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The Application of Singular Value Decomposition to Determine the Sources of Far Field Diesel Engine Noise

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THE APPLICATION OF SINGULAR VALUE DECOMPOSITION TO DETERMINE THE SOURCES OF FAR FIELD DIESEL ENGINE NOISE

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Introduction

- Demand for quieter engines is a constant driving force behind creation of competitive engines
- Determination of dominant noise sources in both the near- and far-fields within an engine is an integral step in development of quieter engines
- A method to assist in noise source identification in the near- and far-fields was desired to reduce the number of time-consuming and expensive fired and motored tests required

Outline

Multiple Input/Multiple Output (MIMO) System

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Transfer Path Estimation Between Inputs and Outputs

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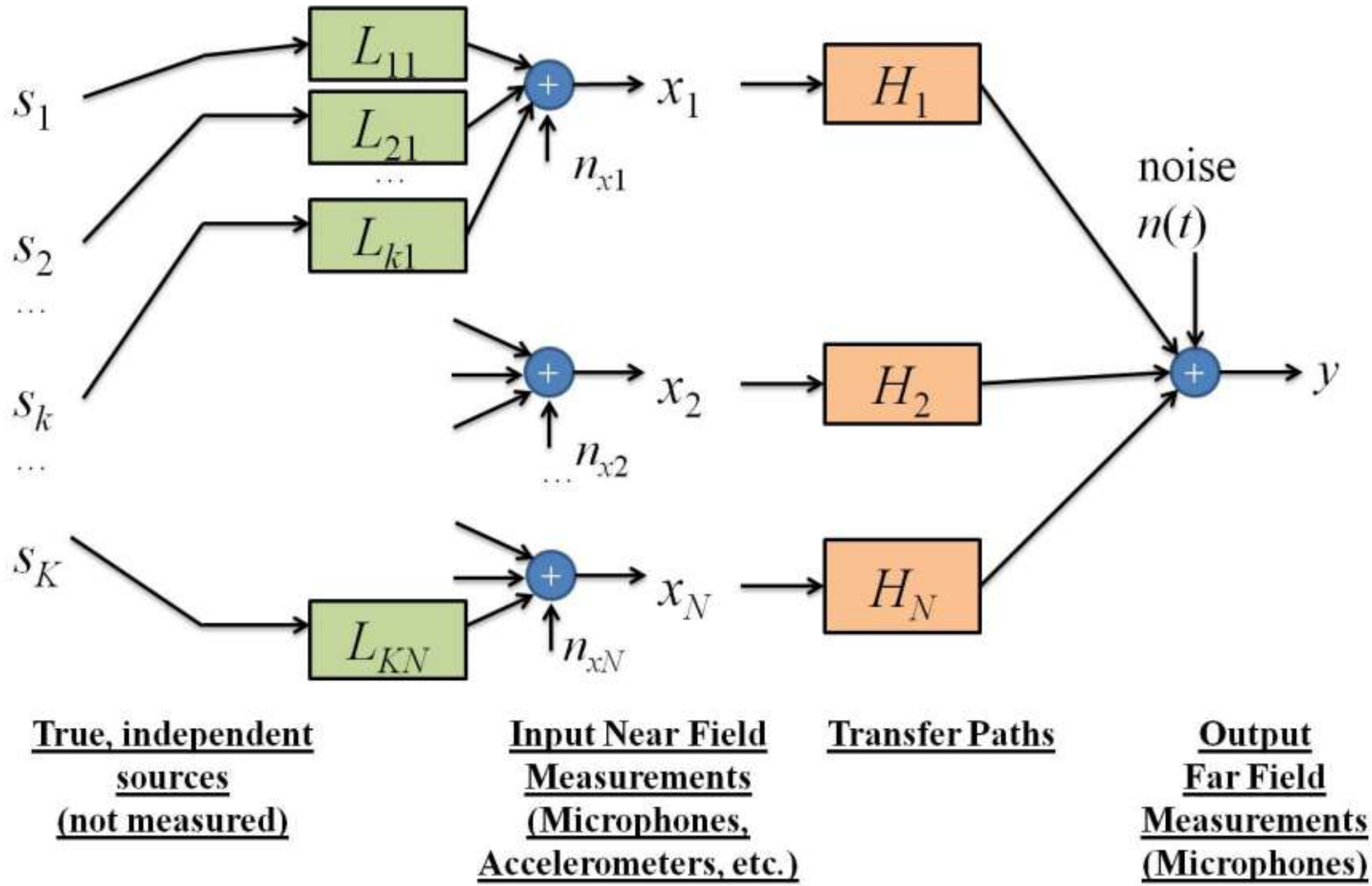
Singular Value Decomposition

↓

SVD Contributions to Near- and Far-Field Measurements

Multiple Input/Single Output System



Solution of Cross-Spectral Matrix Problem

- A method to calculate transfer paths without including repeated information was required.
- In the following simplified equation, H_1 and H_2 are needed

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} H_1 \\ H_2 \end{bmatrix} = \begin{bmatrix} S_{1y} \\ S_{2y} \end{bmatrix}$$

