6-14-2017

Diesel Engine Noise Source Visualization with Wideband Acoustical Holography

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2017-01-1874

NVH in Diesel Engine

Transfer Paths

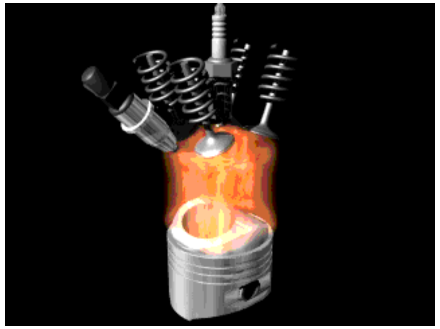
- Environment
- Health
- Safety

Noise Source Identification

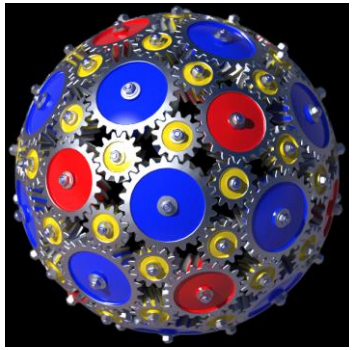
Difficulty in Diesel Engine Noise Source Identification

Complex Noise Sources

- Different Noise Sources
  - Combustion Nosie



  - Mechanical Noise

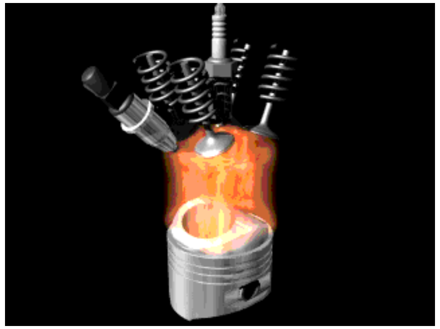


LOUD 1020-node microphone array

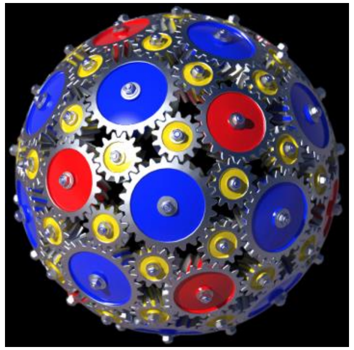
Image source: publications.csail.mit.edu

Complex Noise Sources

- Different Noise Sources
  - Combustion Nosie



  - Mechanical Noise



Goal

- Low cost
- Measurement Friendly

LOUD 1020-node microphone array

Image source: publications.csail.mit.edu

Diesel Engine Noise Source Identification Solution

- Equivalent Source Method
  - More close to the physical noise source
  - With appropriate regularization process, major noise source can be identified
- Partial Field Decomposition
  - Separate uncorrelated noise sources

