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Diesel Engine Noise Source Visualization by Using Compressive Sensing Algorithms

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Outline

- Introduction
- Compressive Sensing
- Experiments
- Summary

Introduction

- Near-Field Acoustical Holography (NAH)

Transfer path

Reconstruction

Unknown sound source

Measurement data

Choose the type of basis functions → Estimate coefficients from measurements → Predict the sound field at any location

Inverse problem

Forward calculation

- Limitation of NAH
  - Generally, a large number of measurements is required
  - Expensive and hard to conduct experiment in industrial setting

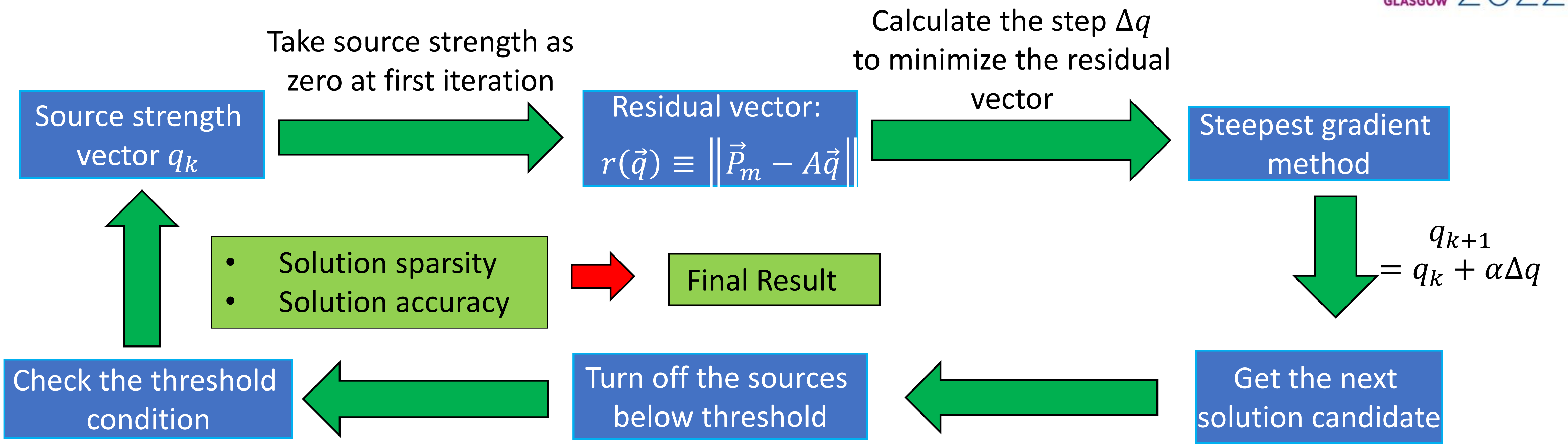
Compressive Sensing

$$\begin{bmatrix} P_1(\vec{\zeta}_1,\omega) \\ P_2(\vec{\zeta}_2,\omega) \\ \dots \\ P_M(\vec{\zeta}_M,\omega) \end{bmatrix} = \begin{bmatrix} g_1(\vec{\zeta}_1|\vec{X}_1,\omega) & g_2(\vec{\zeta}_1|\vec{X}_2,\omega) & \dots & g_W(\vec{\zeta}_1|\vec{X}_W,\omega) \\ g_1(\vec{\zeta}_2|\vec{X}_1,\omega) & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ g_1(\vec{\zeta}_M|\vec{X}_1,\omega) & \dots & \dots & g_W(\vec{\zeta}_M|\vec{X}_W,\omega) \end{bmatrix} \begin{bmatrix} q_1(\omega) \\ q_2(\omega) \\ \dots \\ q_W(\omega) \end{bmatrix}$$

- For an under-determined system (W>M), there is large number of possible solutions, but a solution that indicates sound source locations can be recovered if the solution vector is
  - Sparse
  - Incoherent
- Sparse solution indicates sound source position
- Sparsity vs Accuracy

Wideband Acoustical Holography

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



- Effective algorithm to identify single sound source location with few microphone, good at eliminating "ghost" sources
- If there are multiple sound sources
  - Cannot separate closely-spaced sound sources if wavelength $> d$
  - Algorithm tends to develop solution around strongest sound source
  - Weaker secondary sources tend not to be identified
  - Result are very sensitive to initial solution