Well Conditioned S_{xx} Matrix

S_{xy} Matrix

Transfer Paths

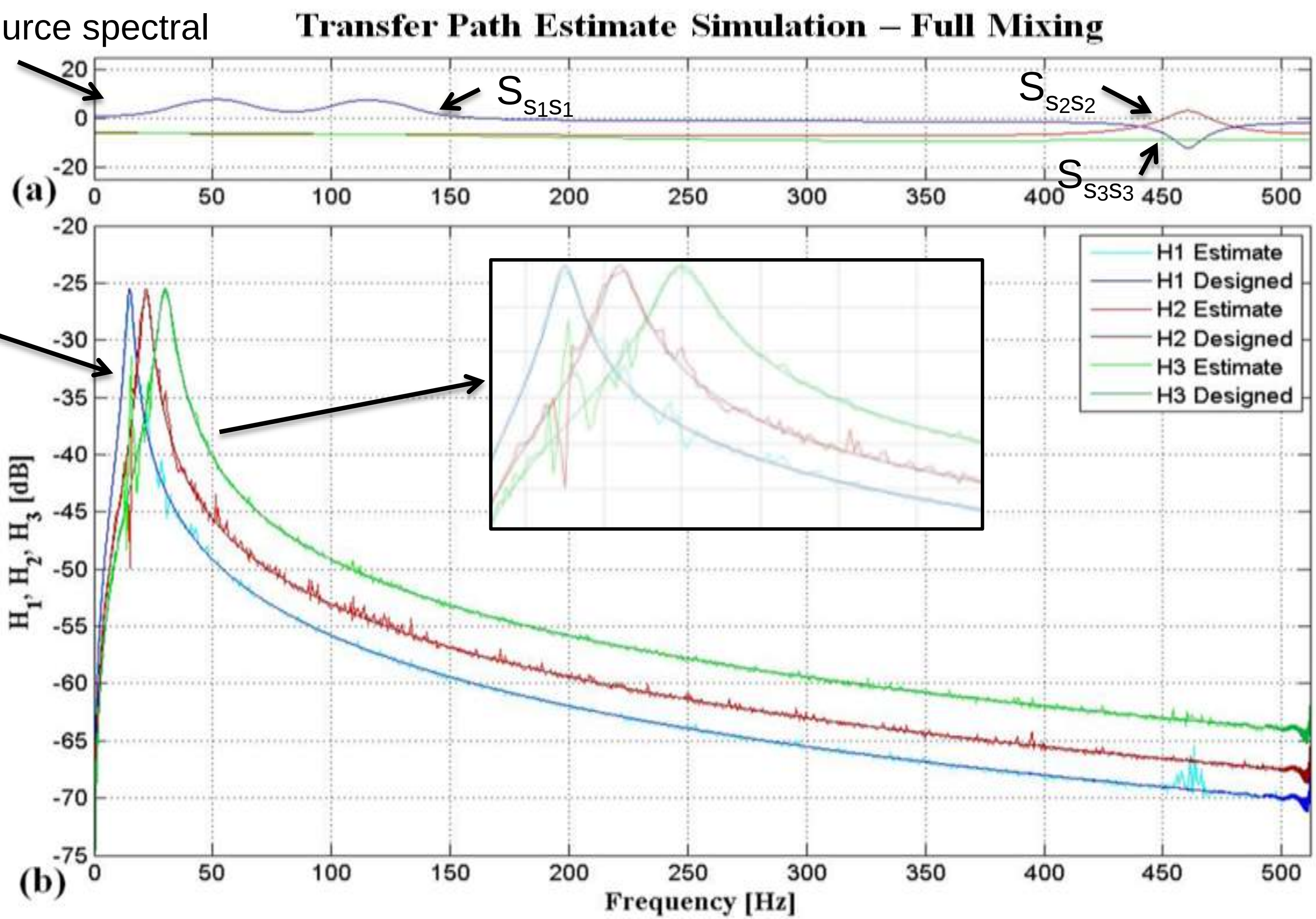
- Solution of this matrix by elementary row operations (Gaussian elimination) was conducted;

$$\begin{bmatrix} S_{11} & S_{12} \\ 0 & S_{22} - \dfrac{S_{12}S_{21}}{S_{11}} \end{bmatrix} \begin{bmatrix} H_1 \\ H_2 \end{bmatrix} = \begin{bmatrix} S_{1y} \\ S_{2y} - \dfrac{S_{1y}S_{21}}{S_{11}} \end{bmatrix}$$