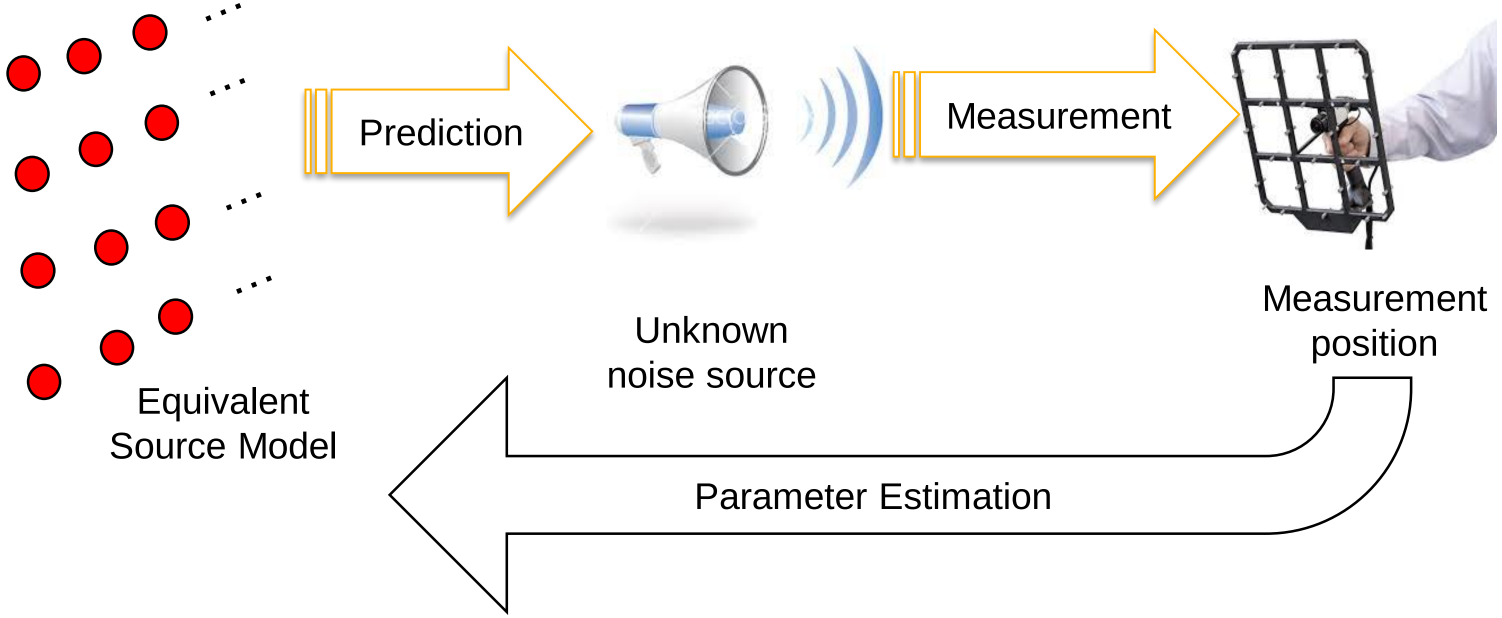


Figure 1: Equivalent Source Method Procedure

Monopoles at Fixed Location

- Expression of a monopole with source strength S

$$P_{S0}(\vec{X}|\vec{X_0},\omega) = S * P_0(\vec{X}|\vec{X_0},\omega) = \frac{Se^{-jk\|\vec{X}-\vec{X_0}\|}}{4\pi\|\vec{X}-\vec{X_0}\|},$$

Where ||.|| denotes the Euclidian norm of a vector, and the wave number $k=\omega/c$, with c is the speed of sound. *S* is a complex number containing the information of both amplitude and phase needs to be estimated.

- The equation of the measured acoustic field at all locations can be written in a matrix form:

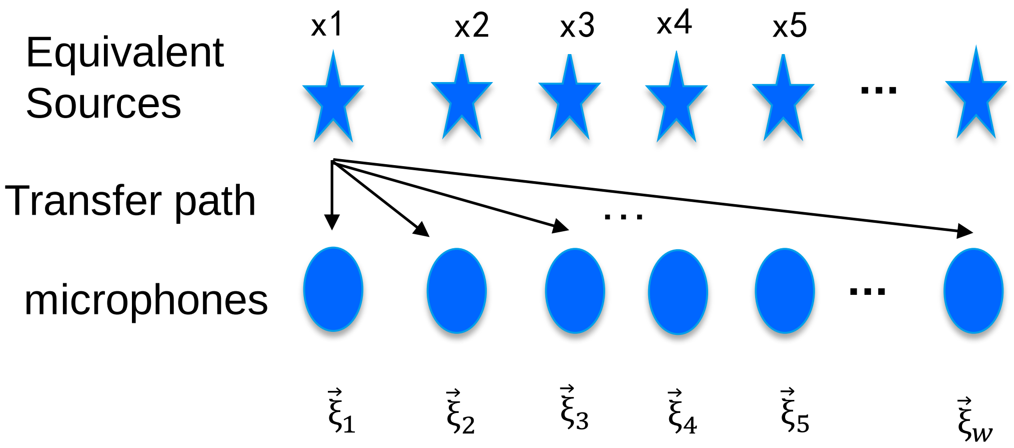
$$\overrightarrow{\hat{P}_m} = A(\vec{X}_S)\vec{S} \quad \rightarrow \quad \vec{S} = \overrightarrow{\hat{P}_m} A(\vec{X}_S)^{-1},$$

Where

$$\overrightarrow{\hat{P}_m} = [\hat{P}_m(\vec{\xi}_1|\vec{X}_S,\omega), \dots \hat{P}_m(\vec{\xi}_W|\vec{X}_S,\omega)]^T,$$

$$A(\vec{X}_S,\omega) = \begin{bmatrix} \vec{P}(\vec{\xi}_1|\vec{X}_S,\omega)^T \\ \vec{P}(\vec{\xi}_2|\vec{X}_S,\omega)^T \\ \dots \\ \vec{P}(\vec{\xi}_W|\vec{X}_S,\omega)^T \end{bmatrix},$$

Appropriate regularization method

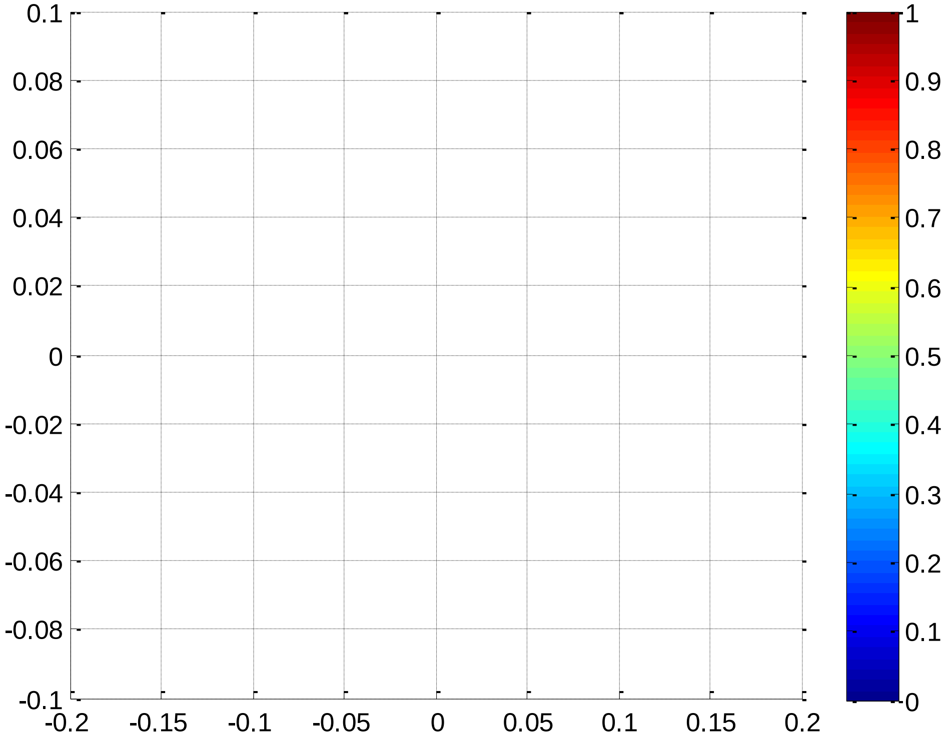


Monopoles at Fixed Locations with Wideband Acoustical Regularization

- Regularization
  - Jorgen Hald. Wideband Holography. *Inter-Noise, Melbourne, Australia,* November 2014.