L1-Norm Minimization

- l_0 -Norm Minimization

$$\text{minimize } \|\vec{\mathrm{q}}\|_0$$

$$\text{s.t.} \quad \vec{\mathrm{P}} = \mathbf{G}\vec{\mathrm{q}}$$

  - Concave function
  - Computationally intractable

- l_1 -Norm Minimization

Weighting parameter

$$\text{minimize } \|\vec{q}\|_1 + \lambda \left\| \mathbf{A}\vec{q} - \vec{P}_m \right\|_2$$

Solution sparsity

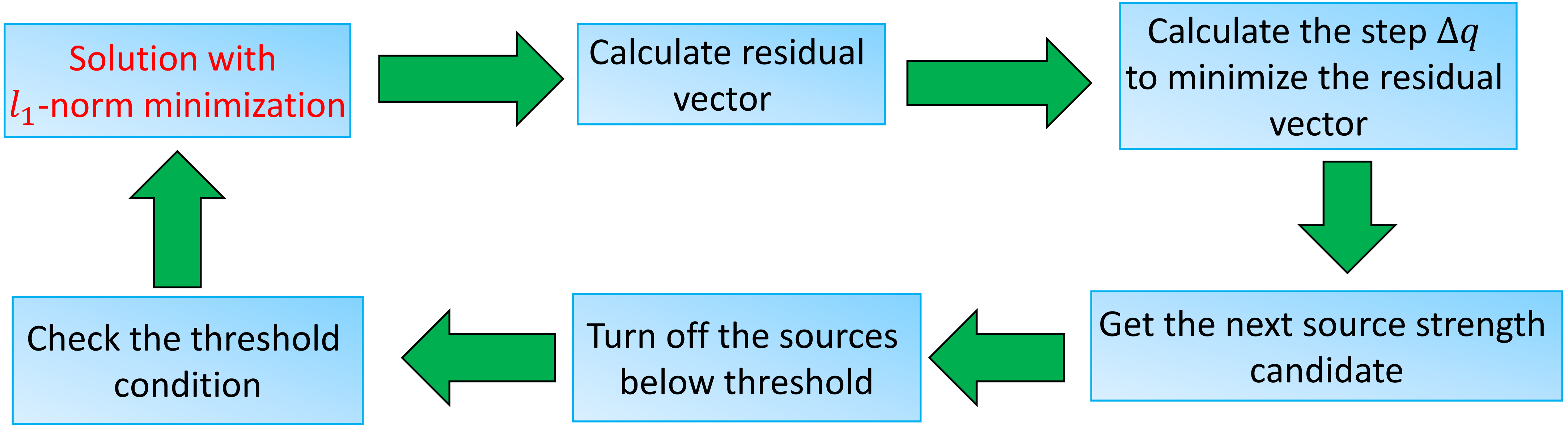
Solution accuracy

  - Good at identifying multiple closely-spaced sources
  - Need to choose weighting parameter properly
    - λ too small: inaccurate solution
    - λ too big: “ghost” sources included

The Hybrid Method

➢ The Hybrid method

1. Begin the search with l_1-norm minimization and a relatively large λ: real sources and ghost sources created
2. Take solution of l_1-norm minimization as initial solution for Wideband Acoustical Holography (WBH): the ghost source can be eliminated by WBH



- Combine the strengths of the two different procedures
  - l_1-norm finds all potential sources (including "ghost" sources)
  - WBH eliminates the "ghost" sources

Monopole Equivalent Source Model

- Expression of a monopole with source strength *q*

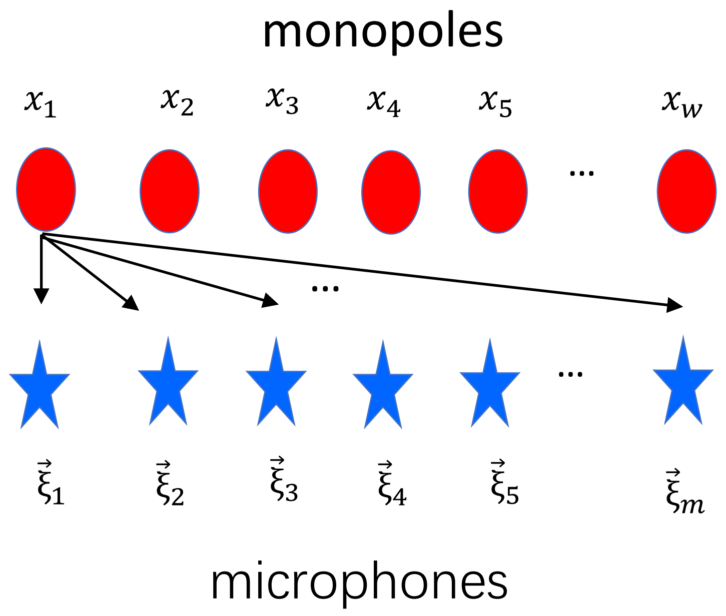
$$P_{S0}\left(\vec{X}\middle|\overrightarrow{X_0},\omega\right) = q\cdot g_0\left(\vec{X}\middle|\overrightarrow{X_0},\omega\right) = q\,\frac{e^{-jk\|\vec{X}-\overrightarrow{X_0}\|}}{4\pi\left\|\vec{X}-\overrightarrow{X_0}\right\|},$$

