Vibro-acoustic Research at the Acoustics Lab, KAIST

Jeong-Guon Ih, Prof.

Acoustics Lab. (http://aclab.kaist.ac.kr)
Center for Noise and Vibration Control (NoVIC)
Department of Mechanical Engineering
Overview

- Lab. Members: (as of Mar. 2014)
  - Ph.D. Students: 6 (1 part-time student)
  - MS Students: 9 (1 dual degree, 1 part-time student)
- Graduates: (Since Feb. 1992): Ph.D. = 26, MS = 49

Thesis topics related to the Inverse Problem

- Current Ph.D. Thesis Topics on Inverse Vibro-acoustics
  - Inverse acoustic estimation of sectional temperature distribution in a duct (TK Kim)
  - Inverse source identification of the fluid machine in a wide duct with flow (YH Heo)
  - Inverse diagnostics of wave propagation in the multi-dwelling building structures (JH Bae)
  - Localized vibration field suppression by utilizing array control technique (SW Hong)
  - Generation of localized vibration in a thin plate by using the array actuators (JH Woo)

- Current MS Thesis Topics on Inverse Vibro-acoustics
  - Leakage detection in a long pipe by using the inverse acoustic method (E Yadollahi)
  - Acoustic source localization by using the multiple 3D-intensity array (F Franek)
  - Inverse estimation of excitation force at multiply joined structural interface (M Fayyazi)
Indirect (Inverse) Prob. in Vibro-acoustics

- Inverse problem
  - Problem in determining the internal physics or past state of a system from indirect measurements

![Diagram showing the inverse problem in vibro-acoustics](image)

**Causes:**
- Unknown input: (vibro-acoustic data in discrete form at the source)

**Effect:**
- Known output with noise: (finite number of vibro-acoustic data at the field)

**Modelled system:**
- (radiation, scattering, reflection, diffraction in continuous domain ... should be modeled in a discrete form)

**Inversion process:**
- Sensor
- Vibro-acoustic source
- Sound pressure

**Regularization:**
- (regularization)
Some Past Works
Indirect Source Identification Using Multiple Microphones

Acoustic Intensity

\[ I(r) = \frac{1}{2} \Re \{ A(r) v^*(r) \} \]

NAH-\textit{spFT}

\[ p_s = F^{-1}[e^{-jkx}(y_s - y_h)F[p_f(x, y_h)]] \]

- Separable coordinates only
- Hypothetical regular plane for complex-shaped source

NAH-iBEM

\[ p_f = (D_f D_s^{-1} M_s + M_f) v_s \equiv Gv_s \]
\[ v_s = G^+ p_f \]

- Singularity prob.: regularization
- BEM modeling

(continued)
**Acoustic Imaging Techniques 2**

- **Indirect Source Identification (continued)**

**HELS**

\[ p^* = \rho c \sum_{i=1}^{N} C_i \psi_i^* \]

\[ C = \rho c^{-1} \left( \left[ \psi_{mn}^* \right]^T \left[ \psi_{mn}^* \right]^{-1} \left[ \psi_{mn}^* \right]^T \right) p_0 \]

- Optimal no. of expansion terms
- Optimal selection of field pts

**ESM**

\[ p_f(r_m; \omega) = \sum_{e=1}^{E} \sum_{j=0}^{J} C_j^e \psi_j(r_m - r_e; \omega) \]

\[ \{C\} = \{U\}\{\Lambda\}\{W^H\}^{-1}\{p_f\} = \{W\}\{\Lambda^{-1}\}\{U^H\}\{p_f\} \]

- Generalization of HELS/iFRF
- Describe complex wave fronts
- Reconstruction error

**iFRF**

\[ Q_s = H^+ p_f \]

\[ H^+ = H^H H^{-1} H^H \]

- Singularity prob.: absorption, regularization
- Resolution
- Same concept with TPA
Ex. Design of Sound Insulation by Inverse FRF

- **Passenger car interior**
  - **Calibration**
    
    $P_m(\omega) = H(\omega)^{m \times n} Q_n(\omega)$
    
    $H^+ = H^H H^{-1} H^H$
  
  - **Identification**
    
    $Q_n(\omega) = H^+(\omega)^{n \times m} \hat{P}_m(\omega)$
    
    $v_S S_S = H^+ P_f$

---

**Sound pressure level (dBA)**

<table>
<thead>
<tr>
<th>Panel name</th>
<th>Front floor</th>
<th>Front tunnel</th>
<th>Dash bottom</th>
<th>Dash center</th>
<th>Dash upper</th>
<th>Dash sides</th>
<th>Rear doors</th>
<th>Heel kick</th>
<th>Package tray</th>
<th>Headliner</th>
<th>Rear floor</th>
<th>Rear tunnel</th>
<th>Bare only</th>
<th>Max only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver's ear position</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>Max only</td>
<td>Window method</td>
<td>Rear center position</td>
<td>Codriver's ear position</td>
<td>Rear center position</td>
<td>Headliner</td>
<td>Rear floor</td>
<td>Rear tunnel</td>
<td>Bare only</td>
<td>Max only</td>
</tr>
</tbody>
</table>