Source strength vector q_k

take source strength
as zero at first iteration



Monopoles at Fixed Locations with Wideband Acoustical Regularization

➢ Regularization

- Jorgen Hald. Wideband Holography. *Inter-Noise, Melbourne, Australia,* November 2014.

Source strength vector q_k

take source strength as zero at first iteration

Calculate residual vector

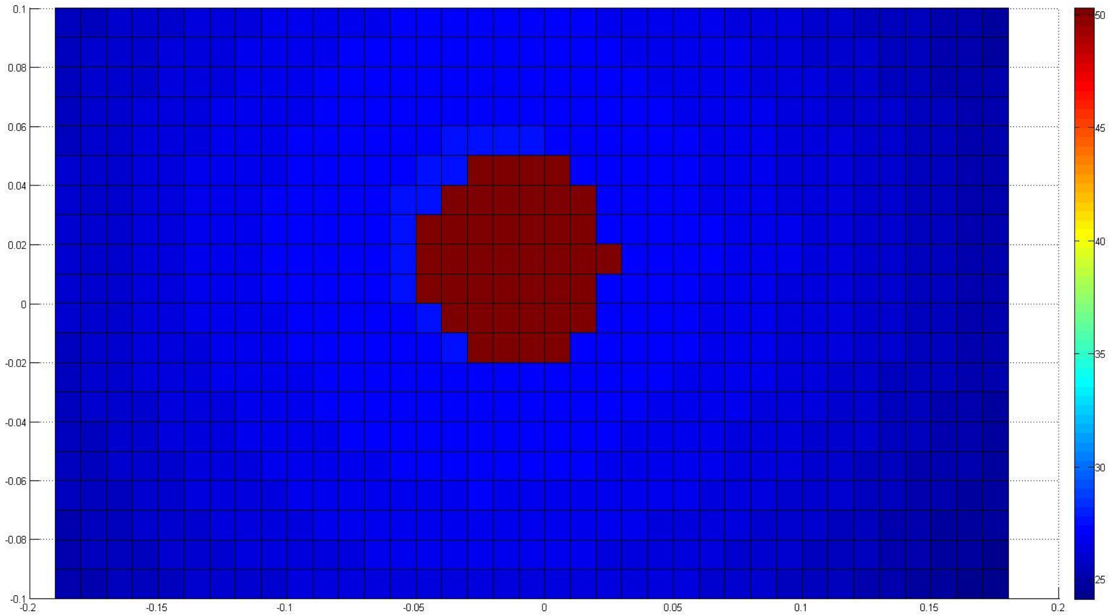
Residual vector: $r(\vec{q}) \equiv \left\| \vec{P}_m - A\vec{q} \right\|^2$

Calculate the step Δq to minimize the residual vector

$\Delta q_k = s_k \vec{w}_k$, where $\vec{w}_k$ is the negative gradient vector, $\vec{w}_k \equiv A^H r(q_k) = A^H(p - Aq_k)$, s_k is the step length to minimum along that direction $s_k \equiv \frac{g_k^H r(q_k)}{g_k^H g_k}$, the vector g_k defined as $g_k \equiv A\vec{w}_k$

$q_{k+1} = q_k + \alpha \Delta q$

Get the next source strength candidate



Monopoles at Fixed Locations with Wideband Acoustical Regularization

➢ Regularization

- Jorgen Hald. Wideband Holography. *Inter-Noise, Melbourne, Australia,* November 2014.

Source strength vector q_k

take source strength as zero at first iteration →

Calculate residual vector

Residual vector: $r(\vec{q}) \equiv \left\| \vec{P}_m - A\vec{q} \right\|^2$ →

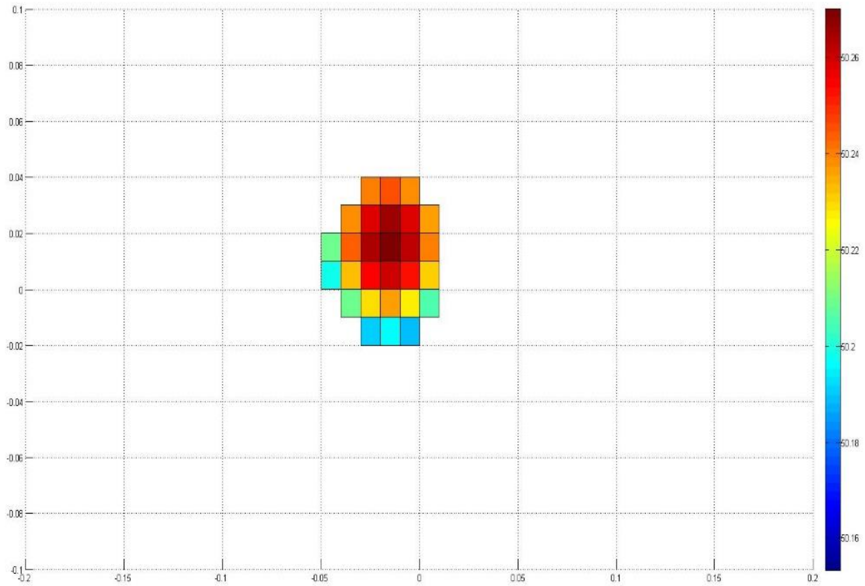
Calculate the step Δq to minimize the residual vector

