometers, etc.)

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Output Far Field Measurements (Microphones)

Singular Value Decomposition

- A method to determine independent spectral characteristics from a set of partially-correlated data

Cross-spectral matrix | Left singular vector | Diagonal singular value matrix | Right singular vector

$$\left[\mathbf{S_{xx}}\right] = \mathbf{U\Sigma V^H} = [\mathbf{u_1}, \mathbf{u}_2, ..\mathbf{u}_N]\, diag[\lambda_1, \lambda_2, ...\lambda_N]\, [\mathbf{v_1}, \mathbf{v}_2, ..\mathbf{v}_N]^H$$

$$\lambda_1 > \lambda_2 > ... > \lambda_N$$

- $\mathbf{S_{xx}}$ is Hermitian symmetric, so $\mathbf{U} = \mathbf{V}$.
- Each singular value λ_i is independent/orthogonal.
- The singular values (also called virtual sources) represent independent spectral information present in input measurements, but are not necessarily representative of a particular physical source.

Singular Value Contribution Plots

- Contributions of singular values to input power spectra help to determine a relationship between virtual and physical sources.

$$\left[\mathbf{S}_{\mathbf{xx}}\right] = \mathbf{U}\Sigma\mathbf{V}^{\mathbf{H}} = [\mathbf{u}_1, \mathbf{u}_2, ..\mathbf{u}_N]\,diag[\lambda_1, \lambda_2, ...\lambda_N][\mathbf{v}_1, \mathbf{v}_2, ..\mathbf{v}_N]^H$$

Color coding example

%
>75
50-75
25-50
5-25
0-5

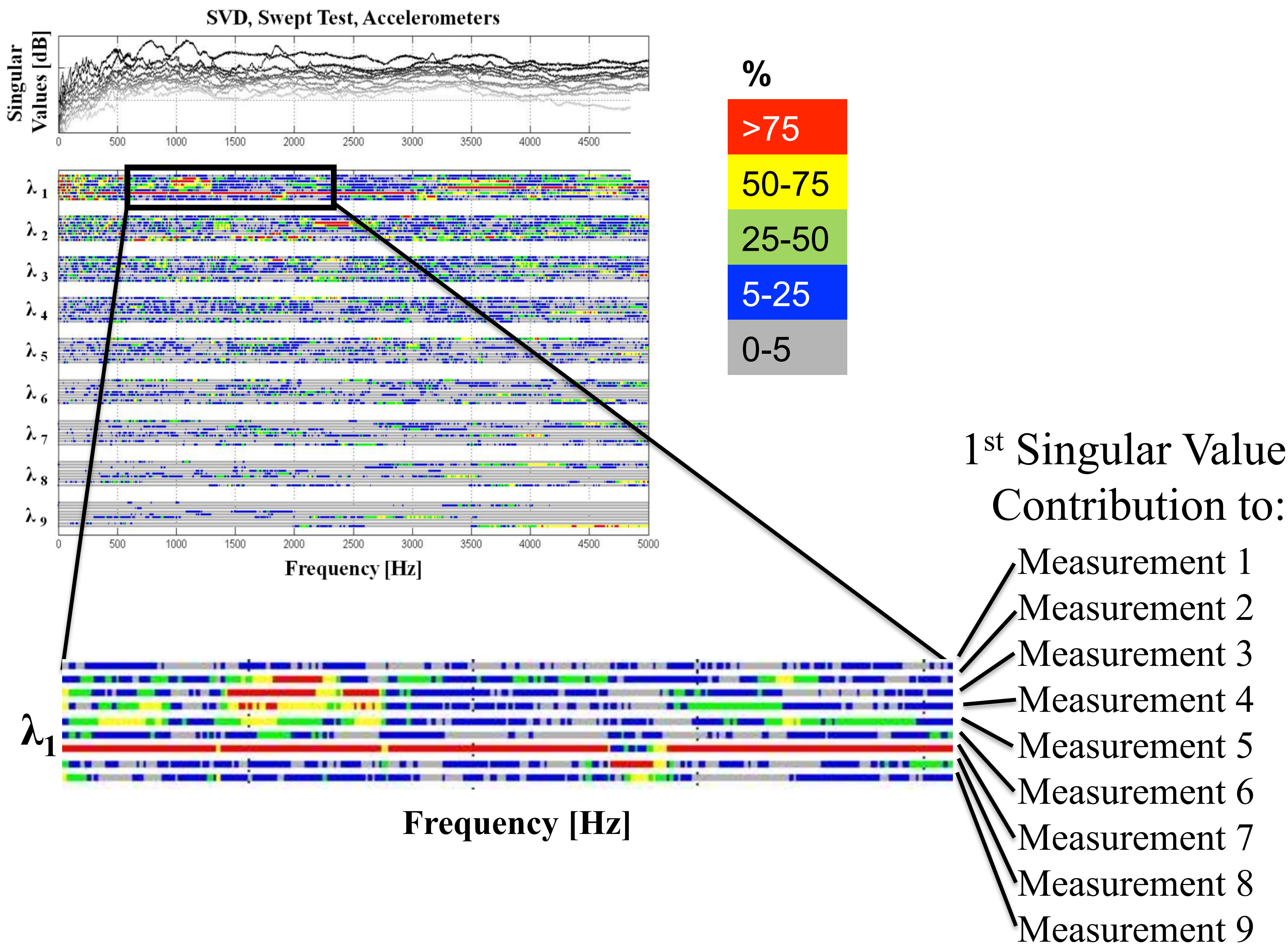
1st Singular Value Contribution — 2nd Singular Value Contribution — n^{th} Singular Value Contribution

$$S_{x_1x_1} = \mathbf{u}_1\lambda_1\mathbf{v}_1^H + \mathbf{u}_2\lambda_2\mathbf{v}_2^H + \ldots + \mathbf{u}_n\lambda_n\mathbf{v}_n^H$$