$\vec{X}$: Field point position

$\overrightarrow{X_0}$: Monopole position

- Matrix formation:

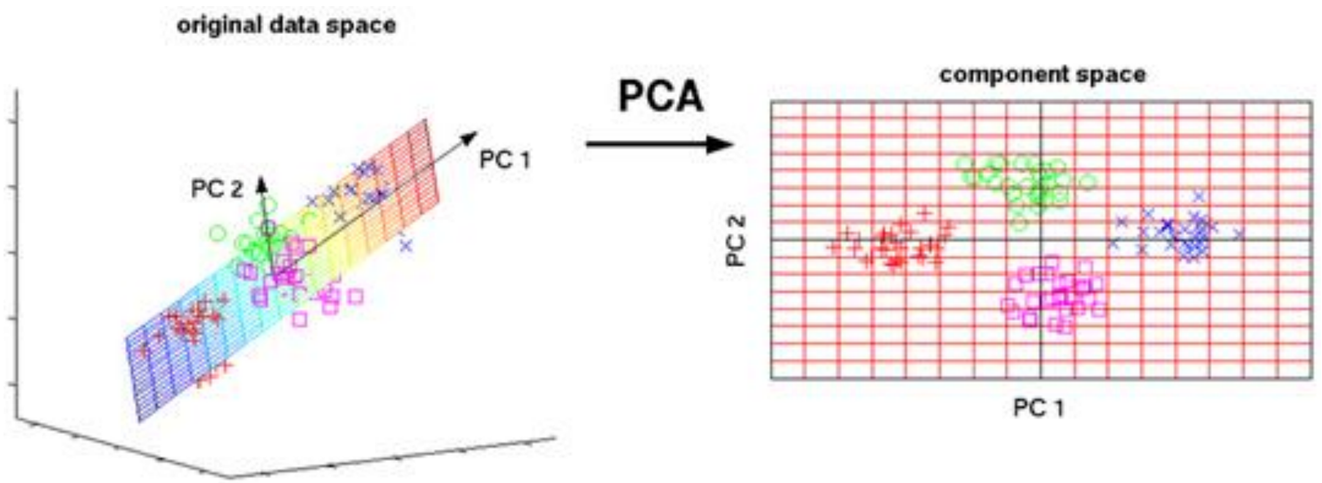
$$\begin{bmatrix} P_1(\vec{\zeta}_1,\omega) \\ P_2(\vec{\zeta}_2,\omega) \\ \cdots \\ P_M(\vec{\zeta}_M,\omega) \end{bmatrix} = \begin{bmatrix} g_1(\vec{\zeta}_1|\vec{X}_1,\omega) & g_2(\vec{\zeta}_1|\vec{X}_2,\omega) & \cdots & g_W(\vec{\zeta}_1|\vec{X}_W,\omega) \\ g_1(\vec{\zeta}_2|\vec{X}_1,\omega) & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ g_1(\vec{\zeta}_M|\vec{X}_1,\omega) & \cdots & \cdots & g_W(\vec{\zeta}_M|\vec{X}_W,\omega) \end{bmatrix} \begin{bmatrix} q_1(\omega) \\ q_2(\omega) \\ \cdots \\ q_W(\omega) \end{bmatrix}$$



Principal Component Analysis

➢Separate incoherent sound sources

- Diesel is a complex sound source: e.g., mechanical noise, combustion noise
- Total field must first be decomposed into mutually incoherent partial fields
- Partial fields processed independently then added on a quadratic basis to give total field