Turn off the sources below threshold

$$q_{k+1,i} = \begin{cases} \tilde{q}_{k+1,i} & if \left|\tilde{q}_{k+1,i}\right| \geq T_k \\ 0 & otherwise \end{cases}$$, where

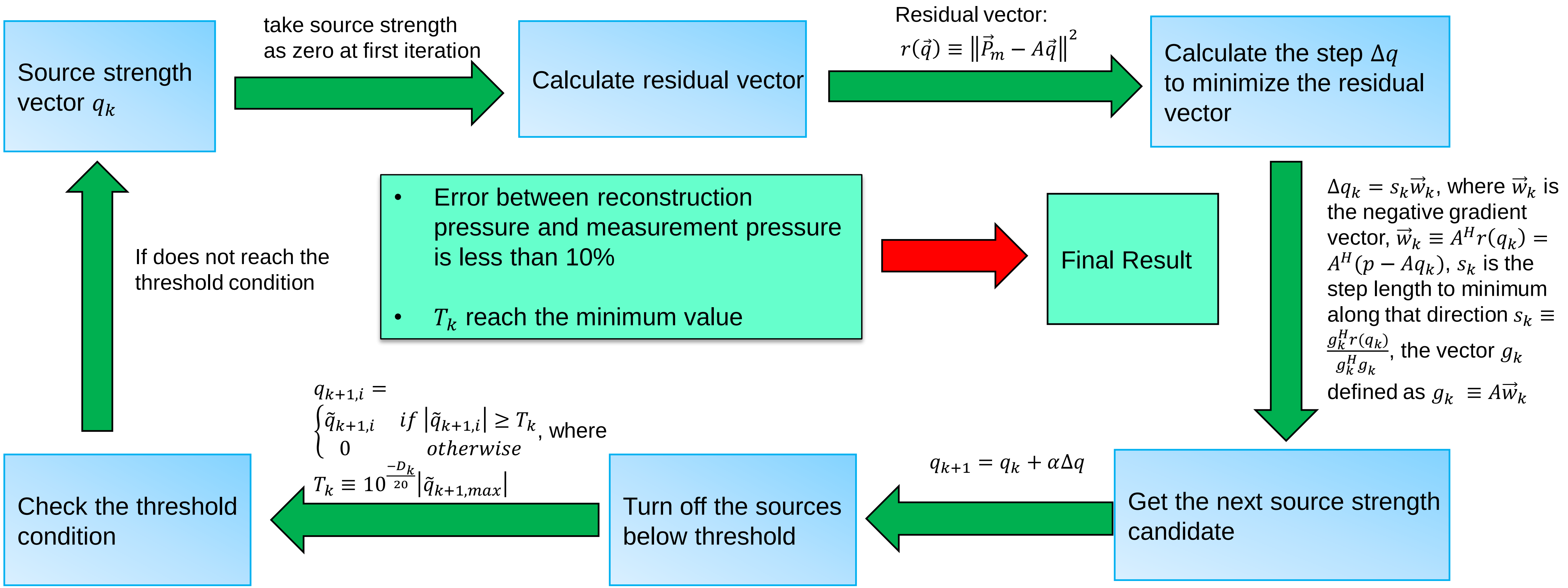
$$T_k \equiv 10^{\frac{-D_k}{20}} \left|\tilde{q}_{k+1,max}\right|$$ ←

Check the threshold condition



Monopoles at Fixed Locations with Wideband Acoustical Regularization

- Wideband Holography
  - Jorgen Hald. Wideband Holography. *Inter-Noise, Melbourne, Australia,* November 2014.