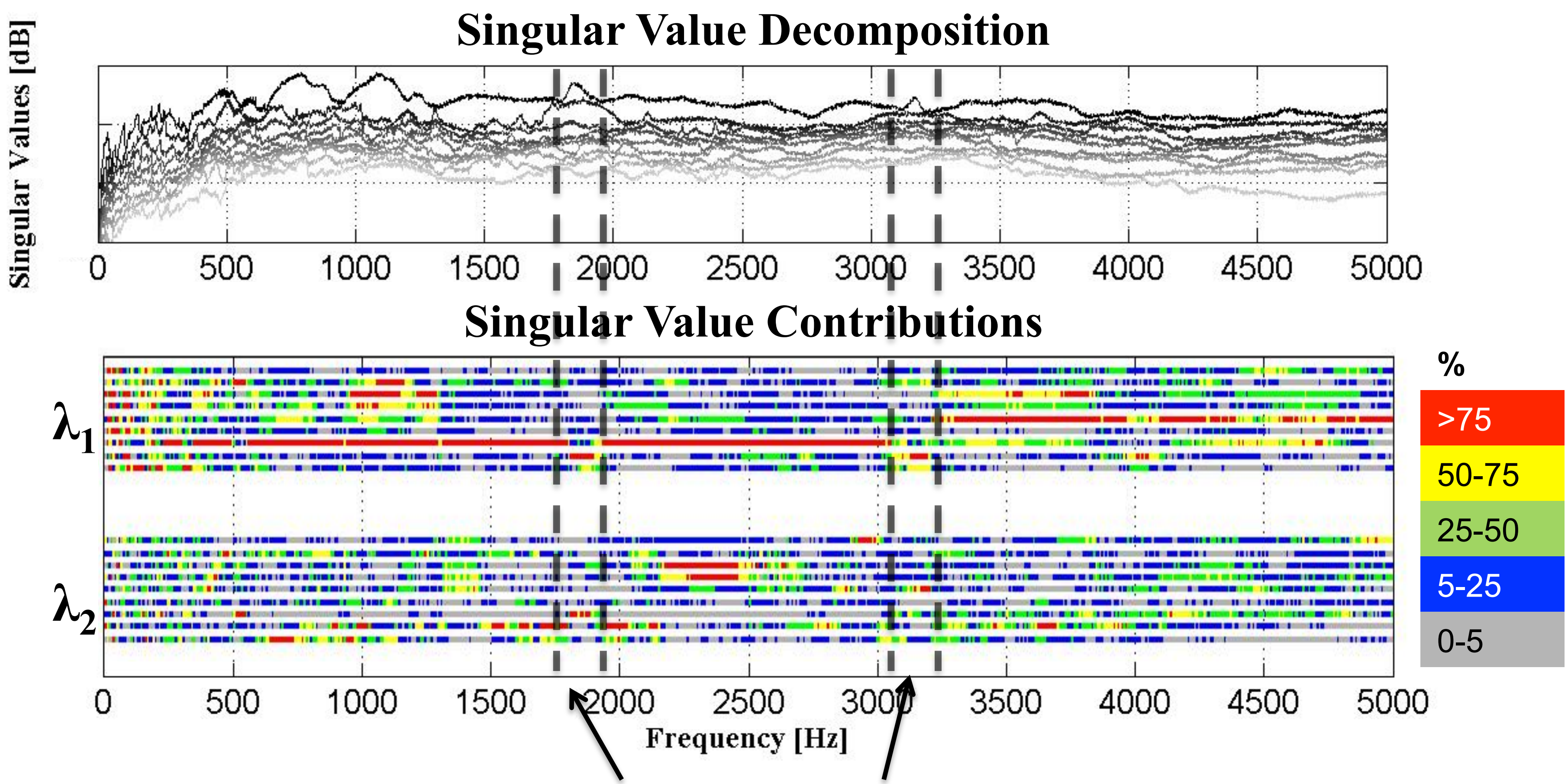
8% — 78%

- Using a color coding scheme depending on the percentage contribution, these can be visualized graphically.

- A similar method is presented in Leclère et al. (2005)


SVD, Swept Test, Accelerometers
Singular Values [dB]
0 500 1000 1500 2000 2500 3000 3500 4000 4500
λ 1
λ 2
λ 3
λ 4
λ 5
λ 6
λ 7
λ 8
λ 9
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000
Frequency [Hz]
%
>75
50-75
25-50
5-25
0-5
1st Singular Value Contribution to:
Measurement 1
Measurement 2
Measurement 3
Measurement 4
Measurement 5
Measurement 6
Measurement 7
Measurement 8
Measurement 9
λ1
Frequency [Hz]

Singular Value Contribution Plot Properties



Swapping singular values

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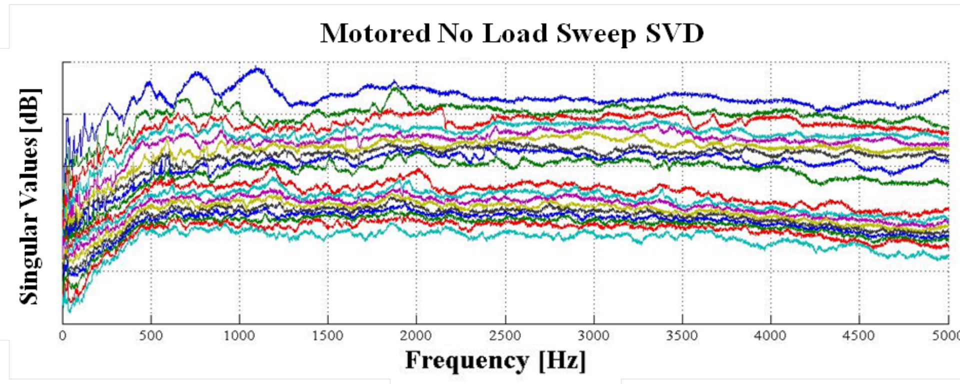
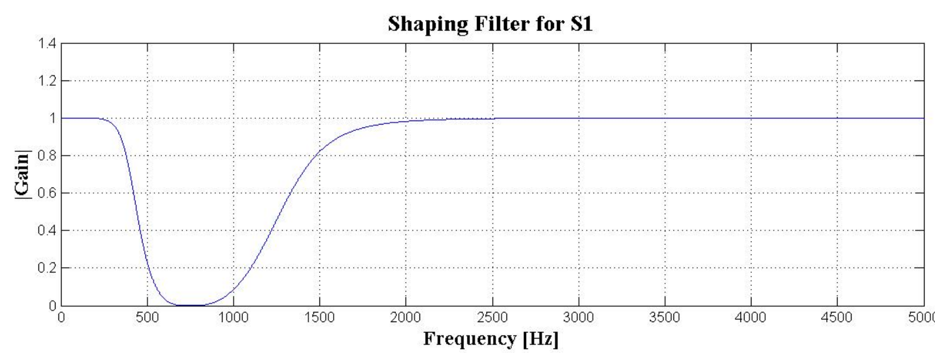
Application of process to real, motored test data