Transfer Path Estimation

Independent source spectral characteristics

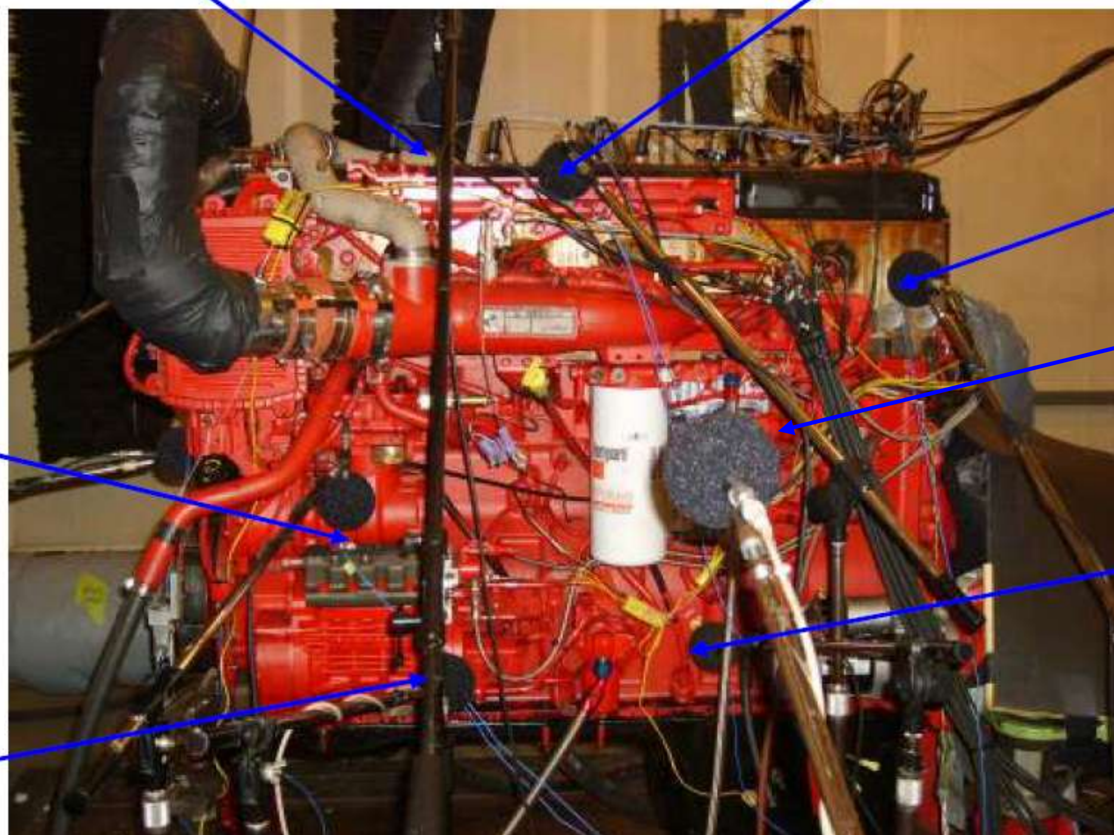
Designed and estimated transfer paths



Testing of Engine

Measurement

Measurement



Measurement

1 Meter
Microphone
(Output)

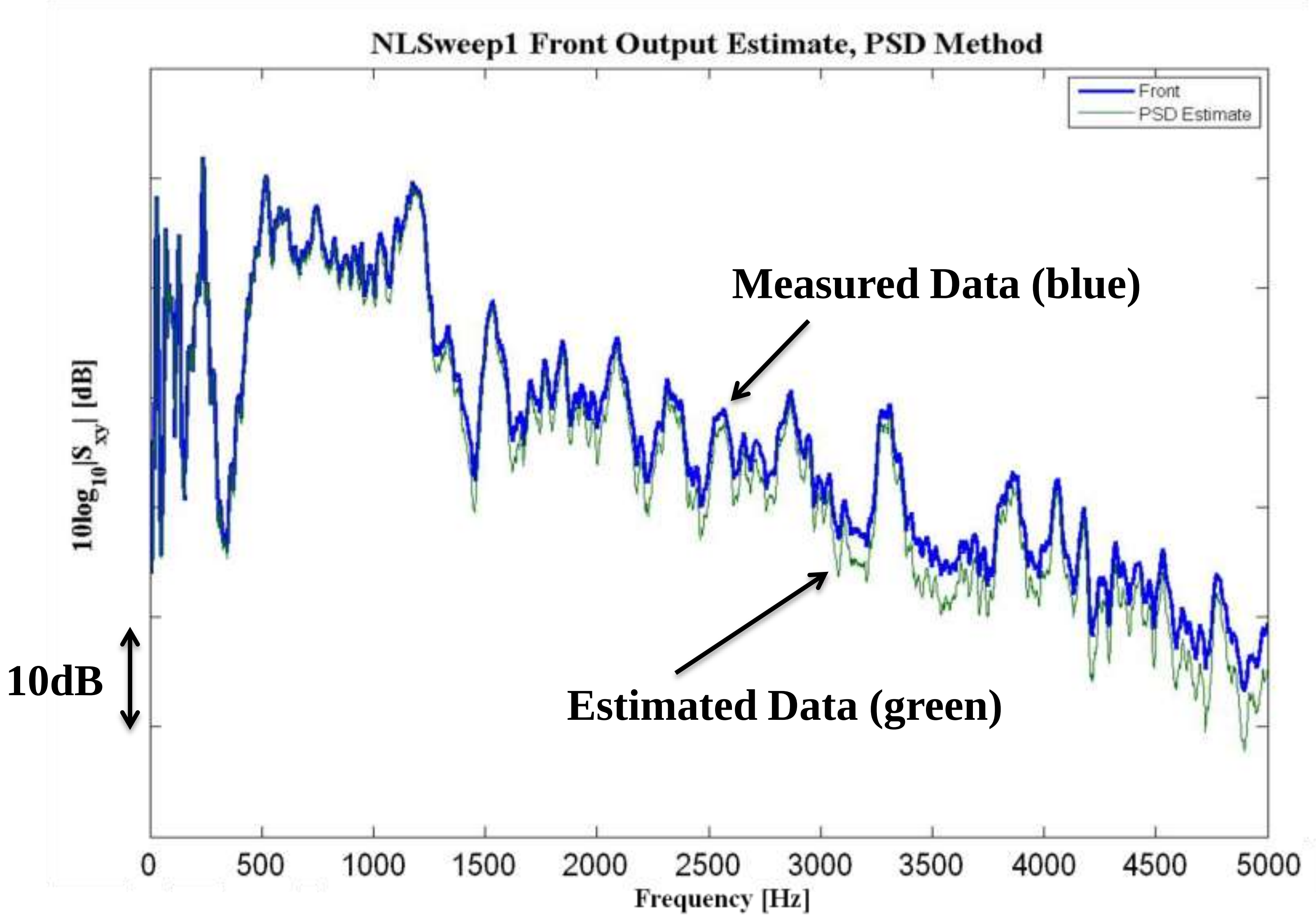
Measurement

Measurement

Measurement

- Each near-field measurement is an accelerometer/near-field microphone pair
- There are also 6 cylinder pressure transducers and 4 far-field microphones

Far Field Estimate Power Spectra



Singular Value Decomposition

Separate noise from uncorrelated sources from the data measured by the inputs

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