- Reconstruct Pressure

$$\mathbf{p} = \mathbf{A}\mathbf{q}\,,$$

- Reconstruct Velocity

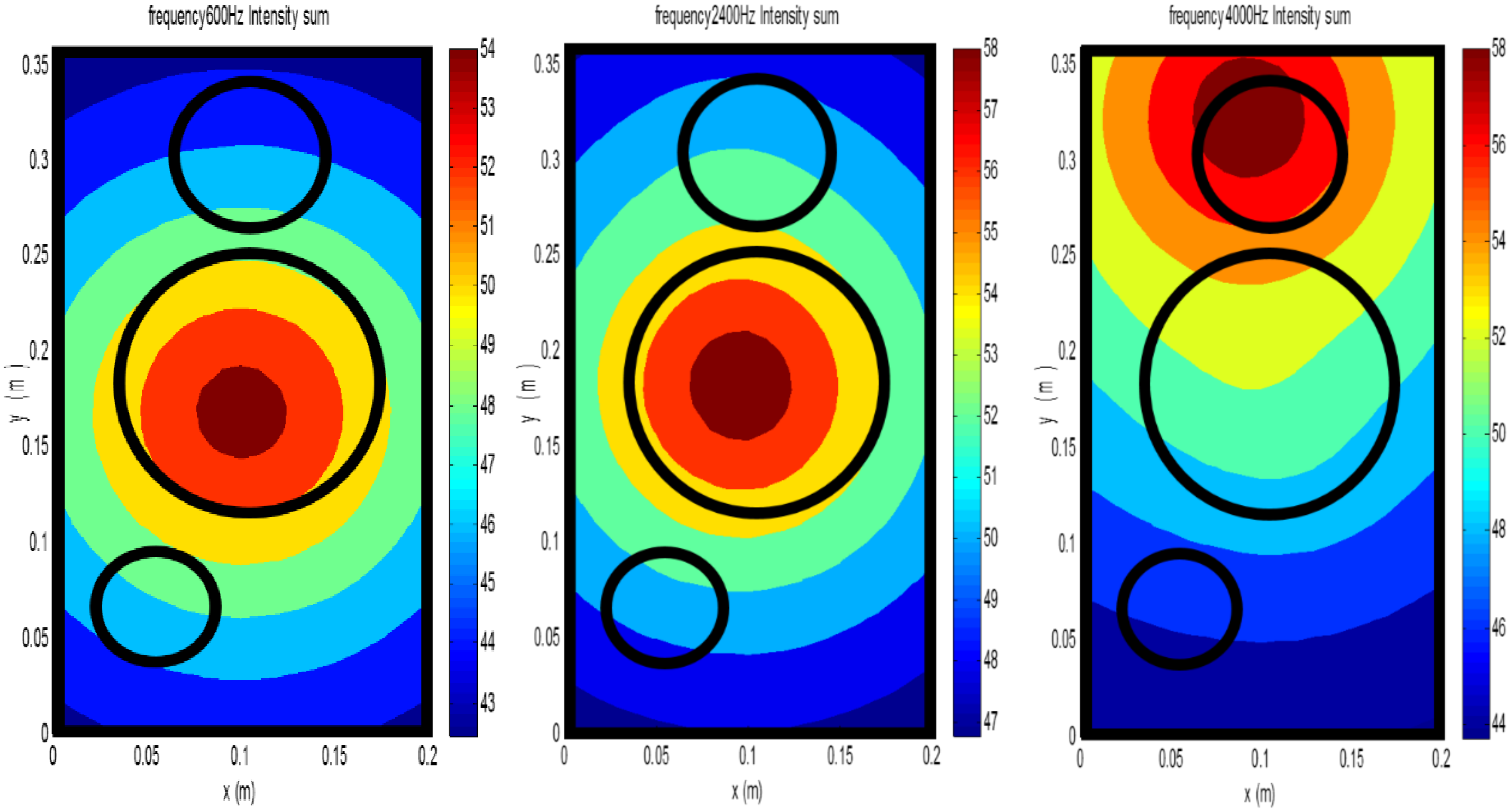
$$V = \frac{P}{\rho c}\left(1 + \frac{1}{jk\left\|\vec{X} - \overrightarrow{X_0}\right\|}\right)$$

- Reconstruct Intensity

$$I = \frac{1}{2}\mathrm{Re}(PV^*)$$

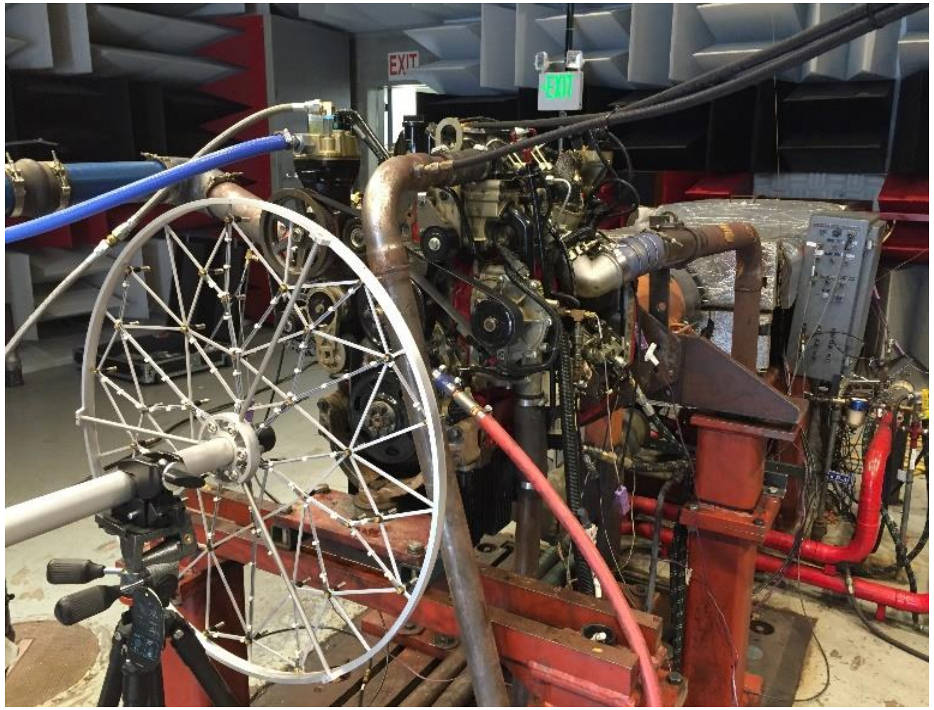
Previous Experiment on Loudspeaker

- T. Shi, Y. Liu, and J. S. Bolton, The Use of Wideband Acoustical Holography for Noise Source Visualization, Noise-Con, Providence, Rhodes Island, USA, 2016