Singular Value Modification Procedure

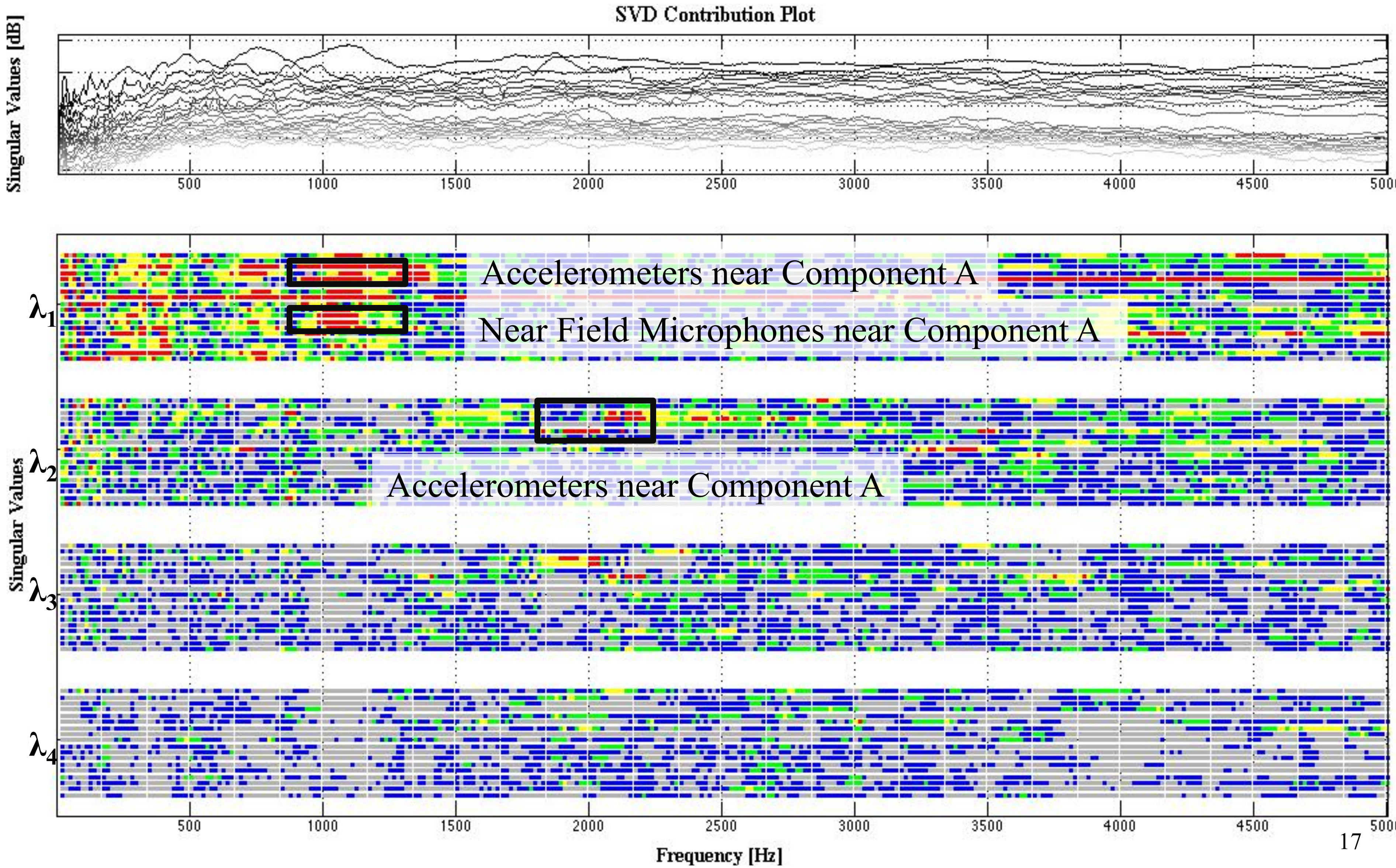
1. Examine relationship between dominant noise source to be modified and near-field singular values using singular value contribution plots.



