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

Michael Hayward
Brandon Sobecki
J Stuart Bolton
Purdue University, bolton@purdue.edu
Patricia Davies
Purdue University, daviesp@purdue.edu

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Modification of simulated far-field engine noise by changing near field measurement singular values

Michael Hayward
Brandon Sobecki
J. Stuart Bolton & Patricia Davies

Ray W. Herrick Laboratory, Purdue University
August 27, 2013
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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).
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).
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

$s_1(t)$

$L_{11}(f)$

$+\quad x_1(t)\quad H_{x_{13}y}(f)$

$L_{21}(f)$

$\quad n_{x_1}(t)$

$\ldots$

$L_{k1}(f)$

$s_2(t)$

$\quad +\quad x_2(t)\quad H_{x_{23}y}(f)$

$\quad n_{x_2}(t)$

$\ldots$

$s_k(t)$

$\quad +\quad x_N(t)\quad H_{x_{N3}y}(f)$

$\quad n_{x_N}(t)$

$s_K(t)$

$L_{KN}(f)$

$\quad +\quad y(t)$

True, independent sources (not measured)

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

Transfer Paths

Output Far Field Measurements (Microphones)

calculate?

noise $n(t)$
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

$$[S_{xy}] = [S_{xx}][H]$$

$H$ 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.)

Transfer Paths

Output Far Field Measurements (Microphones)
Singular Value Decomposition

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

\[
[S_{xx}] = U \Sigma V^H = [u_1, u_2, \ldots u_N] \text{diag} [\lambda_1, \lambda_2, \ldots \lambda_N] [v_1, v_2, \ldots v_N]^H
\]

- \( \lambda_1 > \lambda_2 > \ldots > \lambda_N \)

- \( S_{xx} \) is Hermitian symmetric, so \( U = V \).

- Each singular value \( \lambda_i \) 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.

\[
S_{xx} = U \Sigma V^H = [u_1, u_2, \ldots u_N] \text{diag}[\lambda_1, \lambda_2, \ldots \lambda_N][v_1, v_2, \ldots v_N]^H
\]

Color coding example

<table>
<thead>
<tr>
<th>%</th>
<th>1st Singular Value Contribution</th>
<th>2nd Singular Value Contribution</th>
<th>nth Singular Value Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50-75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25-50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 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)
$\lambda_1$ $\lambda_2$ $\lambda_3$ $\lambda_4$ $\lambda_5$ $\lambda_6$ $\lambda_7$ $\lambda_8$ $\lambda_9$

**1st Singular Value Contribution to:**
- Measurement 1
- Measurement 2
- Measurement 3
- Measurement 4
- Measurement 5
- Measurement 6
- Measurement 7
- Measurement 8
- Measurement 9

---

### Frequency [Hz]

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

### Percentage

- **>75**
- **50-75**
- **25-50**
- **5-25**
- **0-5**
Singular Value Decomposition

Singular Value Contributions

Swapping singular values

Singular Value Contribution Plot Properties
Outline

Introduction
Motivations and objectives

Background
Previously developed methods required for simulation

Process
Method of simulation

Validation
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

- Accelerometers near Component A
- Near Field Microphones near Component A

SVD Contribution Plot

<table>
<thead>
<tr>
<th>Singular Values [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ₁</td>
</tr>
<tr>
<td>λ₂</td>
</tr>
<tr>
<td>λ₃</td>
</tr>
<tr>
<td>λ₄</td>
</tr>
</tbody>
</table>
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

Indicates a swap in singular values
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

True, independent sources (not measured)

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

Transfer Paths

Output Far Field Measurements (Microphones)

$\begin{align*}
\mathbf{L}_1(f) & \rightarrow x_1(t) \\
\mathbf{L}_2(f) & \rightarrow x_2(t) \\
\vdots & \vdots \\
\mathbf{L}_K(f) & \rightarrow x_N(t) \\
\end{align*}$

$H_{x_1,y}(f)$

$H_{x_2,y}(f)$

$\vdots$

$H_{x_N,y}(f)$

$\begin{align*}
\mathbf{n}_{x_1}(t) & \rightarrow x_1(t) \\
\mathbf{n}_{x_2}(t) & \rightarrow x_2(t) \\
\vdots & \vdots \\
\mathbf{n}_{x_N}(t) & \rightarrow x_N(t) \\
\end{align*}$

$\mathbf{n}(t)$

$\begin{align*}
\mathbf{y}(t) & = \mathbf{L}_K(f) + \mathbf{L}_1(f) + \mathbf{L}_2(f) + \cdots + \mathbf{L}_K(f) + \mathbf{n}(t) \\
\end{align*}$

manipulate to reflect changes to SV

simulate
Singular Value Modification Procedure

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

\[
\begin{bmatrix}
S_{xy} \\
S_{xx}
\end{bmatrix} = \begin{bmatrix}
S_{xx}
\end{bmatrix} H = U \Sigma V^H H
\]

4. \[
\begin{bmatrix}
S_{xy,\text{shaped}}
\end{bmatrix} = U \Sigma_{\text{shaped}} V^H H
\]

5. \[
\begin{bmatrix}
S_{xy,\text{shaped}}
\end{bmatrix} = U \Sigma V^H H_{\text{shaped}}
\]

Designed

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

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

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

Introduction
Motivations and objectives

Background
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Process
Method of simulation

Validation
Application of process to real, motored test data
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

Measured and Simulated Far-Field PSDs

- Measured Test 1
- Measured Test 2
- S1 Modified Only
- S1-S4 Modified

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

- Measured Test 1
- Measured Test 2
- Simulated Test 2 without Component A

Measured and Simulated Far-Field PSDs
Method Validation

Measured and Simulated Far-Field PSDs

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

Measured Test 1

Measured Test 2

S1 Modified Only

S1-S4 Modified

Measured Test 1

Measured Test 2

Simulated Test 2 without Component A
Method Validation

Measured and Simulated Far-Field PSDs

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

- Measured Test 1
- Measured Test 2
- Simulated Test 2 without Component A

Measured Test 1
Measured Test 2
S1 Modified Only
S1-S4 Modified
Method Validation

Measured and Simulated Far-Field PSDs

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

- Measured Test 1
- Measured Test 2
- Simulated Test 2 without Component A

Measured S1 Modified Only
- S1-S4 Modified

Frequency [Hz]
Method Validation

Measured and Simulated Far-Field PSDs

- Measured Test 1
- Measured Test 2
- S1 Modified Only
- S1-S4 Modified

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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