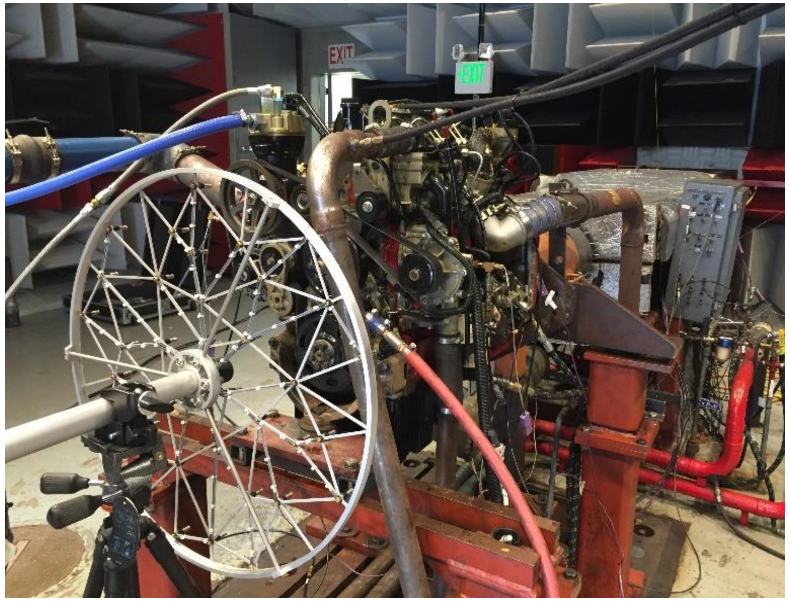
Diesel Engine Test

➢ Walesboro Noise and Vibration Laboratories, Cummins

- ISF-3.8 liter engine
- Operation condition: 750 rpm and 1000 rpm idle
- 36 channels combo array (35 microphones were used)
- Measurement distance 0.58 m
- Measurement duration 10 second
- Sound field reconstructed on engine front face

➢ Equivalent source plane

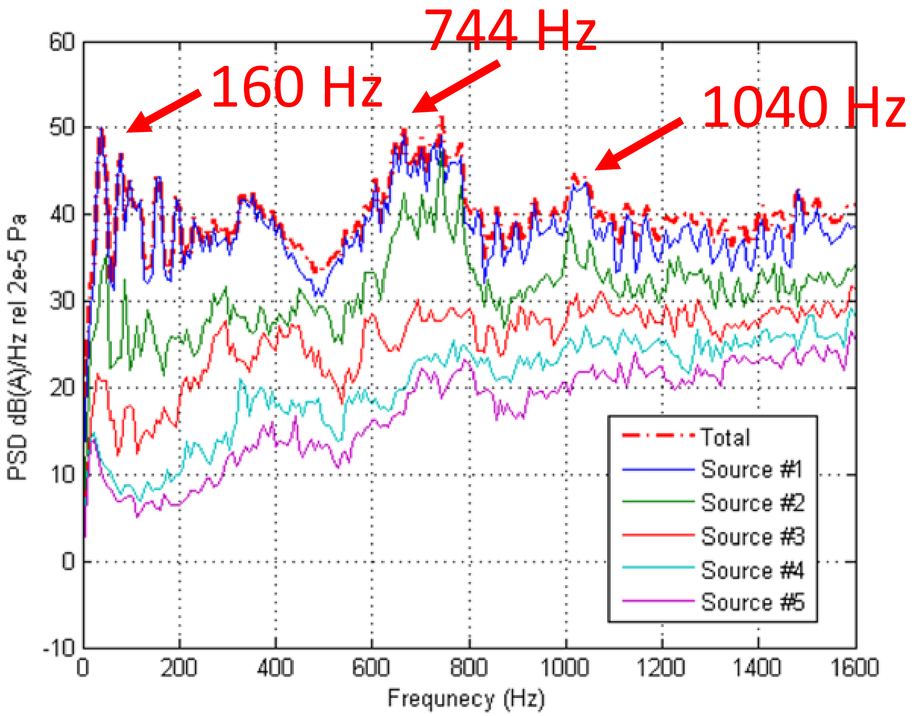
- 0.02 m behind the engine front face, 0.6 m from the microphone array
- $0 < x < 0.68$ m, $0 < y < 0.48$ m
- Monopole spacing 0.01 m in x and y-direction
- 3381 monopoles