2. Design shaping function(s) of input singular value(s) to simulate physical modification.

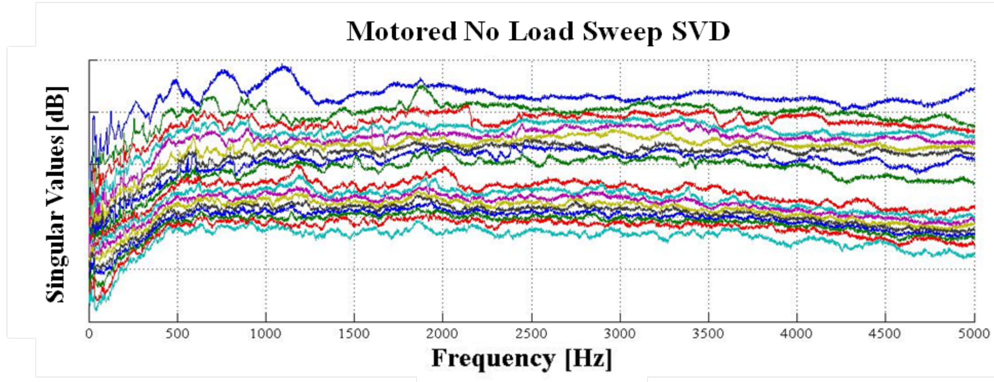


Singular Value Modification Procedure

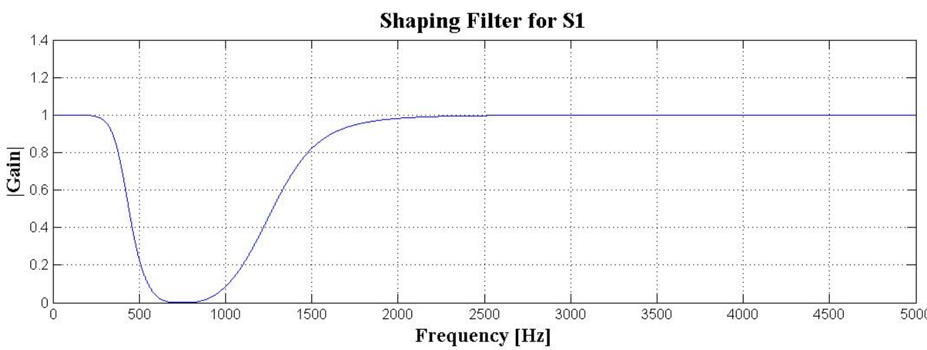


Singular Value Modification Procedure

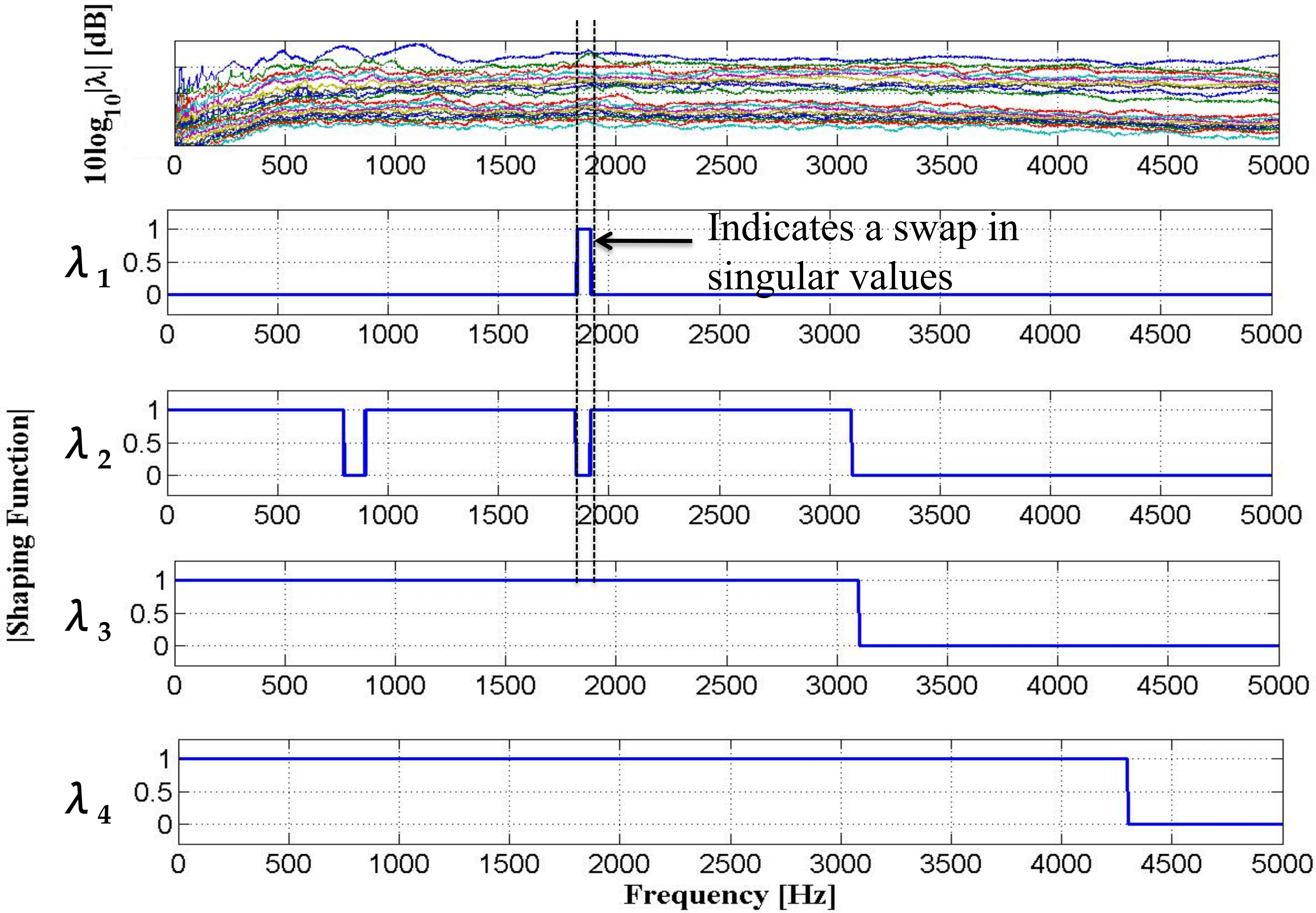
1. Examine relationship between dominant noise source to be modified and near-field singular values using singular value contribution plots.



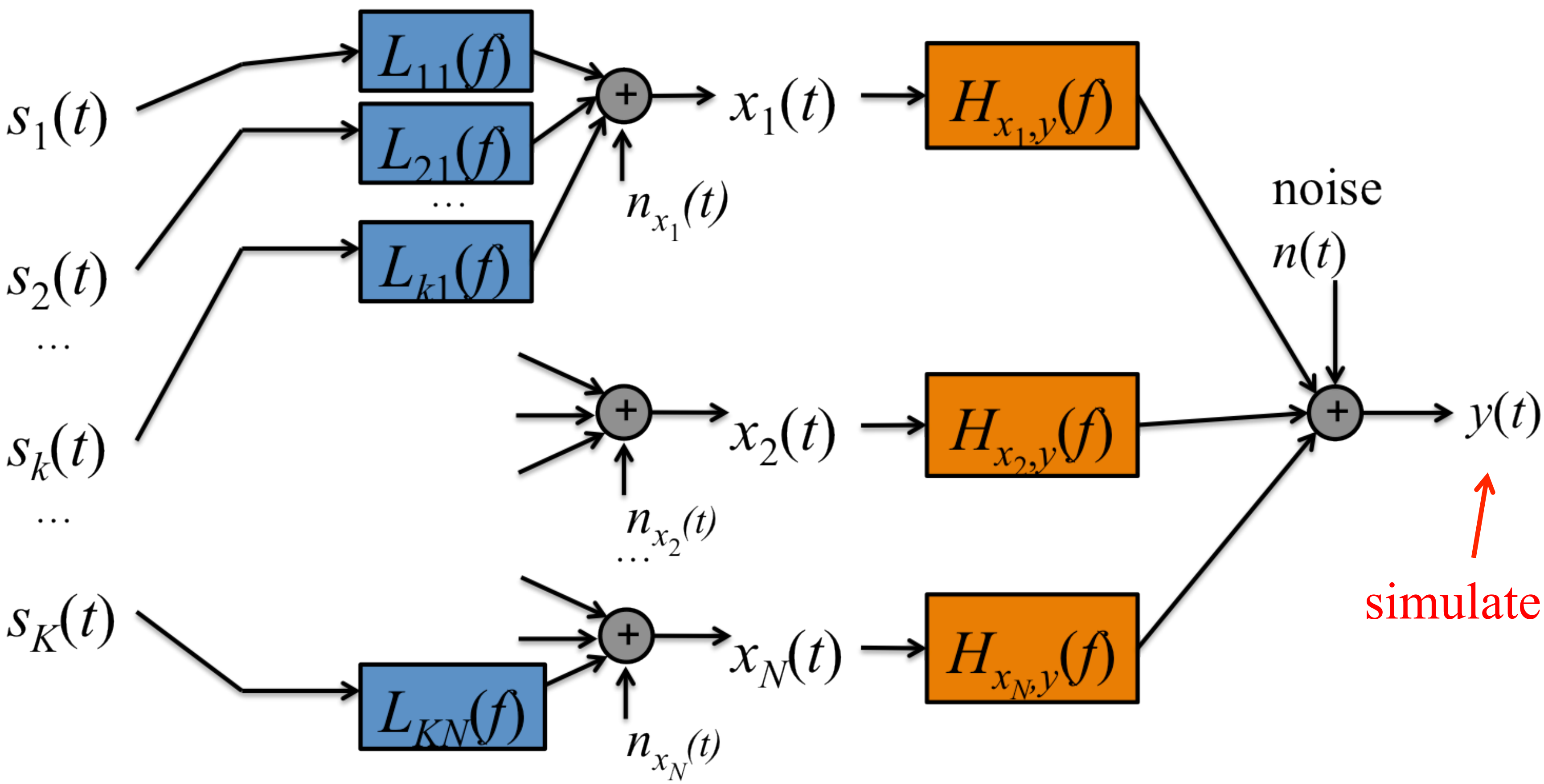
2. Design shaping function(s) of input singular value(s) to simulate physical modification.