Diesel Engine Test

- ISF-3.8, 4 cylinders 3.8 liter engine
- 36 channels combo array (35 microphones were used)
- One set of measurement
  - 0.58 m from diesel engine
  - Sampling frequency 25.6 kHz
  - 10 second measurement
- Signal Processing
  - 6400 Fourier points
  - Averaged over 20Hz (±8Hz from calculate frequency)
  - Welch's averaged periodogram method
  - Segment length 0.2s
  - Hann window with 50% overlap



Experiment setup in Cummins Walesboro NVH Lab, Columbus, IN

Partial Field Decomposition

- Identify and separate different noise sources

$$\mathbf{p} = \mathbf{H}_{rp}^{\mathrm{T}}\mathbf{r},$$

Relation between measurement and reference

35 measurement channels were using as reference channels

$$\mathbf{C}_{rr} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^{\mathrm{H}} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{U}^{\mathrm{H}},$$

Singular value decomposition

$$\widehat{\mathbf{P}} = \mathbf{C}_{rp}^{\mathrm{T}}\mathbf{U}^{*}\boldsymbol{\Sigma}^{-\frac{1}{2}} = \mathbf{H}_{rp}^{\mathrm{T}}\mathbf{U}^{*}\boldsymbol{\Sigma}^{1/2},$$

where the *i*th column vector of $\widehat{\mathbf{P}}$ represents the *i*th partial field.

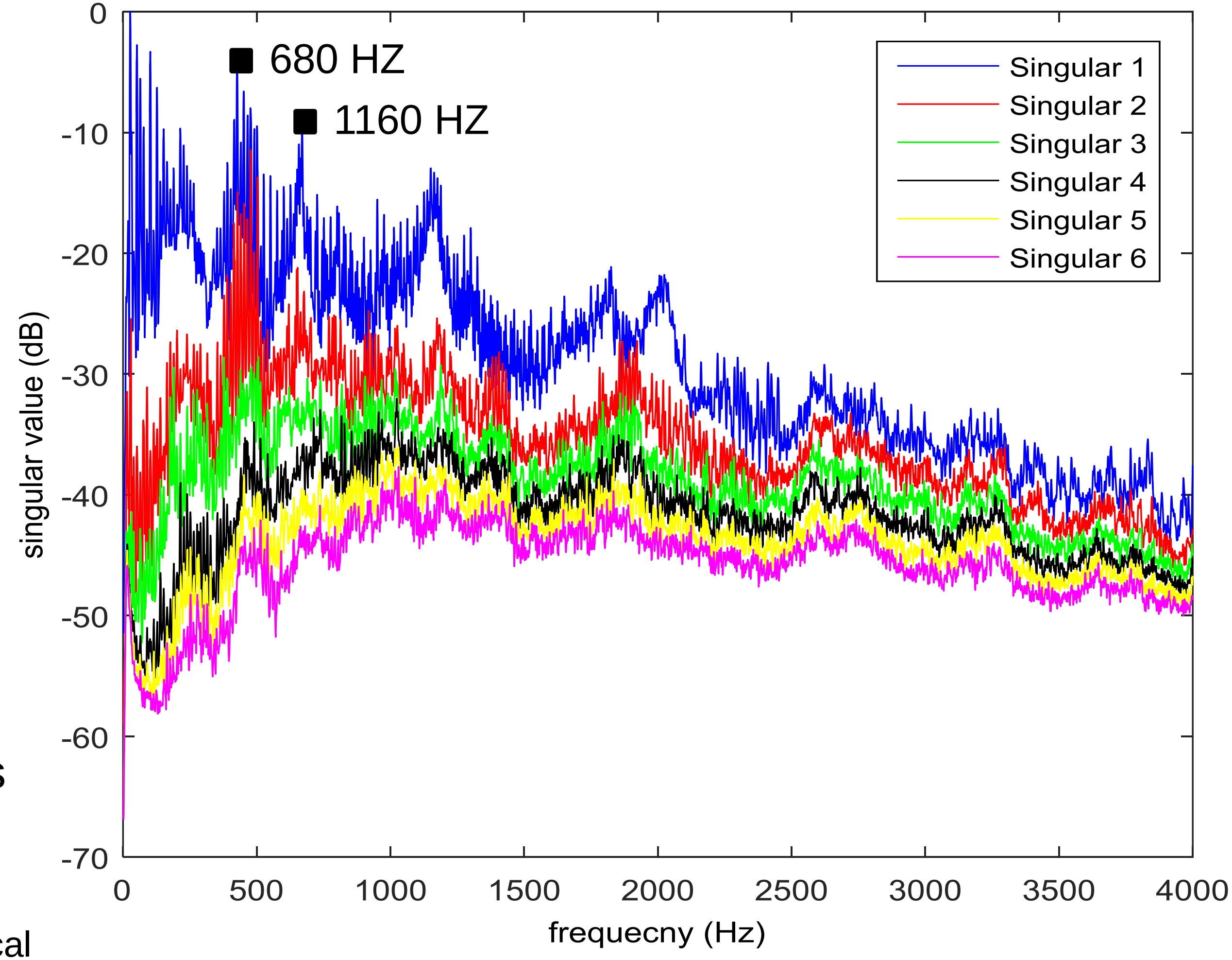
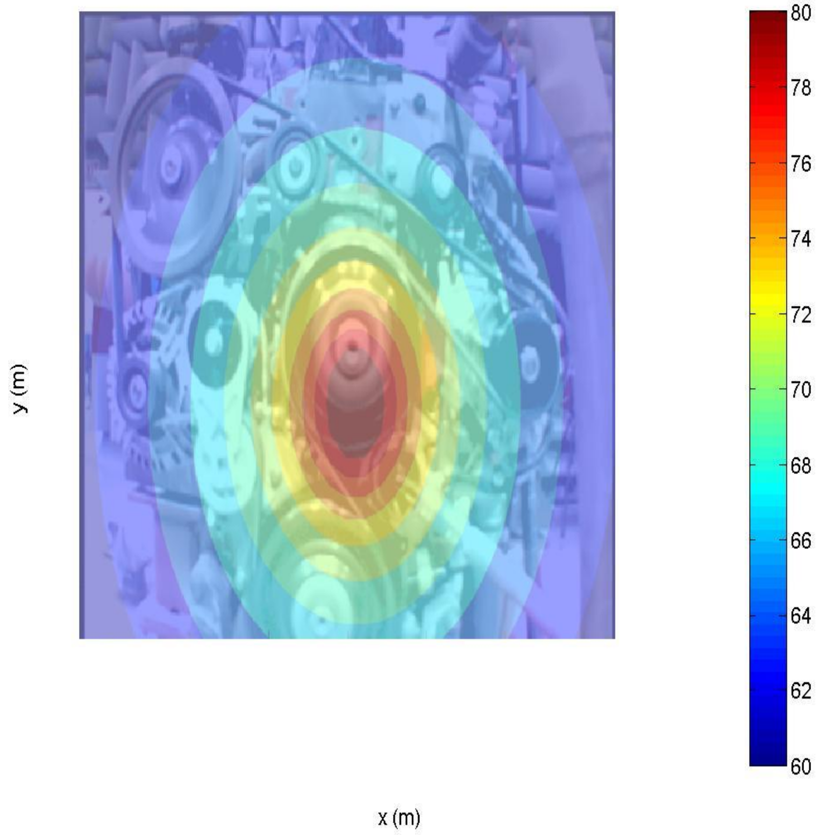


