KAIST: Korea Advance Institute of Science and Tech (4000 undergrad, 4000 grad, 600 faculty members)
NOVIC: Center for Noise and Vibration Control (7+7 faculty members, 35 M.Sc. 50 Ph.D. about 500 graduates since)

C.W. Lee: Rotor Dynamics, Golf Dynamics
Younsik Park: Structural Modification and Modal Analysis
Kwang-Joon Kim: Vibration Isolation
J.G. Ih: BEM, BEM holography, Active Control
Youngjin Park: Active Sound Control, HRTF Customization
Jungwoo Choi: 3D sound and audio


Sound Visualization & Manipulation

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2013. 4. 29.
We can take a picture using a camera
Can we take the picture of sound?
Or, can we *draw* the picture of sound?
Sound visualization and manipulation

**Sound Visualization**
- See what we want using *microphone array*

**Sound Manipulation**
- Draw what we want using *loudspeaker array*
Sound Visualization
Introduction

[†] SMInstruments

Sound Visualization and Manipulation
What is sound visualization?

The first attempt to visualize the sound

Color organ by Bainbridge Bishop (1893, US)

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[†] A souvenir of the color organ, with some suggestions in regard to the soul of the rainbow and the harmony of light, Bainbridge Bishop, The De Vinne Press, 1893.
What is sound visualization?

Many means to express organ sound

[†] Sound field by five in-phase monopoles
Sound visualization as a mapping

Measured data → MAPPING → Acoustic image
Sound visualization as a mapping

The result of sound visualization depends on the selection of **basis function**

[†] This illustration is a modified version of the figure, pp.111-112, Science with a Smile (Robert L. Weber, Institute of Physics Publishing, 1992)
Category of sound visualization

Two popular visualization methods using different types of basis functions

Sound Visualization

Non-parametric method
Acoustic Holography

Provides information of the source surface. (pressure, particle velocity, intensity..)

Parametric method
Beamforming

Only provides information of the source location.
One-dimensional case

\[ p(x_0, t) = P(x_0)e^{-j\omega t} \]

\[ p(x_1, t) = p(x_0, t) \times H(x_1 | x_0, \omega) \]

What We See

What isMeasured

Propagation or Prediction
I. Acoustic Holography

**Three-dimensional case**

*What we see* (sound field)

*What is measured:* (pressure & velocity on the boundary)

*Propagation* (or prediction)

Kirchhoff-Helmholtz integral equation

\[
P(\vec{r}; f) = \frac{1}{4\pi} \int_{S_0} \left\{ P(\vec{r}_0; f) \frac{\partial G(\vec{r} | \vec{r}_0; f)}{\partial n_0} - \frac{\partial P(\vec{r}_0; f)}{\partial n_0} G(\vec{r} | \vec{r}_0; f) \right\} dS_0
\]
I. Acoustic Holography: example

Prediction of Mona Lisa’s image by Acoustic Holography

Source plane

Measurement plane

What we see

What is measured

Propagation

What we see: (magnitude plot)
II. Beamforming

Plane wave propagation model

Scan vector (modeled signal)

\[ W = \begin{bmatrix} W_1 & W_2 & W_3 & W_4 & \cdots & W_M \end{bmatrix}^T \]

measured pressure

\[ P = \begin{bmatrix} P_1 & P_2 & P_3 & P_4 & \cdots & P_M \end{bmatrix}^T \]

\[ Power(\theta) = E\left[ |P^H W|^2 \right] \]

Scan vector \( W \) is the basis function of beamforming method.
II. Beamforming: example

Prediction of Mona Lisa’s image by beamforming

Source plane

Propagation

Measurement plane

What we see

What is measured

Beamforming power
ACOUSTIC HOLOGRAPHY: APPLICATIONS
Moving Frame Acoustic Holography

• Magnetic levitation train

- Pressure distribution at source plane (900Hz)
- Intensity plot (900Hz)

• 28 microphones
• Constant moving speed
• Pure tone source
Cylindrical Acoustic Holography

King Seong-Deok bell

- Step by step measurement
- Microphone array
  - Number of microphone: 30
  - Aperture size: 4.42 m
  - Microphone spacing: 0.15 m
  - Radius of hologram: 0.2 m

Sound Visualization and Manipulation
BEAMFORMING: APPLICATIONS
Temporal basis function

- Source localization using two different basis functions

Beamforming of an impulsive signal interfered by steady sound
Time domain beamforming of impulsive source

◊ Impulsive signal interfered by steady noise

K-21 Infantry Fighting Vehicle
0.8m from top of the turret
Idle level (98 dB)
Moving 5~20 km/h (106~112 dB)
Real time implementation using FPGA

- Digital MEMS microphone + FPGA (Field Programmable Gate Array)

Advantages:
- High Frame Rate
- Unique Portable Design
- Light Weight
- Simple Connection
- Compact Controller
- Low Price
Real time implementation using FPGA

- Engine noise visualization
The selection of basis function leads to different results.
Sound manipulation problem

What if we replace the microphone array with a loudspeaker array?

Sound Visualization

source plane

measurement plane
Sound Manipulation
Introduction

Objective of sound manipulation

How can he make *what he wants to hear at his seat*?

How can we manipulate a sound field at a desired region?  
*Zone control of sound field*
What to draw on the selected zone?

- Basis function depends on the **impression** of sound we want to draw.