Singular Value Shaping Functions



Far-field Simulation



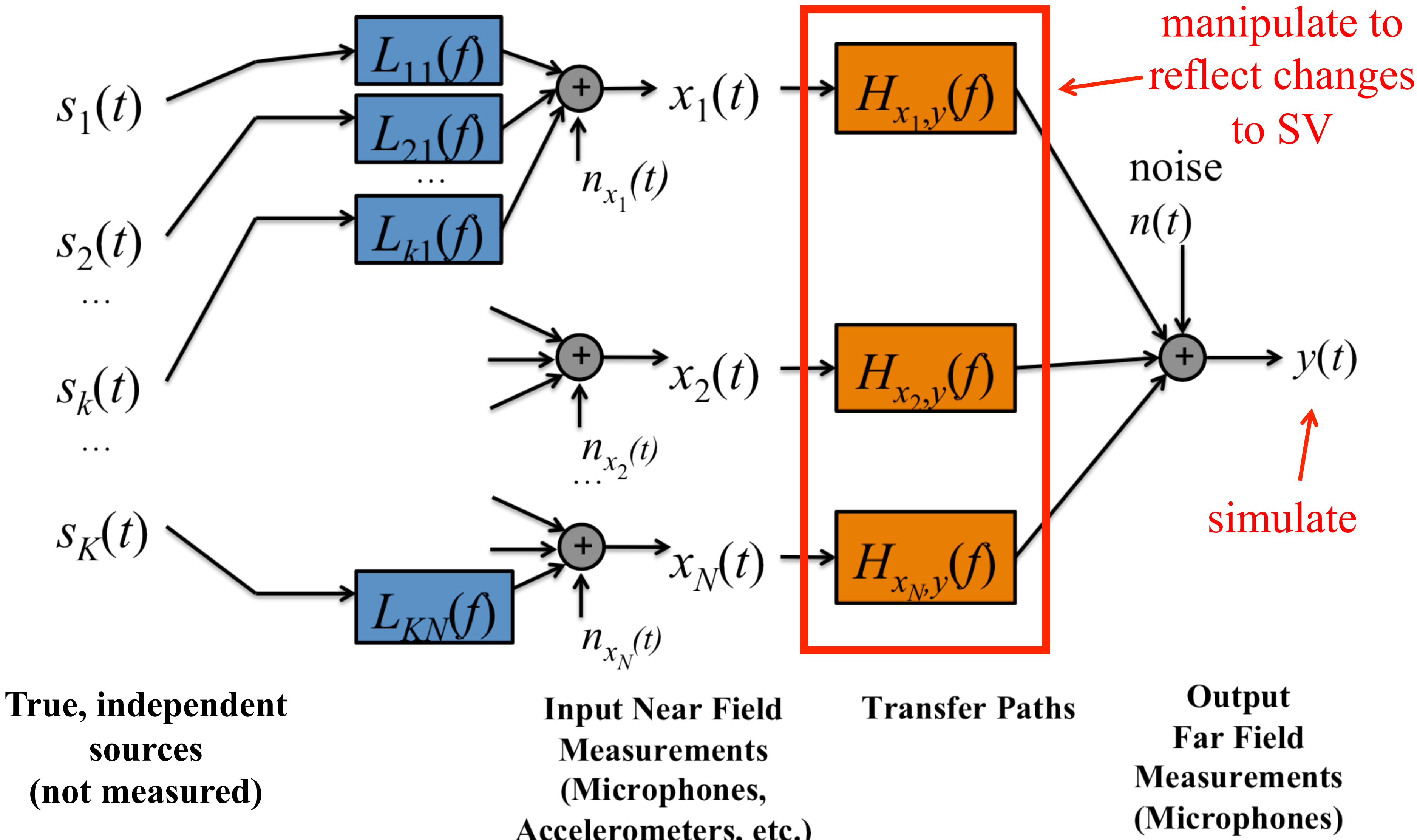
True, independent sources (not measured)

Input Near Field Measurements (Microphones, Accelerometers, etc.)

Transfer Paths

Output Far Field Measurements (Microphones)

Far-field Simulation



Singular Value Modification Procedure

3. Express relationship between the measured spectra can be as:

$$\left[\mathbf{S}_{xy}\right] = \left[\mathbf{S}_{xx}\right]\mathbf{H} = \mathbf{U\Sigma V}^{\mathbf{H}}\mathbf{H}$$

Designed

4. $$\left[\mathbf{S}_{xy,\text{shaped}}\right] = \mathbf{U\Sigma}_{\text{shaped}}\mathbf{V}^{\mathbf{H}}\mathbf{H}$$

5. $$\left[\mathbf{S}_{xy,\text{shaped}}\right] = \mathbf{U\Sigma V}^{\mathbf{H}}\mathbf{H}_{\text{shaped}}\,.$$

Unknown $\mathbf{H}_{\text{shaped}}$

Singular Value Modification Procedure

7. Solve for unknown set of transfer paths, $\mathbf{H}_{\text{shaped}}$, between measured input and simulated output $y_{\text{simulated}}$.

$$\mathbf{H}_{\text{shaped}} = \left[\mathbf{V}^{\text{H}}\right]^{-1} \Sigma^{-1} \Sigma_{\text{shaped}} \mathbf{V}^{\text{H}} \mathbf{H}$$

8. Calculate simulated far-field time history by convolving measured input signals, $x_i(t)$, with newly-calculated impulse response of the transfer paths, $h_{\text{shaped},i}$.

$$y_{\text{simulated}}(t) = \sum_{i=1}^{N} \int_{-\infty}^{\infty} x_i(\tau)\, h_{\text{shaped},i}(t-\tau)\, d\tau$$