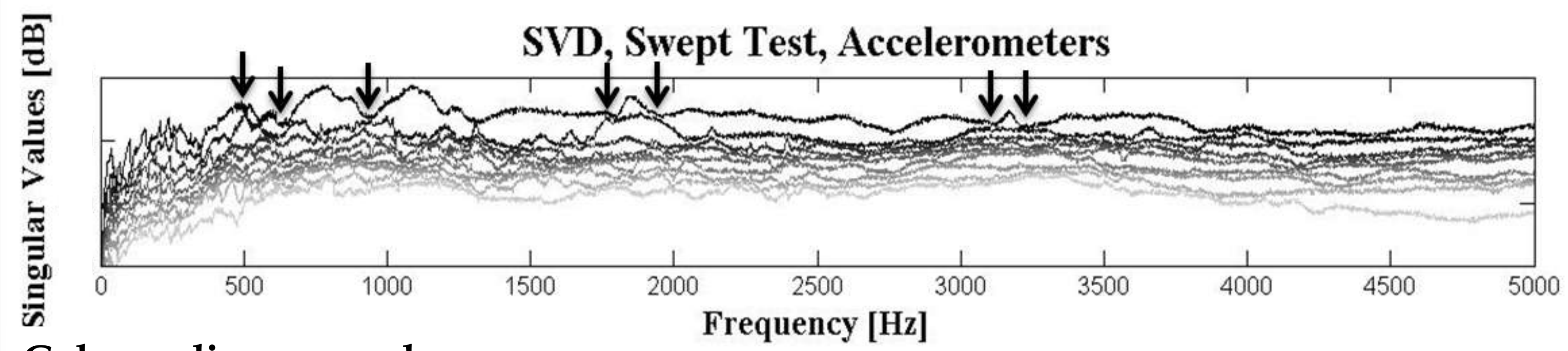
$$U = V \qquad \lambda_1 > \lambda_2 > ... > \lambda_N$$

$[\mathbf{S}_{xx}]$= Cross spectral matrix
N = Number of input measurements to system
λ_i = Singular value
$\mathbf{u_i}$ = Left singular vector
$\mathbf{v_i}$ = Right singular vector
u = **v** in this case

Conducting a decomposition on the accelerometer or near field microphone spectral density matrices will help us identify the number of uncorrelated sources being measured, and potentially their relative strength.

Golub G H and Loan C F V 1996 *Matrix Computations*, 3rd Edition, (Baltimore: Johns Hopkins University Press).