Figure 1: Singular value decomposition result

- Moohyung Lee and J. Stuart Bolton, “Scan-based near-field acoustical holography and partial field decomposition in the presence of noise and source level variation,” *J. Acoust. Soc. Am.*(2005)

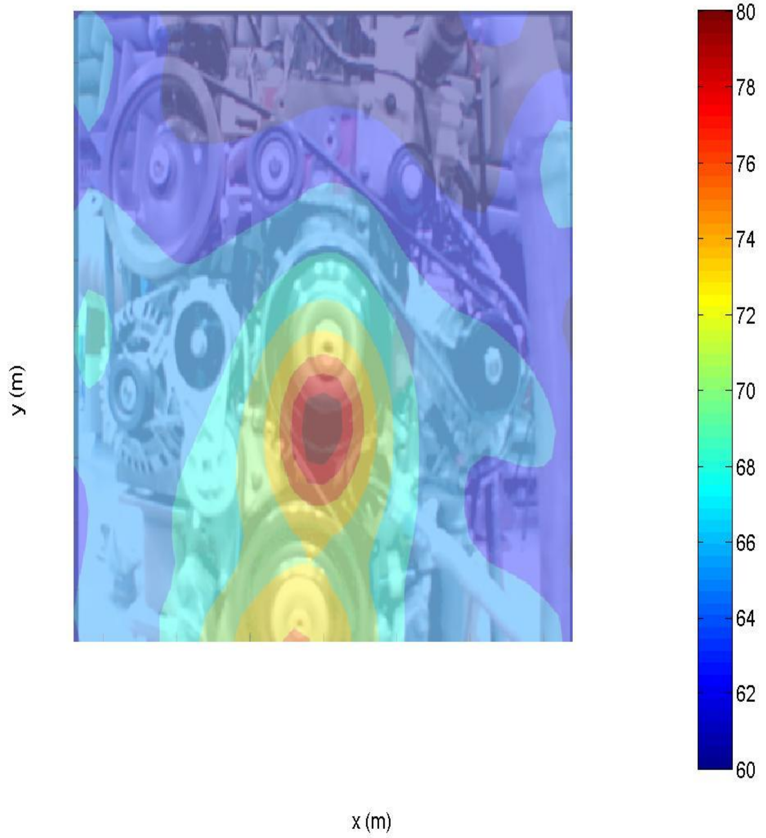
750 RPM Low Idle
First Partial Field Reconstruction