Validation

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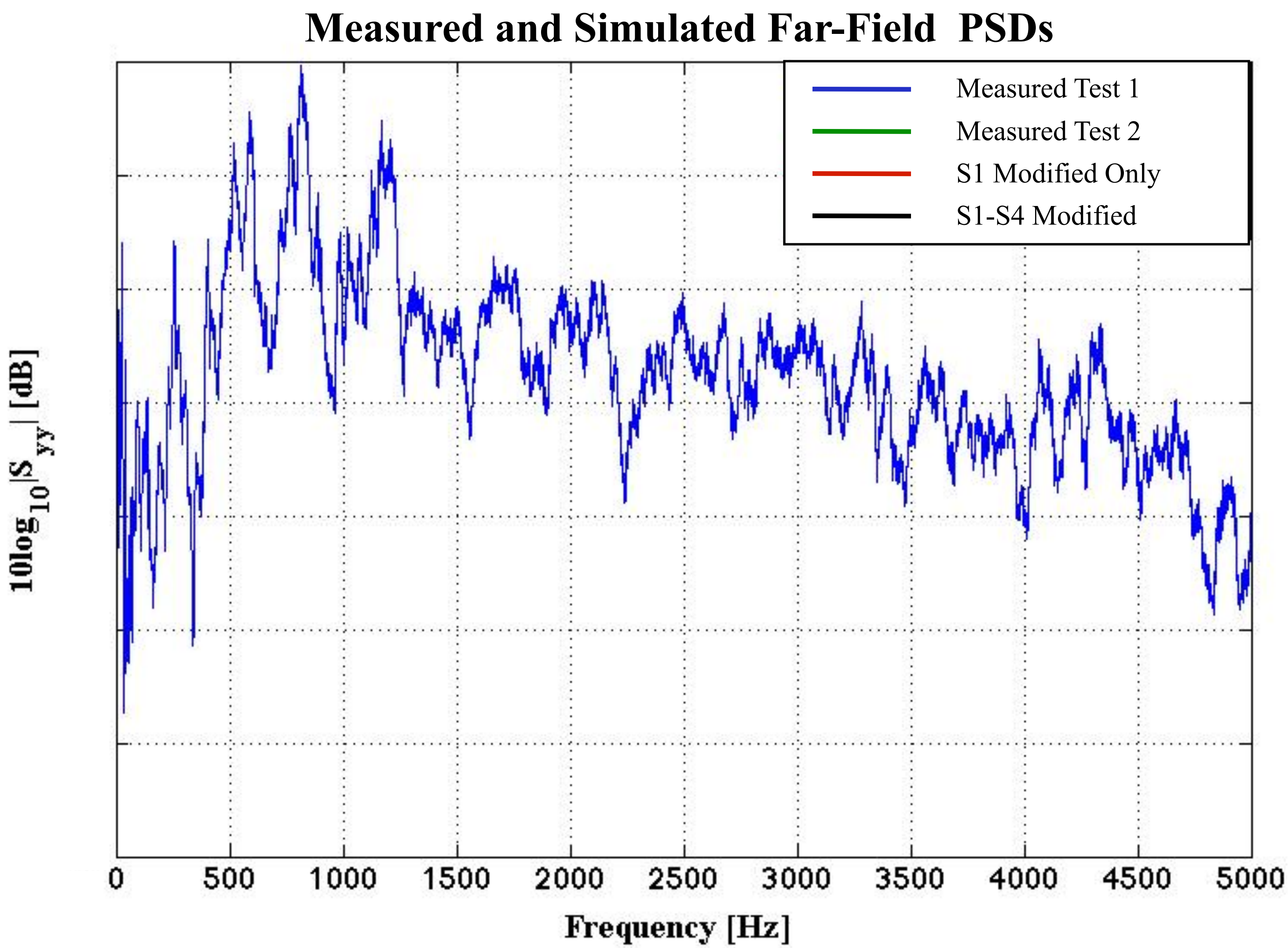
Validation Test Information

- Two separate motored tests were conducted at Roush Industries
- Engine configuration was constant between the two tests except for the presence of Component A
  - Test 1 included Component A in the engine configuration
  - Test 2 was operated without Component A

Method Validation



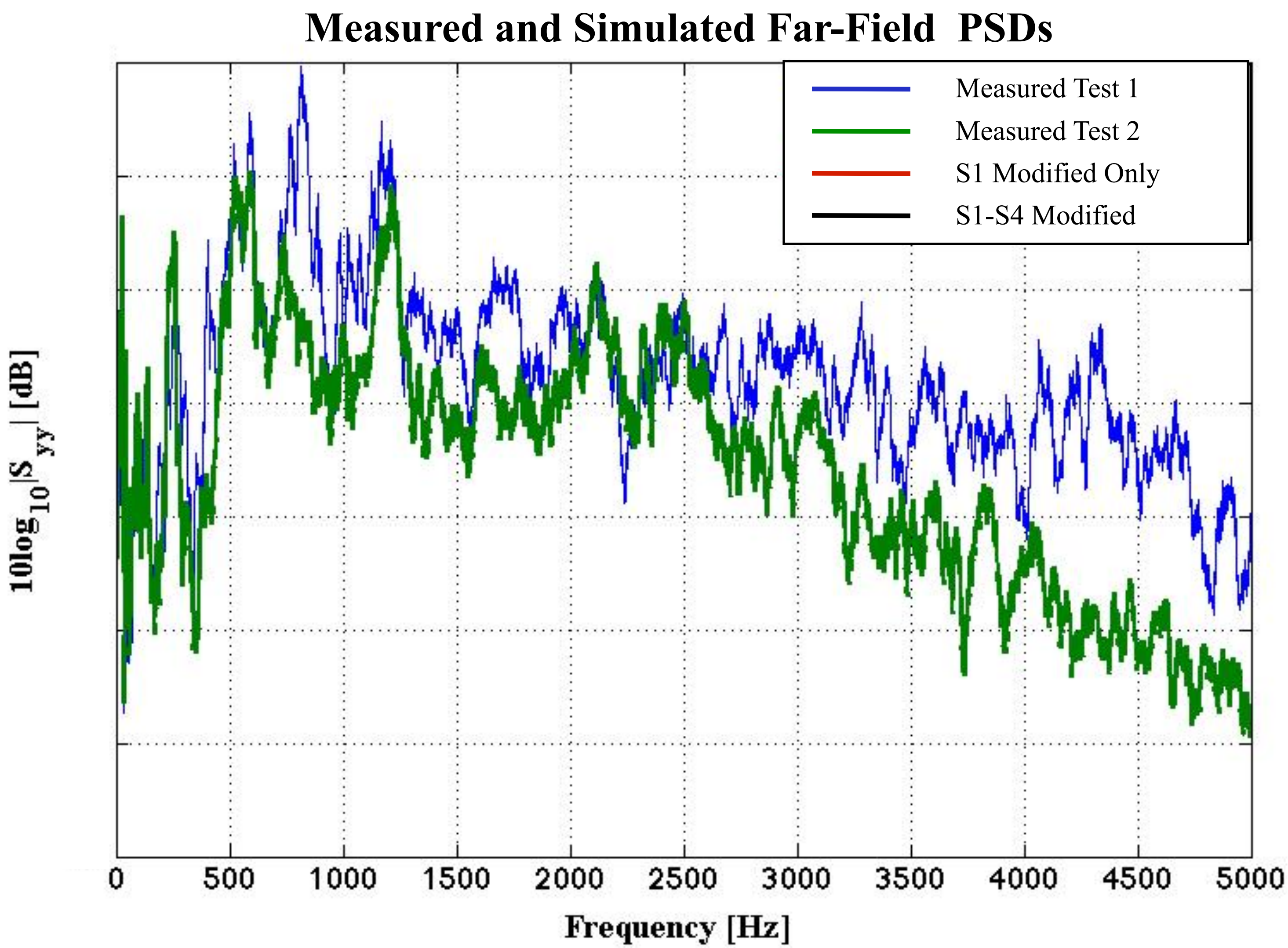
Sounds Generated (45-50s, 5 seconds in length)