SVD Example and Decomposition



Color coding example

1st Singular Value Contribution

2nd Singular Value Contribution

nth Singular Value Contribution

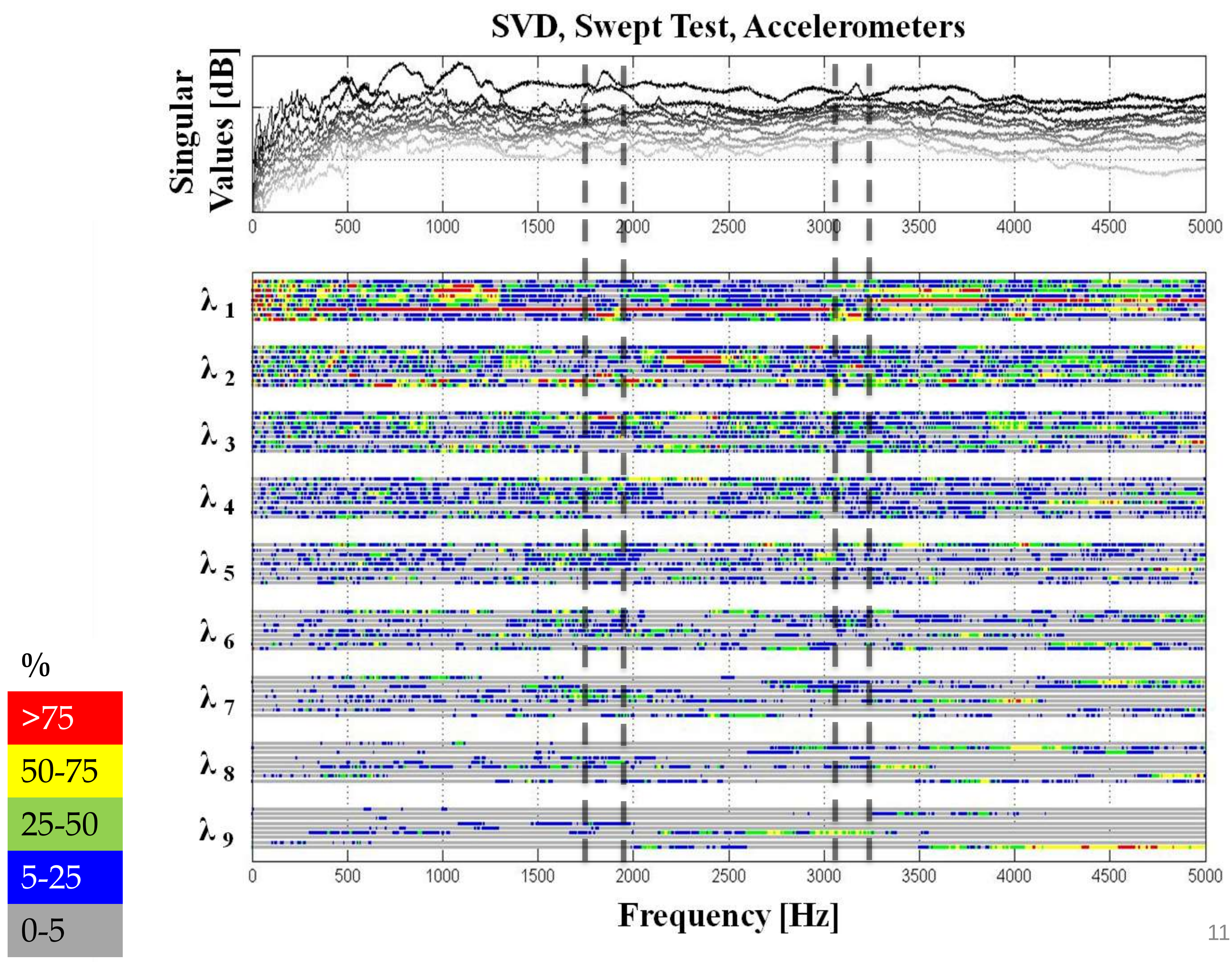
$$S_{x_1x_1} = \mathbf{u}_1\lambda_1\mathbf{v}_1^H + \mathbf{u}_2\lambda_2\mathbf{v}_2^H + \ldots + \mathbf{u}_n\lambda_n\mathbf{v}_n^H$$