Experiment setup in Cummins Walesboro Noise and Vibration Lab, Columbus, IN

750 RPM Condition

➢ Principal Component Analysis Result

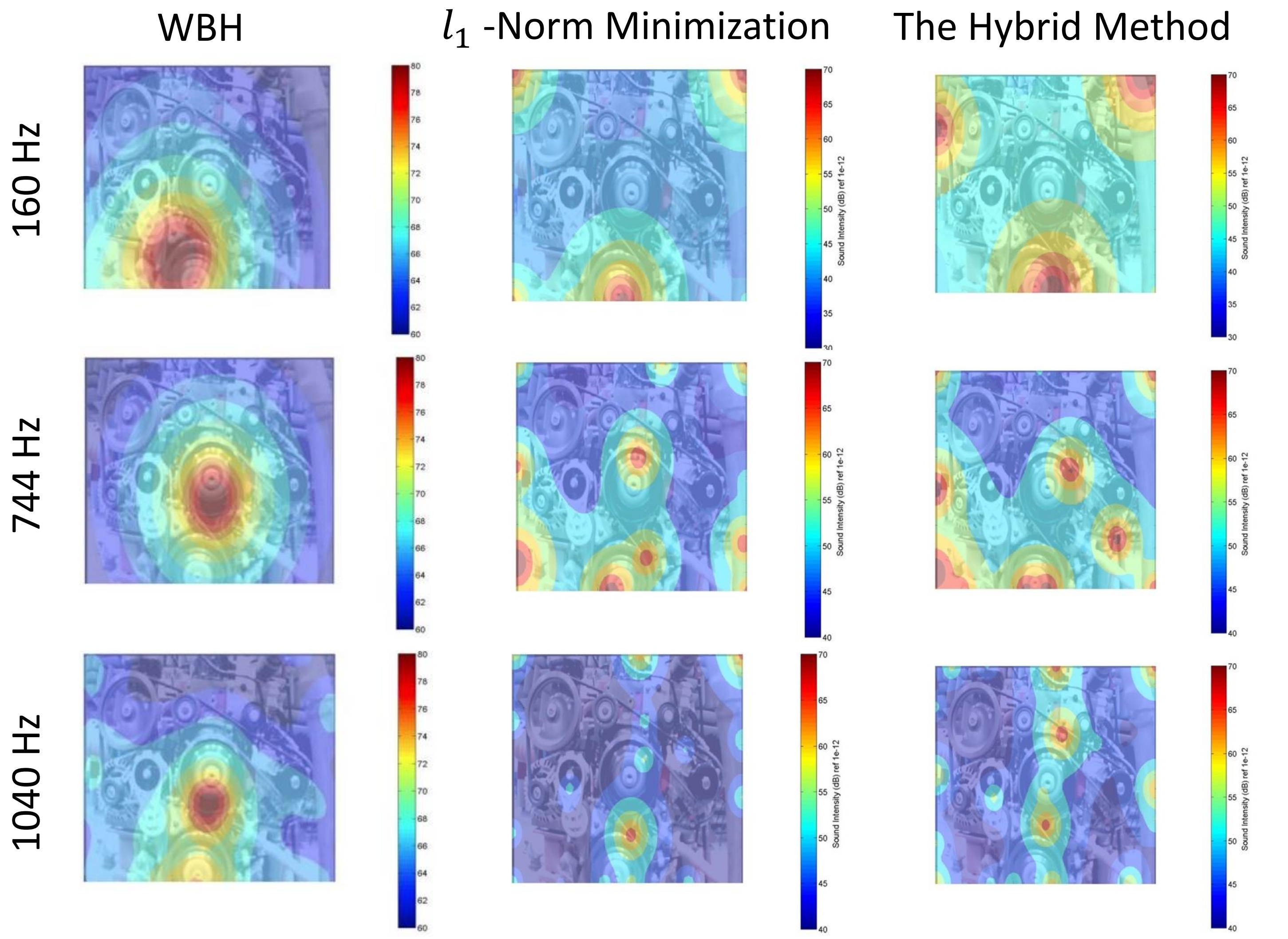


➢ Compared with WBH, other algorithms show better spatial resolution and recovers more detail of major sound source locations