Measured Test 1

Measured Test 2

Simulated Test 2 without Component A

Method Validation



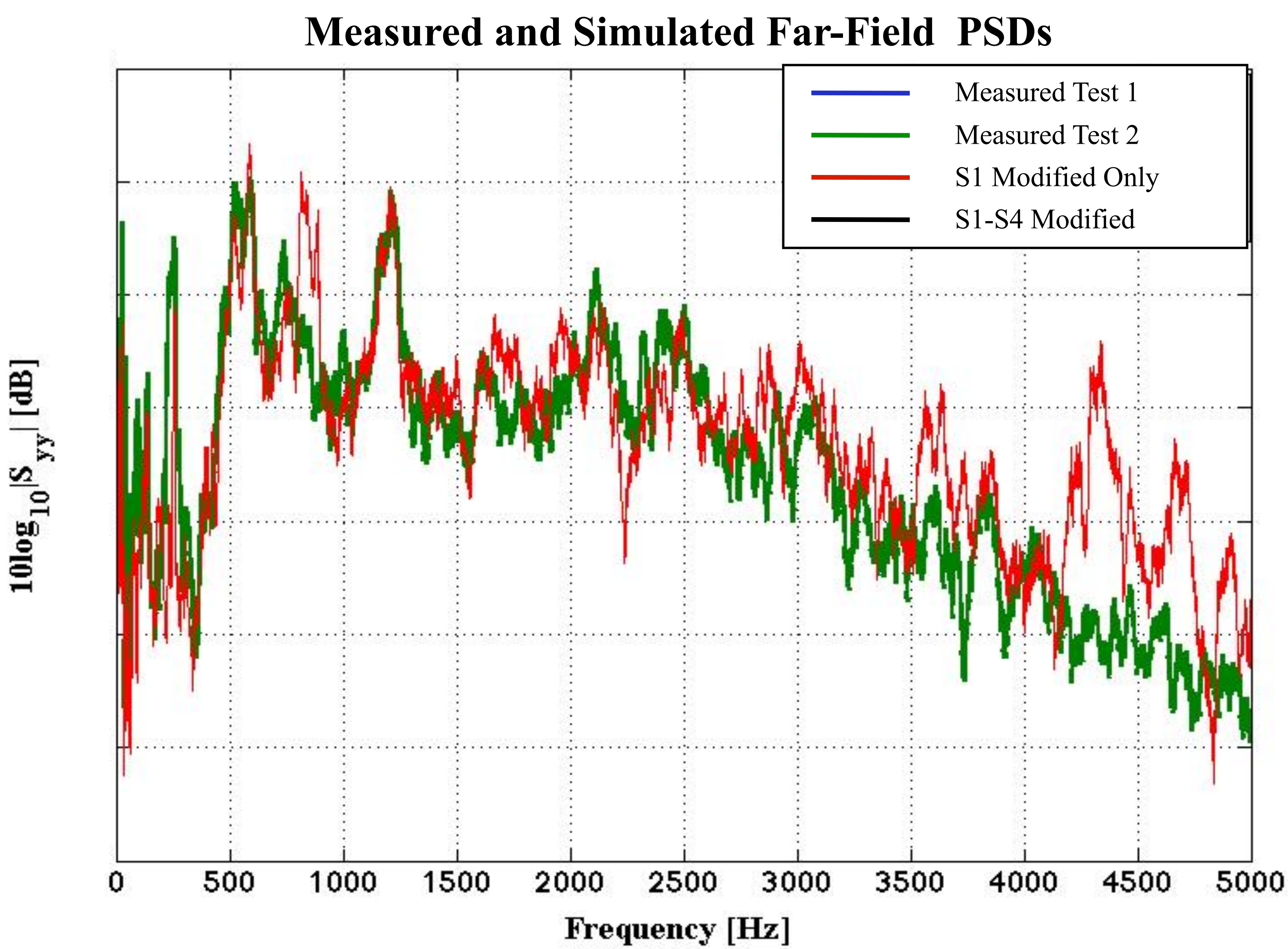
Sounds Generated (45-50s, 5 seconds in length)