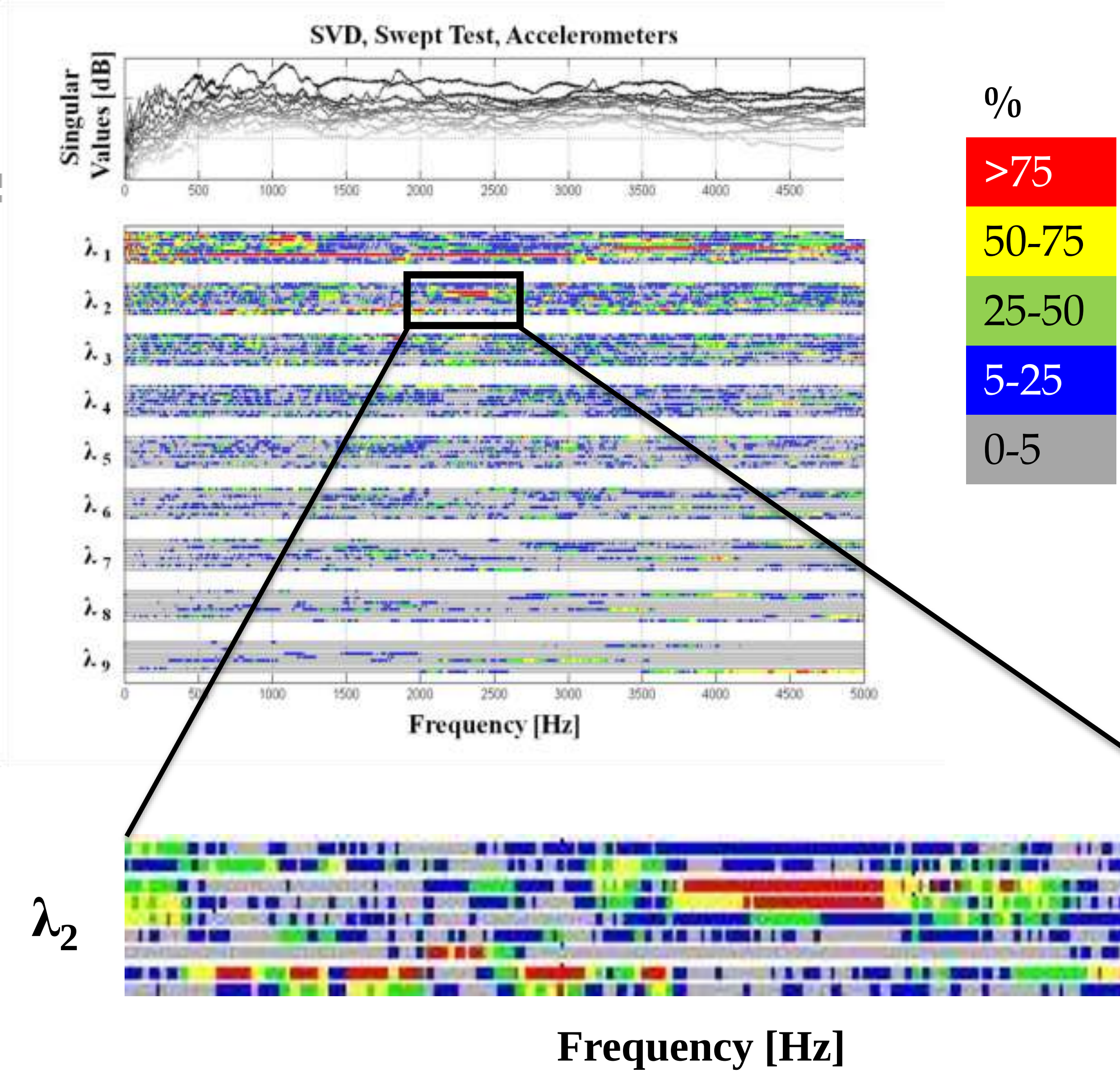
8%

78%

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

- Using a color coding scheme depending on the percentage contribution, these can be visualized graphically.
- A more detailed description of this method can be found in Hayward, Bolton & Davies (2012).


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

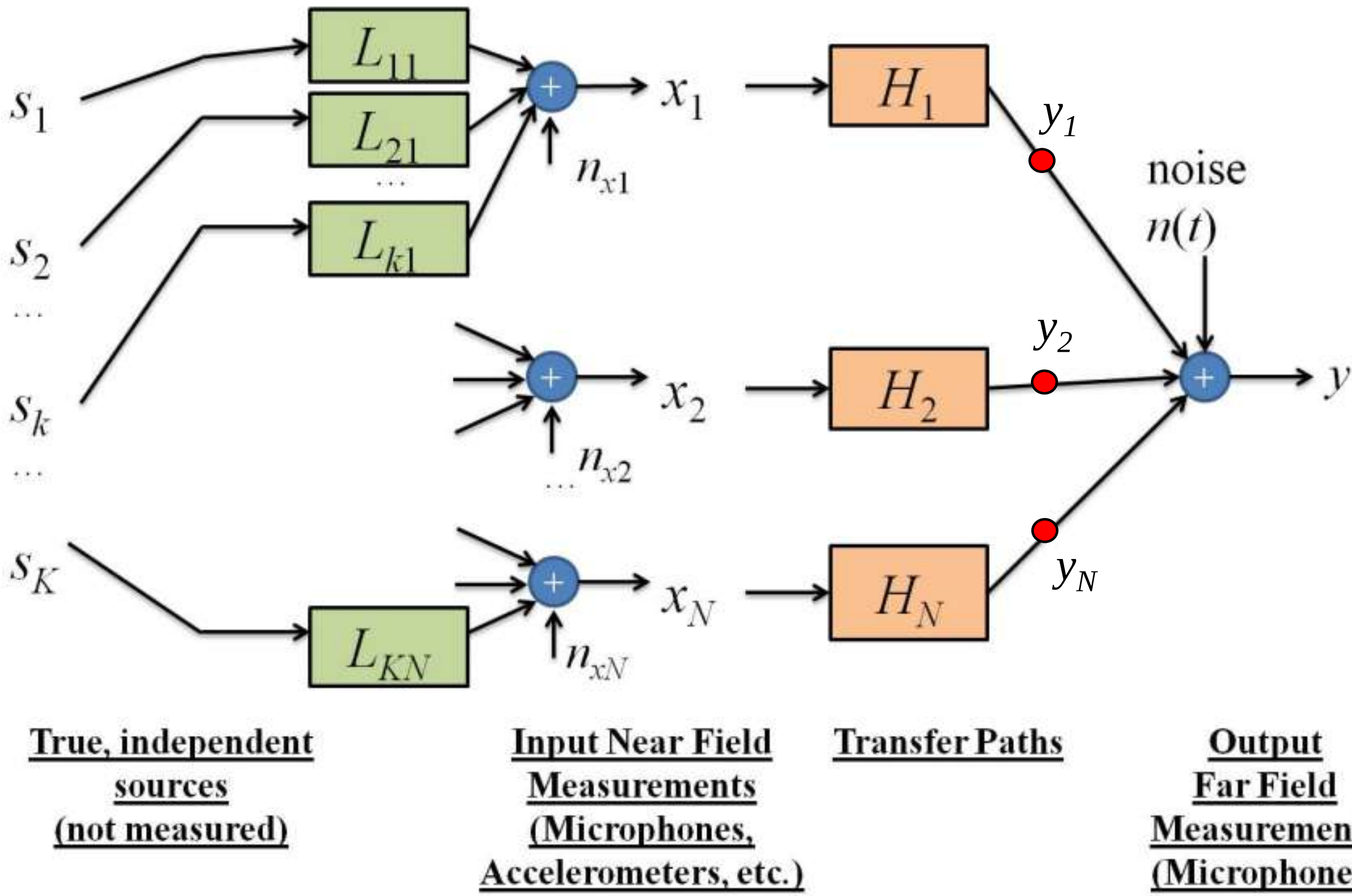


Note: This analysis uses input measurement data – contribution of singular values at output is not used