680 Hz



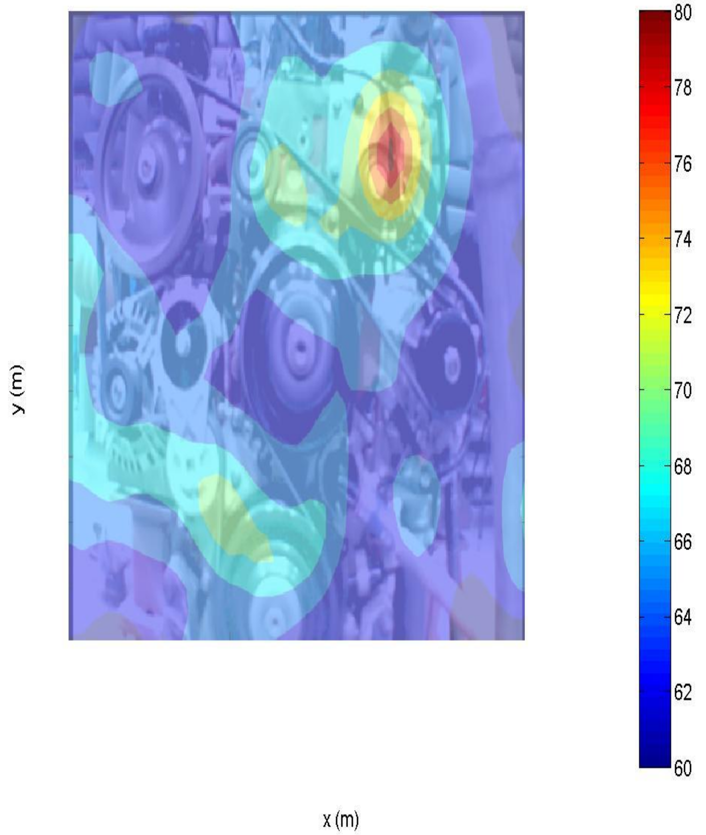
- Crank Pulley

1160 Hz



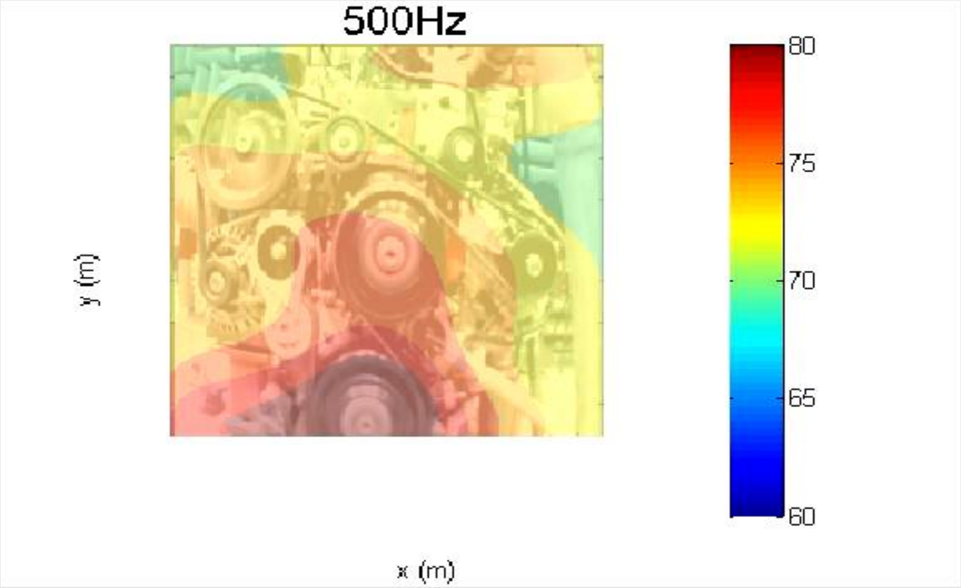
- Crank Pulley
- Fun Hub Pulley

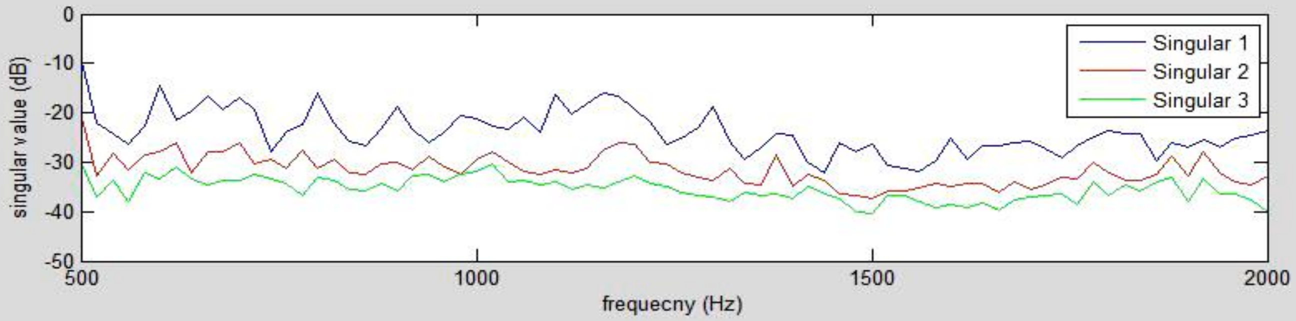
3560 Hz



- Lifting Bracket

750 RPM Low Idle





Conclusion

- An equivalent source model composed of a monopole distribution at fixed locations in combination with the WBH regularization process was discussed

- A test on a diesel engine with a 35 channels microphone array was conducted at Cummins NVH lab.

- The major noise sources at different frequencies could be successfully localized and visualized with the combination of ESM model and partial field decomposition