➢ The hybrid method gives the best indication of the sound source locations

➢ Noise Source Visualization

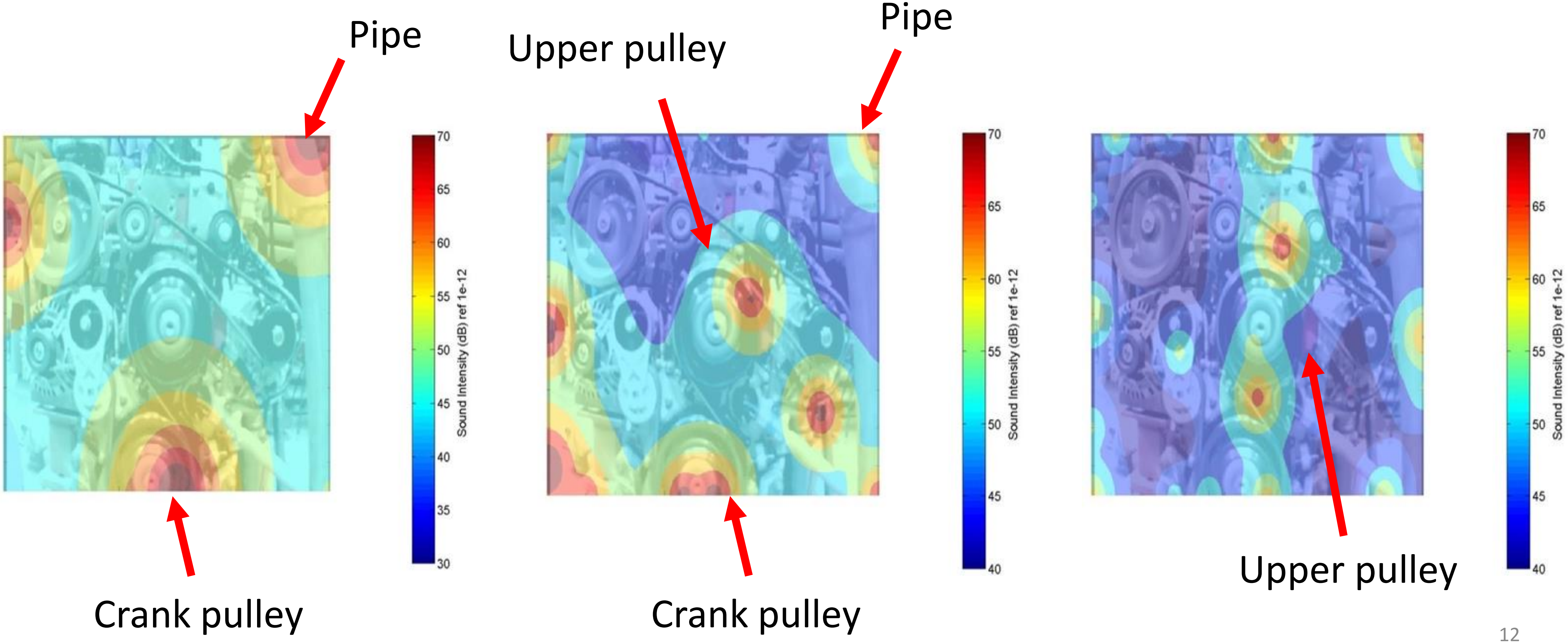
- Acoustic Intensity



750 RPM Condition

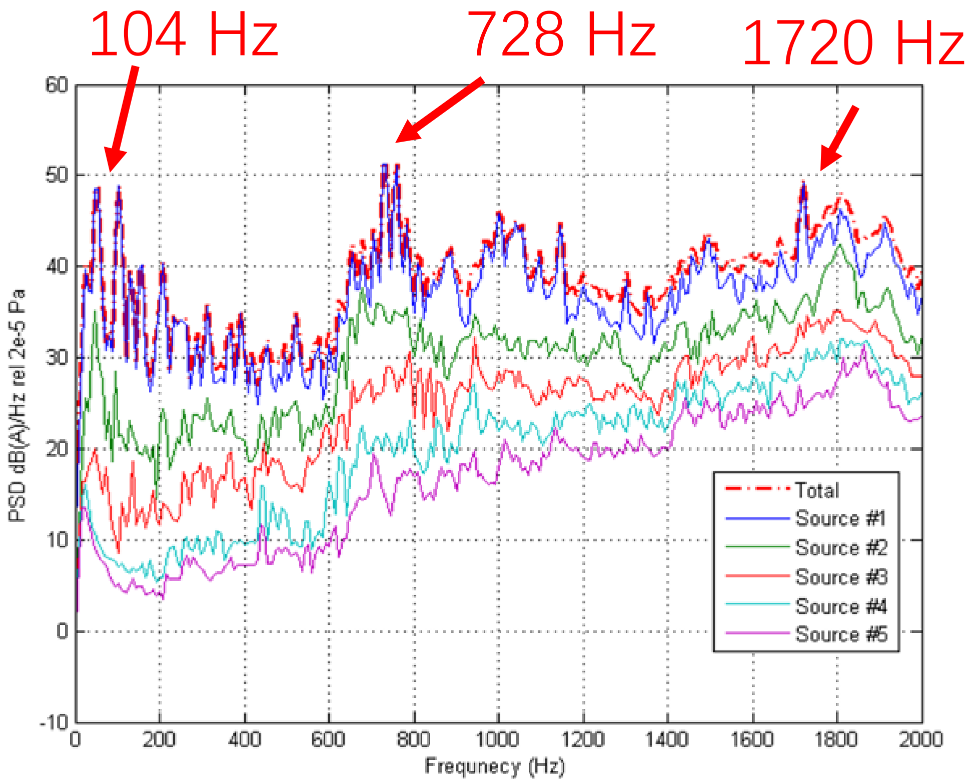
- Hybrid Mode – Acoustic Intensity on Engine Front Face