2nd Singular Value Contribution to:

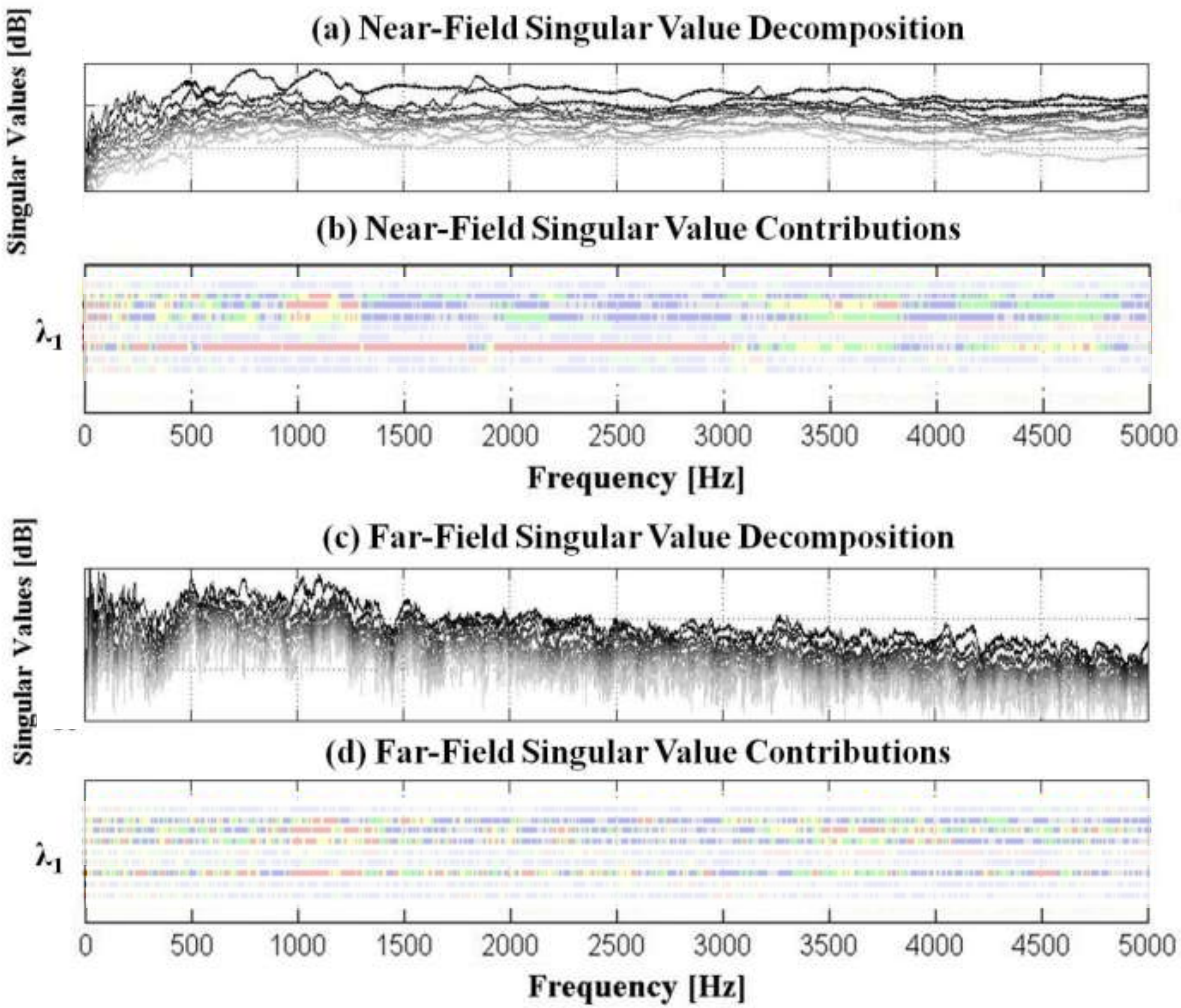
Measurement 1
Measurement 2
Measurement 3
Measurement 4
Measurement 5
Measurement 6
Measurement 7
Measurement 8
Measurement 9