**Boundary Microphones**

**Candidate sources**

**Actual sources**

**Identification**

$Q_n(\omega) = H(\omega)^{n \times m} \hat{P}_m(\omega)$

$v_S S_S = H^+ P_f$
Ex. 16 Gasoline Engine
Source reconstruction by ESM & BEM⁻¹

Surface intensity @ 3000 RPM

150 Hz (E3)
200 Hz (E4)

Animated surface velocity field
Ex. Washing M/C: Vib. Response of Tub Varying the Motor Speed

3rd order of motor excitation, 384-486 Hz

RPM (625-800)

time = 17.75 s, rpm = 627, freq = 384 Hz

Measured hologram

Restored velocity

Acoustics Lab., NoViC
Ex. Impact-borne Tire Noise & Vibration

- Vibro-acoustic test with 205/65R15 tire & holography

- Wave propagation on tread/sidewall due to an impact
Recent Works Related to the Vibro-acoustic Inverse Problem
In-duct Source ID for Fluid Machines

- **Fluid machines**
  - Identification of noise generation mechanism
  - Difficulties
    - No directly measurable reference source signal
    - Propagation of high order modes, noise due to turbulence, & fast rotation

- **Source identification for aero-acoustic source in duct**
  - Conventional methods bear poor spatial resolution

- Source identification considering the evanescent modes and the rotation of source?

![Diagram of source identification process](image)
A Preliminary Experimental Result

- **Measurement setup**
  - Power Amplifier (B&K 2716)
  - Compression driver (Selenium D250-X)
  - Aluminum plate (10t)
  - Signal analyzer and generation system (Pulse 3560D)

- **Velocity field at source plane (kR<1.84)**
  - <Air blower>
  - <Axial fan>
Source ID vs. Design: A similar concept

- **Comparison of holographic source ID & source design**

**Source identification**

- **Source design for a rendered field**

\[ v_s = G^+ p_f \]

\[ A_{source} = G^+ H_{target} \]

- Solve the problems of **source design or field control** by using the equivalent concept of the **acoustical holography**.
Exterior: Zonal & Directional Control

Loudspeaker array for creating zones of silence and free wave propagation, simultaneously

Control result at the xy-plane over a height of z=2d

Source array

Uninterested zone

Zone of free wave propagation

Zone of silence

3D boundary

SPL re. $p_{\text{max}}$

$\text{Re}(p)/\text{Re}(p_{\text{max}})$

100 Hz

300 Hz

500 Hz

700 Hz

1000 Hz
Interior: Free Prop. from a Corner Source

- **Design:** Spherical wave prop. emanating from left-lower corner
  - Irregular shaped room, Initial array = 36 sources, Reduced array = 18 sources
  - Wall boundary condition: rigid, Room BE = 2621 nodes, 5238 triangular elements

- **Simulation result with noise (SNR=-25 dB)**

<table>
<thead>
<tr>
<th>200 Hz</th>
<th>300 Hz</th>
<th>400 Hz</th>
<th>500 Hz</th>
<th>600 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="200 Hz" /></td>
<td><img src="image" alt="300 Hz" /></td>
<td><img src="image" alt="400 Hz" /></td>
<td><img src="image" alt="500 Hz" /></td>
<td><img src="image" alt="600 Hz" /></td>
</tr>
</tbody>
</table>

*Optimized actuators using EfI method*
Creation of a Localized Vibration

- **Location of Actuators: periphery of an elastic plate only**
  - Utilization of central part for electronic components
  - Array actuators exciting elastic (glass) plate

- **Condition of target vibration field**
  - **Hot zone**: a localized sector for vibration sensing
  - **Cold zone**: null field for vibration perception

- **Traveling wave control method**
  - Frequency & magnitude: determined by considering the tactile feeling

\[
\begin{align*}
[G]_{pxN} [E]_{Nxd} &= [V]_{pxd} \quad \Rightarrow \quad [E]_{Nxd} &= [G]^\dagger_{Nxp} [V]_{pxd}
\end{align*}
\]

- \(G\): Transfer matrix (input signal & vel. response)
- \(E\): Matrix of input signals
- \(V\): Matrix of velocity responses
- \((\cdot)^\dagger\): pseudo inverse
- \(N\): Number of actuators
- \(p\): Number of observation points
Experimental Setup and Results

- Actuators and observation points
  - Actuator: 20 mm spacing
    - $\lambda_b/8$: Consideration of aliasing effect
  - Uniform arrangement of 34 actuators
  - 7x11 observation points