160 Hz | 744 Hz | 1040 Hz

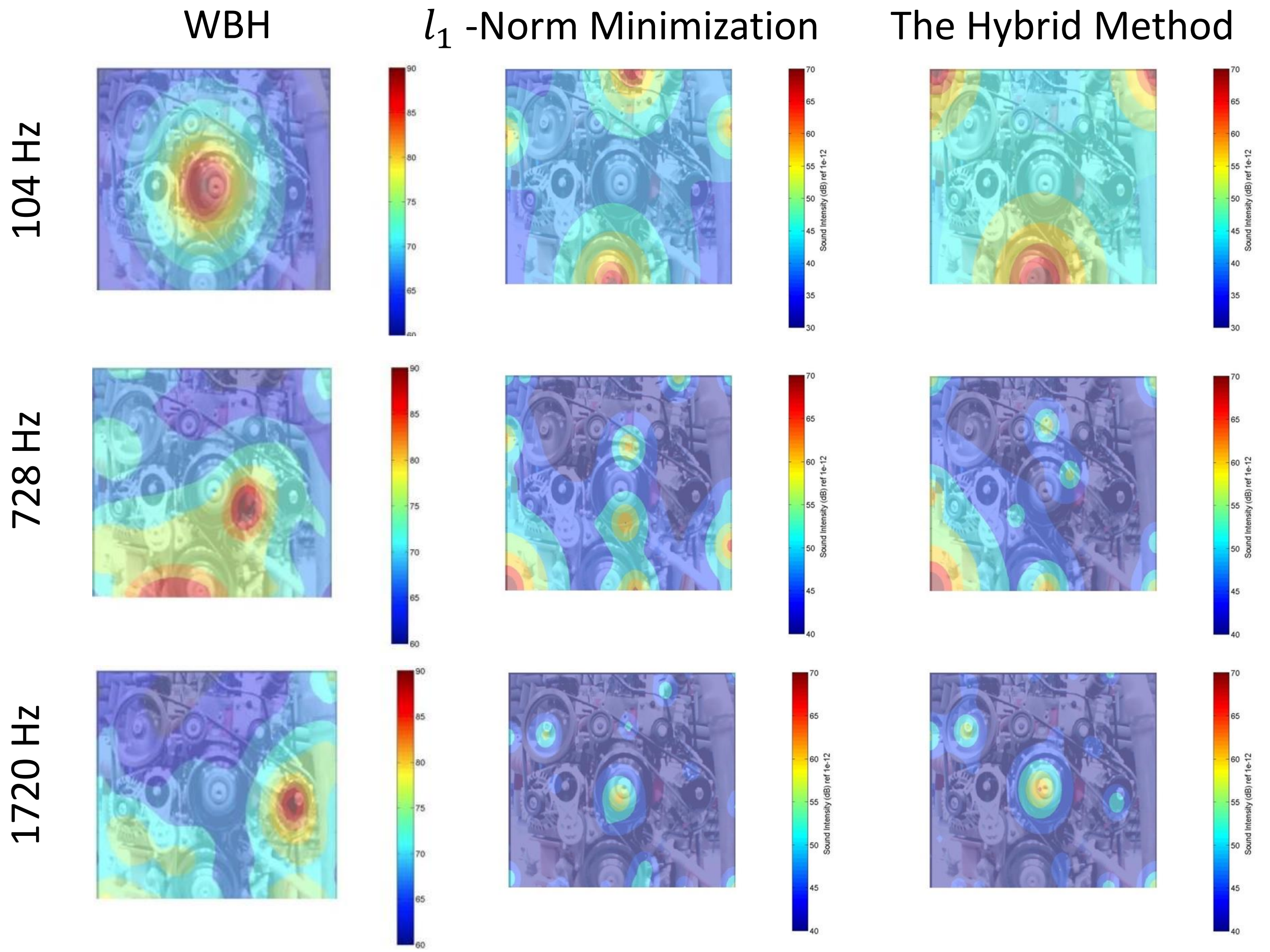


1000 RPM Condition

- Principal Component Analysis Result



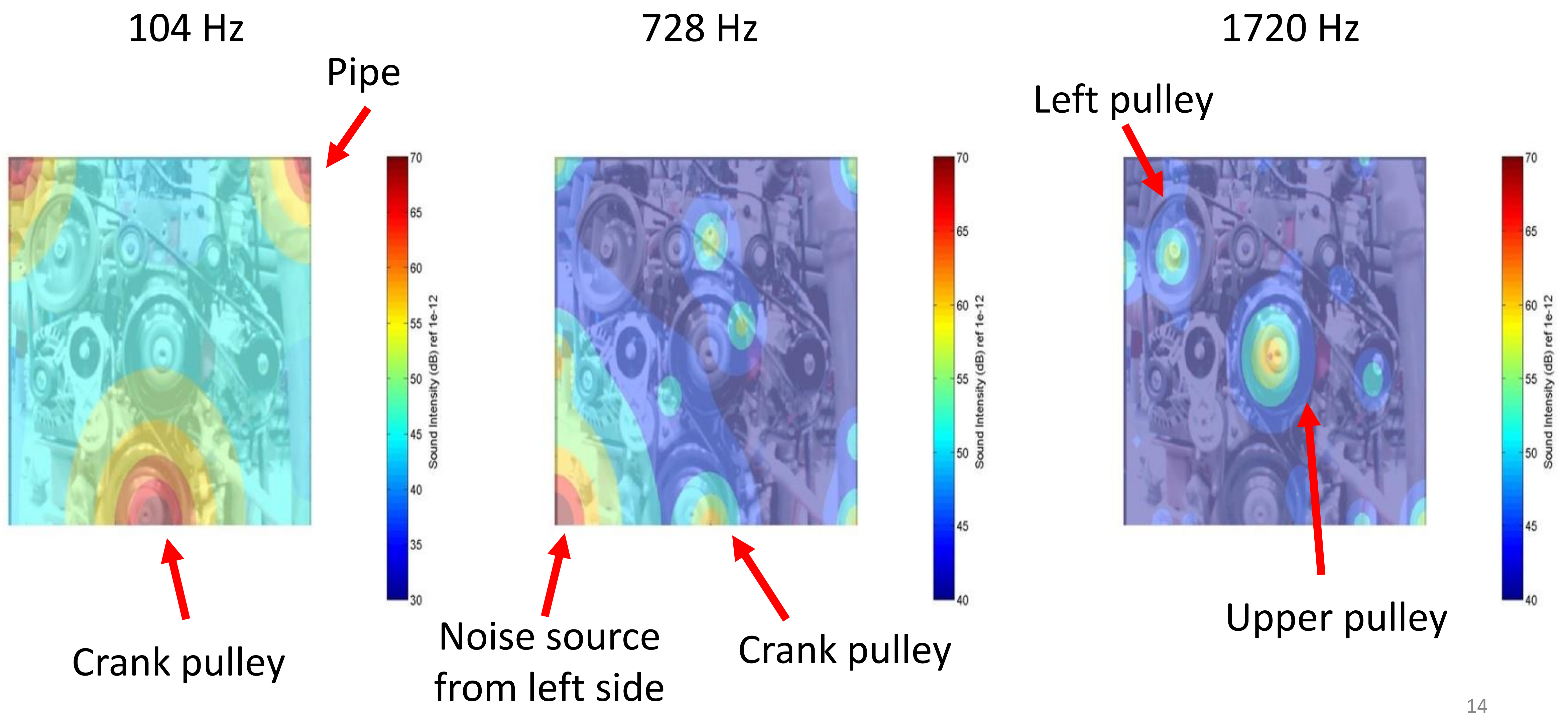
- Noise Source Visualization
  - Acoustic Intensity



- Both algorithm identified major sound source location at different frequencies successfully
- The hybrid method gives a clearer indication of the sound source location and relative strengths

1000 RPM Condition

- Hybrid Mode – Acoustic Intensity on Engine Front Face



Summary

- Motivation

Noise source identification → Near-field Acoustical Holography (NAH) → Fewer microphone measurements → Compressive Sensing

- Model and Algorithm

  - l_1-norm minimization
  - Hybrid method

  → Monopole equivalent source model

- Diesel Engine Test

- The above-mentioned algorithms can identify major sound sources with relatively small number of measurements and relatively large measurement distance

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