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A Comparison of Near-Field Acoustical Holography Methods Applied to Noise Source Identification

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NOISE AND VIBRATION

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NEAR-FIELD ACOUSTICAL HOLOGRAPHY METHODS APPLIED TO NOISE SOURCE IDENTIFICATION

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Outline

- Introduction
- Near-field Acoustical Holography Methods
- Simulation
- Experiments
- Summary

Introduction

- **Acoustics challenge in automobile industry**
 - Electrification
 - New sound source
 - Sound quality requirement
 - Fast effective measurement to identify sound sources

Near-field Acoustical Holography (NAH)

- Construct a model to describe the acoustic field generated by the source based on the near-field microphone array measurement

- NAH is a powerful tool to identify sound source
 - Measurements can be taken at a distance from the source and the sound field can be visualized in three-dimensional space
 - Large number of measurements is required to avoid different measurement errors: e.g., spatial aliasing, windowing errors, etc.
 - Economically costly, and hard to perform

NAH Methods Used in Present Work

- Statistically Optimized Near-field Acoustical Holography (SONAH)
 - Hald, J., "Basic theory and properties of statistically optimized near-field acoustical holography," *Journal of the Acoustical Society of America* 125.4: 2105-2120, 2009.
 - Wideband Acoustical Holography (WBH)
 - J. Hald "Wideband Acoustical Holography," *Proceedings of INTER-NOISE 2014*, Melbourne, Australia, pp. 308-320, 2014.
 - l_1 -norm minimization
 - Chardon, Gilles, et al. "Near-field acoustic holography using sparse regularization and compressive sampling principles." *Journal of the Acoustical Society of America* 132.3: 1521-1534, 2012.
 - Motivation
 - Facilitate NAH measurement process
 - Fewer restrictions on microphone array
 - Wide application of NAH in industry
-

Statistically Optimized Near-field Acoustical Holography

- Elementary Wave Equation

$$p(\vec{r}_i) = \sum_{n=1}^N a_n \psi_n(\vec{r}_i), \quad i = 1, \dots, I$$

Measured pressure at position $\vec{r}_i$

Complex coefficients

Elementary wave function at position $\vec{r}_i$

- Matrix formulation: $\vec{P} = B\vec{a}$

- Unknown in this equation is the complex expansion coefficients $\vec{a}$
 - If $I \geq N$: Least-square solution with Tikhonov regularization
 - If $I \leq N$: Least-norm solution with Tikhonov regularization
 - Sound pressure at position $\vec{r}$: $p(\vec{r}) = \sum_{n=1}^N a_n \psi_n(\vec{r})$

- The complex expansion coefficients obtained on the measurement plane may not be able well describe the sound field at prediction position

Statistically Optimized Near-field Acoustical Holography

- Reconstruct sound pressure at $\vec{r}$ by a linear combination of the measured sound pressure

- The inverse problem can be solved with least-norm method with Tikhonov regularization

Wideband Acoustical Holography (WBH)

- Monopole based equivalent source method
 - Expression of a monopole with source strength q

$$P_{S0}(\vec{X}|\vec{X}_0, \omega) = q \cdot g_0(\vec{X}|\vec{X}_0, \omega) = q \frac{e^{-jk\|\vec{X}-\vec{X}_0\|}}{4\pi\|\vec{X}-\vec{X}_0\|},$$

Field point position

Monopole location

- Matrix formation

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

Wideband Acoustical Holography (WBH)

L1-Norm Minimization

- Objective function with monopole distribution

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

Solution
sparsity

Weighting
parameter

Solution
accuracy

- M. Grant, S. Boyd, and Y. Ye CVX: software for disciplined convex programming

- l_1 -norm and l_2 -norm

– l_1 -norm: $\|\vec{q}\|_1 = \sum_{i=1}^m |q_i|$

– l_2 -norm: $\|\vec{q}\|_2 = \sqrt{q_1^2 + q_1^2 + \dots + q_m^2}$

- Careful choosing the weighting parameter
- l_1 -norm for source strength and l_2 -norm for residual

Parameters in Different Methods

- SONAH
 - $\vec{c}(\vec{r}) = (\mathbf{B}^H \mathbf{B} + \varepsilon \mathbf{I})^{-1} \mathbf{B}^H \vec{\alpha}(\vec{r})$, where the regularization parameter is selected with L-curve method
- WBH
 - $\vec{q}_0 = \vec{0}$; $\alpha = 1$; $D_0 = 0.1$ dB; $\Delta D = 1.0$ dB
- l_1 -Norm Convex Optimization
 - $\lambda = 10$
- Particle velocity
 - $\vec{u}_z(\vec{r}) = \frac{-1}{j\omega\rho_0} \frac{\partial p(\vec{r})}{\partial z}$
- Sound intensity
 - $\vec{I}_z(\vec{r}) = \frac{1}{2} \text{Re} \left(p(\vec{r}) \vec{u}_z^*(\vec{r}) \right)$
- Sound power
 - $W = \int_S \vec{I}_z dS$

Simulation

- One monopole reconstruction simulation
 - Equivalent source plane
 - $0 < x < 0.4$ m, $0 < y < 0.4$ m
 - 0.02 m monopole spacing in x and y -direction
 - 441 monopoles
 - Virtual measurement
 - $-0.4 < x < 0.4$ m, $-0.4 < y < 0.4$ m
 - 0.1 m microphone spacing
 - 81 microphones
 - White noise with 30 dB Signal-to-Noise Ratio (SNR) was added into the measurement
 - Reconstruction at 1000 Hz