Measured Test 1

Measured Test 2

Simulated Test 2 without Component A

Method Validation



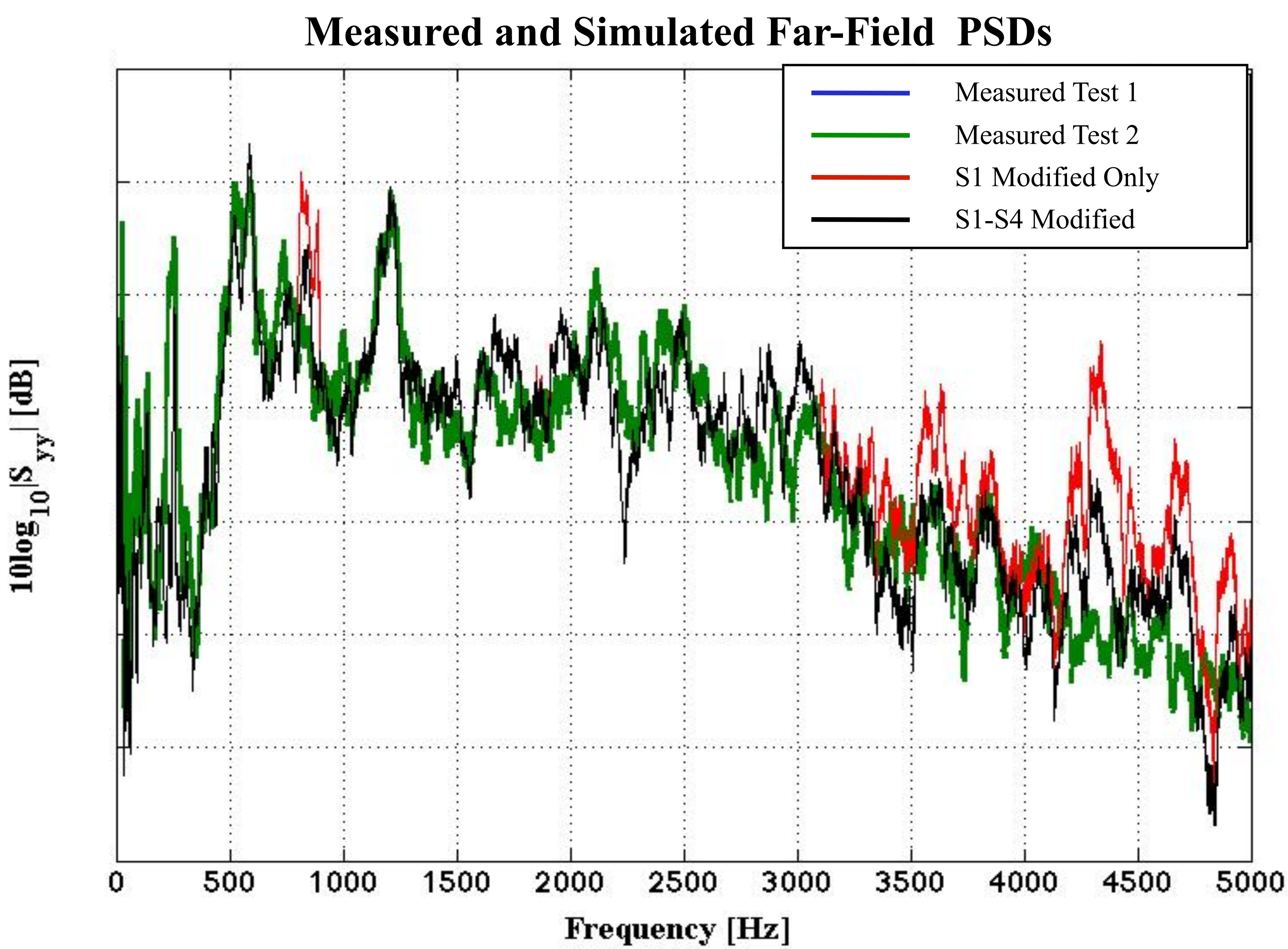
Sounds Generated (45-50s, 5 seconds in length)

Measured Test 1

Measured Test 2

Simulated Test 2 without Component A

Method Validation



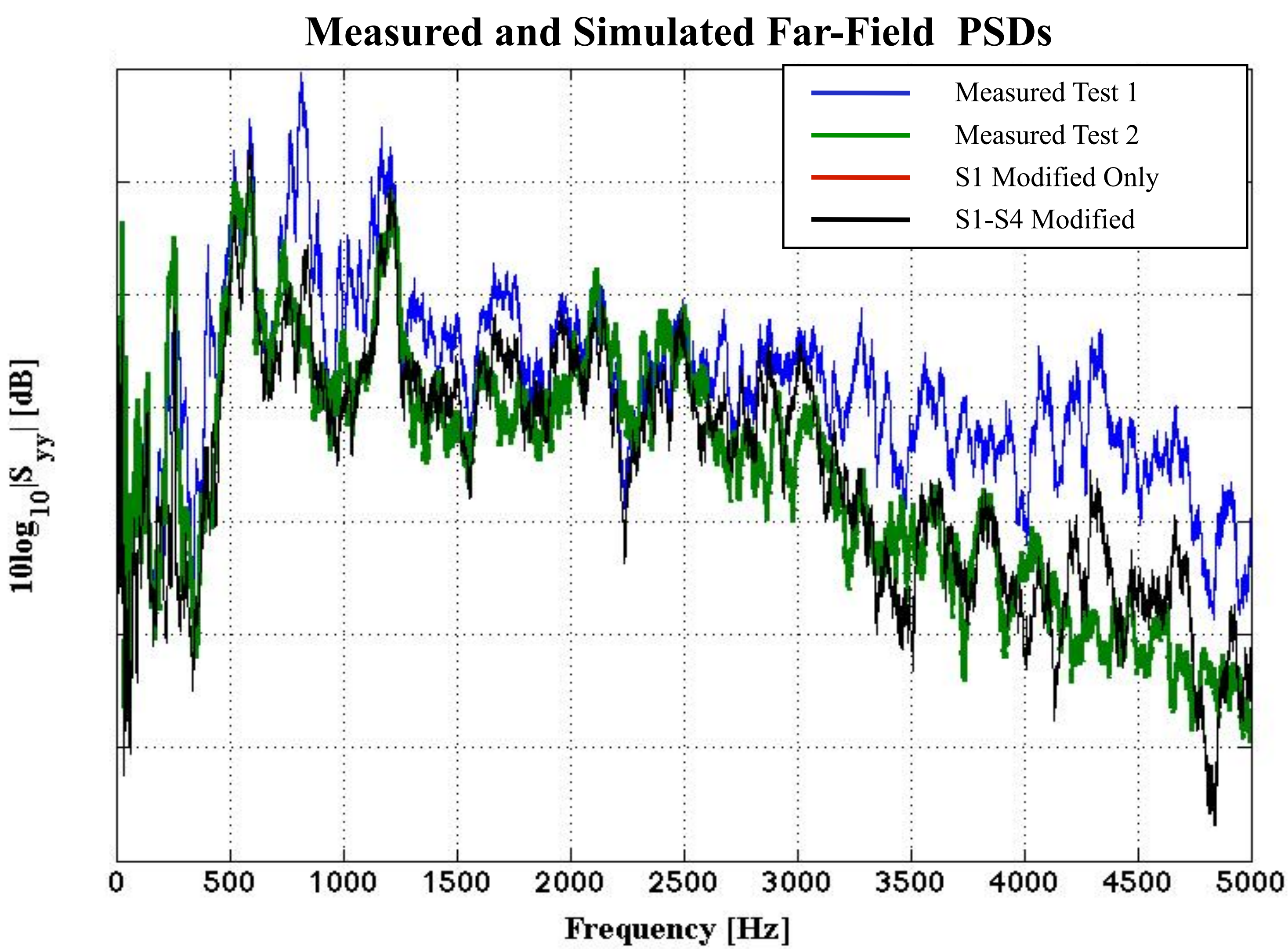
Sounds Generated (45-50s, 5 seconds in length)

Measured Test 1

Measured Test 2

Simulated Test 2 without Component A

Method Validation



Sounds Generated (45-50s, 5 seconds in length)

Measured Test 1

Measured Test 2

Simulated Test 2 without Component A

Singular Value Modification Summary

- Physical modification to an engine can be simulated through alteration of singular values, and recalculation of transfer paths between the near- and far-field.
- This method was validated through application to a motored test in which the contribution of Component A was successfully removed across most of the frequency range of interest.
- Method can only be applied to singular values that exhibit a strong relationship with physical sources (i.e. dominant noise sources, or sources measured with no mixing).

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