Far Field Source Contributions



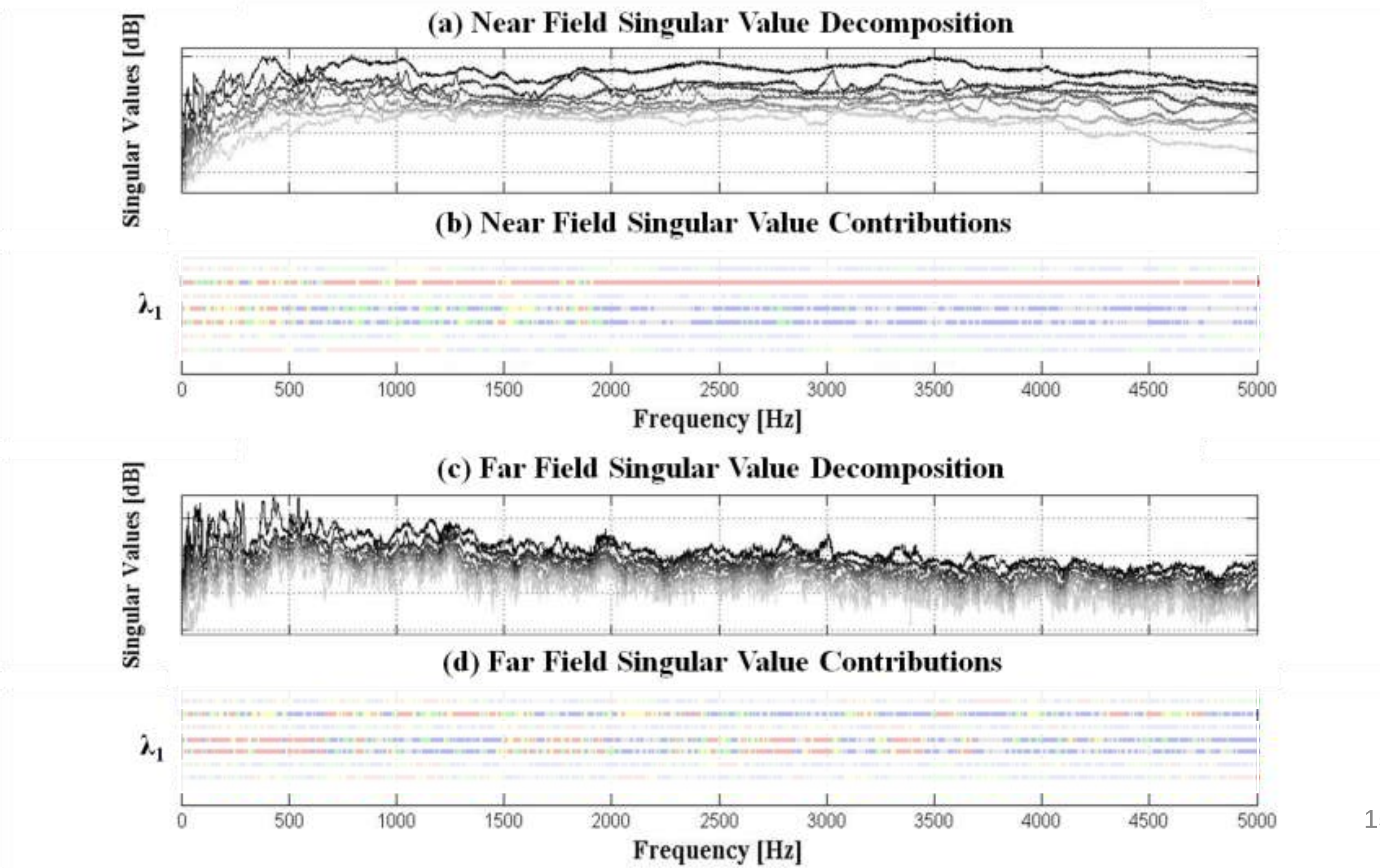
With calculated transfer paths, far-field time histories can be calculated, and source contributions to the far field can be determined

Near-Field and Far-Field Contribution Comparison Example 1



Near-Field and Far-Field Contribution Comparison Example 2

The analysis below is was conducted on data from a different engine, in a full loaded sweep test, with a different set of transducers



Conclusions

- Transfer paths from input to output measurements can be accurately estimated through solution of a cross-spectral matrix problem.
- Contributions of each independent virtual source to real, physical near-field locations can be determined through singular value contribution plots.
- Utilization of input measurements and estimated transfer paths yield both accurate far-field estimate time histories, and SVD contribution plots demonstrating virtual source contributions in the far-field.
- Analysis of the singular values and their contributions to near- and far-field measurement power spectra allows inferences to be drawn regarding the characteristics of dominant noise sources within the engine.

References

Otte D, Sas P and Van de Ponseele 1988 *Noise Source Identification by use of Principal Component Analysis*, Proceedings of Inter-Noise 88 (France: Anvignon)

Kompella MS, Ufford DA, Davies P and Bernhard RJ 1996 *A technique to determine the number of incoherent sources contributing to the response of a system*, Mechanical Systems and Signal Processing, vol. 8 no. 4 pp. 363-380

Leclère Q, Pèzerat C, Laulagnet B and Polac L 2005 *Application of Multi-Channel Spectral Analysis to Identify the Source of a Noise Amplitude Modulation in a Diesel Engine Operating at Idle*, Applied Acoustics, vol. 66 no. 7 pp. 779-798

Hayward, M.D., Bolton, J.S., and Davies, P. 2012 *Connecting the singular values of an input cross-spectral density matrix to noise sources in a diesel engine*, INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Vol. 2012, no. 2, pp. 9583-9593, Institute of Noise Control Engineering

Singular Value Decomposition

Golub G H and Loan C F V 1996 *Matrix Computations*, 3rd Edition, (Baltimore: Johns Hopkins University Press).