Monopole with unit source strength

Intensity Reconstruction Result at 1000 Hz

True intensity

SONAH

l_1 -norm minimization

WBH

- All methods are able to identify the monopole position

- SONAH reconstructed a more extended sound source
- WBH reconstructed a very concentrated result
- l_1 -norm minimization seems most accurate

- Sound power level (ref: $1 \times 10^{-12} \text{W}$)

True	76.5 dB
WBH	71.6 dB
L1-norm minimization	76.4 dB
SONAH	76.8 dB

Simulation

- Baffled plate vibration reconstruction simulation
 - Equivalent source plane
 - $0 < x < 0.4$ m, $0 < y < 0.4$ m
 - 0.02 m monopole spacing in x and y-direction
 - 441 monopoles
 - Virtual measurement
 - $-0.4 < x < 0.4$ m, $-0.4 < y < 0.4$ m
 - 0.1 m microphone spacing
 - 81 microphones
 - White noise with 30 dB Signal-to-Noise Ratio (SNR) was added into the measurement
 - Reconstruction at 1000 Hz

Point of excitation

Intensity Reconstruction Result at 500 Hz

True intensity

SONAH

l_1 -norm minimization

WBH

- All methods are not able to fully reconstruct sound field detail
 - SONAH reconstructed some details
 - WBH only identified the excitation point
 - l_1 -norm minimization reconstructed the sound field as several point sources
- Sound power level (ref: 1×10^{-12} W)

True	66.1 dB
WBH	59.9 dB
L1-norm minimization	65.0 dB
SONAH	64.8 dB

Intensity Reconstruction Result at 1000 Hz

True intensity

SONAH

l_1 -norm minimization

WBH

- All methods are not able to fully reconstruct sound field detail
 - SONAH reconstructed some details
 - WBH only identified the edges, which are the strongest points
 - l_1 -norm minimization reconstructed the sound field as several point sources
- Sound power level (ref: 1×10^{-12} W)

True	76.5 dB
WBH	65.8 dB
L1-norm minimization	76.2 dB
SONAH	76.2 dB

Experiment

- Sound field reconstruction
 - Sound source: loudspeaker (Infinity Primus P163)
 - Input signal: white noise (bandwidth 25.6 kHz) generated by PULSE software
 - Intensity probe scan measurement at near and far-field
- Intensity probe
 - Bruel and Kjaer type 3654 intensity probe
 - Sound intensity at the middle of two microphones
 - $$I_z = \frac{1}{2} \frac{1}{\omega \rho_0 \Delta} \text{Im}(P_1 P_2^*)$$
 - Patched measurement
 - $p = H_{rp}^T r$
 - An equivalent simultaneous microphone array measurement can be calculated

Measurement Set-up

- Measurement plane
 - $-0.05 \text{ m} < x < 0.22 \text{ m}$, $-0.05 \text{ m} < y < 0.4 \text{ m}$
 - Measurement taken at 0.05 m from loudspeaker front face
 - Measurement spacing: 0.06 m in x , and y -directions
 - 160 measurements in total
 - Equivalent to a regular rectangular microphone array
- Data processing in PULSE
 - 10 second measurement at each point
 - Sampling frequency: 25.6 kHz
 - Hann window: 0.25 second 50% overlap
 - 100 averages

Equivalent source plane Set-up

- Equivalent source (monopole) plane
 - $-0.05 \text{ m} < x < 0.22 \text{ m}$, $-0.05 \text{ m} < y < 0.4 \text{ m}$
 - 0.02 m behind the loudspeaker front face
 - 0.01 m spacing in both x, and y-directions
 - 1288 monopoles
- Reconstruction plane
 - Reconstruction plane is 0.055 m from loudspeaker front face
 - Reconstruction plane is also where the intensity measured
 - $-0.05 \text{ m} < x < 0.22 \text{ m}$, $-0.05 \text{ m} < y < 0.4 \text{ m}$
 - Measurement spacing: 0.03 m in x, and y-directions
 - Reconstruction will be directly compared with measurement

Intensity Reconstruction Result at 800 Hz

- Sound power level (ref: 1×10^{-12} W)

Measurement	47.9 dB
WBH	27.8 dB
L1-norm minimization	34.1 dB
SONAH	40.8 dB

- At low frequency SONAH method reconstructed better result than the other two methods
- The sound source is spatially spread, which is hard for monopole model to reconstruct

Intensity Reconstruction Result at 2400 Hz

True intensity

SONAH

- Sound power level (ref: 1×10^{-12} W)

Measurement	46.3 dB
WBH	39.9 dB
L1-norm minimization	46.5 dB
SONAH	47.5 dB

l_1 -norm minimization

WBH

- l_1 -norm minimization accurately reconstructed sound power
- SONAH does a better job in separating the closely-spaced sources

Intensity Reconstruction Result at 4000 Hz

- Sound power level (ref: $1 \times 10^{-12} \text{W}$)

Measurement	49.5 dB
WBH	43.2 dB
l_1 -norm minimization	43.8 dB
SONAH	46.8 dB

- As frequency increases the sound source is more concentrated and the wavelength becomes small, so WBH and l_1 -norm minimization reconstruct the sound source better than at low frequency

Summary

Noise source
identification

Near-field
Acoustical
Holography (NAH)

Fewer
microphone
measurements

- SONAH
- WBH
- l_1 -norm minimization

Concentrated sound source

Spatially-extended sound source

- Concentrated sound source
 - All methods are able to identify the sound source location
 - WBH and l_1 -norm minimization yield more accurate location
- Spatially-extended sound source
 - All methods are able to identify the largest amplitude region
 - SONAH method recovered most sound field details
- Depending on the sound source type, it is crucial to choose the appropriate NAH method to ensure accurate sound field reconstruction

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*Thank
you*