- Definition of performance index
  - Fulfillment of the rendered target pattern
  - Ratio between designed hot zone and actual controlled area (CP1) or normally sensible area (CP2) (Also, tactile threshold & limen are considered)

- Experimental results
  - 2x2 division
    - CP1 = 55 %, CP2 = 35 %
  - 3x3 division
    - CP1 = 60 %, CP2 = 40 %
Acoustic Pyrometry

**Inverse estimation of temperature field**
- Based on the inverse Radon transform & the fact that \( t_d = L/c, c = \sqrt{\gamma RT} \)
- \( \psi_n \) = basis function to approximate the speed of sound

\[
t_d = L \int \sum_{n=1}^{q} A_n \psi_n ds = \sum_{n=1}^{q} A_n L \int \psi_n ds = \sum_{n=1}^{q} A_n \Psi_n
\]

\[
t_d \ p \times 1 = \Psi_n \ p \times q \ A_n \ q \times 1
\]

\[
A_n \ q \times 1 = \Psi_n \ p \times q \ t_d \ p \times 1
\]

**Image enhancement of reconstruction result**
- Stabilization of inverse solution – regularization technique

Reference & reconstructed result

Suppression of small singular value

\[
A_n = VF^{\alpha} \Lambda^{-1} U^H t_d
\]

\[
F^{\alpha} = \text{diag} \left( \frac{\lambda_q^2}{\alpha^3 + \lambda_q^2 \alpha + \lambda_q^2 \alpha^2}, \ldots \right)
\]

Calculation condition=16-sensor, 64 interpolation points
Inverse Estimation of Sectional Temp.

- Enhancement of reconstruction result II
  - Optimal selection of interpolation points by genetic algorithm

- Reconstruction of uniform ambient temperature field

**Deployment of interpolation points**

- Equidistant
- Optimal

**Reference & reconstructed result**

- Initial result
- Enhanced result
- Case I: Optimal interpolation points
- Case I + regularization

*Calculation condition=16-sensor, 64 interpolation points
*: regularized reconstruction result

**Reference & reconstructed result**

**Deployment of interpolation points**

- Equidistant
- Optimal

**Reference & reconstructed result**

- Initial result
- Enhanced result
- Case I: Optimal interpolation points
- Case I + regularization

*Calculation condition=16-sensor, 64 interpolation points
*: regularized reconstruction result
Research Works
by Other Members at NoViC, KAIST
- **MRI Noise**
  - Intense noise accompanies with strong magnetic field of MRI ($L_p = 130/110$ dB in 3/1.5 T) for a finer image
  - Hearing loss potential and annoyance of patients

- **Proposed ANC system**
  - Feedforward FXLMS algorithm is improper → Use of quasi-periodicity of MRI noise following SPE sequence
  - Actuator = Non-magnet speaker, Error mic. = ECM mic.

- **Simulation**
  - Target freq. peaks : 70 – 2500 Hz

- **Experiment** (Computing power limit of HW)
  - Target freq. peaks : Top 80 peaks only

---

<table>
<thead>
<tr>
<th></th>
<th>Simulation</th>
<th></th>
<th>Experiment</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ANC off</td>
<td>ANC on</td>
<td>Reduction</td>
<td>ANC off</td>
</tr>
<tr>
<td>Overall level (dB)</td>
<td>118.0</td>
<td>89.5</td>
<td>28.5</td>
<td>118.0</td>
</tr>
<tr>
<td>Overall level (dBA)</td>
<td>113.2</td>
<td>81.9</td>
<td>31.3</td>
<td>113.2</td>
</tr>
<tr>
<td>Mean level at target (dB)</td>
<td>115.0</td>
<td>81.4</td>
<td>33.6</td>
<td>114.7</td>
</tr>
</tbody>
</table>
● **Semi-active control of structural vibration**
  - Truss space structure with low damping
  - Equivalent damping ratio represented by normal force and modal displacement
  - Control the normal force by piezo actuator
  - Maximize damping for the 1\textsuperscript{st} mode
  - Successful in reducing the transient vib.

● **Nonstationary power flow analysis**
  - Classification of airplane engine
  - Analysis of vib. power with varying engine RPM
  - Classification of engines by comparing the vib. power levels
Acoustics and Vibration Lab.: Yang-Hann Kim

Sound visualization

Beam forming, Acoustic holography

Eyeglasses for the hearing impaired

Sound manipulation

Soundbar home theater system

Sound ball System, Spatial Equalization

Application to car audio system

Dark zone (low sound energy)
All results shown in this presentation are contributed from the former and current Acoustics Laboratory members, in particular, by IY Jeon, A Oey, WH Cho, TK Kim, YH Heo, and JH Woo, being conducted as their thesis and project works.