**Sound Manipulation**

- **Radiating sound ball**
  - Drawing a desired shape of wavefront

- **Focused sound ball**
  - Drawing dot(s) in space
I. Radiating sound ball: overview

- Reproduction of the sound field from a radiating sound ball over the zone of interest
II. Focused sound ball: overview

- Generation of a focused sound ball in the zone of interest
I. Radiating sound ball: mathematical expression

One-dimensional case

\[ p(x_0, t) = P(x_0)e^{-j\omega t} \]

What we can control

Propagation (transfer function)

What to manipulate

Loudspeaker

\[ p(x_1, t) = p(x_0, t) \times H_E(x_1 | x_0, \omega) \]

(transfer function)
I. Radiating sound ball: mathematical expression

 três-dimensional case

Kirchhoff-Helmholtz integral equation

\[ P(\vec{r}, f) = \int_S \left\{ P(\vec{r}_s, f) \frac{\partial G(\vec{r} | \vec{r}_s; f)}{\partial n_s} - \frac{\partial P(\vec{r}_s, f)}{\partial n_s} G(\vec{r} | \vec{r}_s; f) \right\} dS \]

What to manipulate (sound field)
What we can control (pressure & velocity on the boundary)
Propagation (transfer function)
II. Focused sound ball: mathematical expression

Regional sound focusing: acoustic brightness and contrast control[^1]

- Maximizing energy ratio between acoustically bright zone and dark zone

\[
\alpha = \frac{e_b}{J_0} = \frac{s^H R_b s}{H_0^2 s^H s} \quad \text{Potential energy in } V_b
\]

\[
\beta = \frac{e_b}{e_d} = \frac{s^H R_b s}{s^H R_d s} \quad \text{Potential energy in } V_d
\]

- Find maximum brightness or contrast by eigenvalue analysis

\[R_b s_\alpha = \alpha_{\text{max}} H_0^2 s_\alpha\]

: Acoustic brightness control

\[R_t^{-1} R_b s_\beta = \beta_{\text{max}} s_\beta\]

: Acoustic contrast control

Radiating Sound Ball: Applications
Example

- **3D reproduction of a virtual source**

- $N_{spk} = 194$ (Lebedev quadrature grids), Control source at $2\lambda$, Virtual source at $1\lambda$
Implementation

KAIST multichannel loudspeaker system

24ch. Line array

49ch. Spherical array

Amplifiers

DA Converters

User interface

Smart phone or Tablet PC

PC

Wi-Fi
Realization

- Demo: Interface for virtual sources realization
Focused Sound Ball: Applications
Regional focusing: applications

Personal audio system

A personal audio system can be used without uncomfortable earphones or headsets and bothering user’s neighbors.

Regional focusing: applications

- Personal audio system: control results

Comparison of Pressure Field
Equal Input
Vs.
Acoustic Contrast Control

Frequencies of interest: 800 Hz ~ 5 kHz
Regional focusing: applications

Personal audio system with scattering effect\([†]\)

- Effect of listener’s head scattering:

- Control results considering scattering effect:

We can **visualize** and **manipulate** any sound field by choosing appropriate basis function!

[†] This illustration is a modified version of the figure, pp.111-112, Science with a Smile (Robert L. Weber, Institute of Physics Publishing, 1992)
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Acknowledgment

Prof. J. W. Choi
Dr. M. H. Song
Mr. D. H. Seo, K. W. Kim, K. H. Kim, J. M. Lee, D. S. Kang, Ph.D. Candidate
Ms. M. R. Lee, M.S. Candidate
of NOVIC KAST

SMInstruments

Thank you
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Appendix
Mona Lisa Beamforming
Theory of Sound Focusing with Four Principles (+ - × ÷)
Sound Focusing Problem

Manipulation of focused sound beam by adjusting excitation function of loudspeaker array

\[ P(r, \theta) = \int_{-L/2}^{L/2} q(x) \frac{e^{jkR}}{R} \, dx \]

\[ \approx \frac{e^{jkr}}{r} \int_{-L/2}^{L/2} q(x) e^{-jk \sin \theta x} \, dx \]

Excitation function (unknown)

We can design the beam pattern with four principles (+ - × ÷).
Beam shaping and steering by \textit{gain weighting} and \textit{time delay}

\[ b(\theta) \]

\[ q(x) = w(x) e^{i\omega \tau(x)} \]

\text{Gain weighting}

\text{Time delay: } \tau(x) = \frac{\alpha x}{c}
Differential sources can produce a directional radiation pattern despite limitation of the aperture size.

**Excitation function for dipole beam pattern**

\[ q(x) = \delta(x + \frac{\Delta x}{2}) - \delta(x - \frac{\Delta x}{2}) \]

\( \Delta x : \text{source spacing} \)
Design various beam shapes by *multiplication of beam patterns*
Theorem: Optimization with Energy Ratio

Maximization of energy ratio

- Acoustic contrast control:
  Maximization of energy ratio between at bright zone and dark zone
  \[
  \text{Maximize } \beta = \frac{p_b^H p_b}{p_d^H p_d}
  \]

- Acoustic brightness control:
  Maximization of ratio between energy at bright zone and input power
  \[
  \text{Maximize } \alpha = \frac{p_b^H p_b}{q^H q}
  \]
Theory of Virtual Source Generation
How can we reproduce 1D sound from a virtual source inside control zone?

Target field

\[ P_t(x, f) = \begin{cases} 
  A e^{j k (x - x_v)} & \text{for } x_v \leq x : \text{right going wave} \\
  A e^{-j k (x - x_v)} & \text{for } x < x_v : \text{left going wave}
\end{cases} \]
By considering *time-reversed propagation*, right going wave can be generated.

\[ H(x | x_1, f) = Ae^{-j k (x-x_v)} \quad \text{for} \quad x_1 \leq x \]

\[ P_{t, \text{tr}}(x, f) = \left\{ \begin{array}{ll}
Ae^{-j k (x-x_v)} & \text{for} \quad x_v \leq x \\
Ae^{j k (x-x_v)} & \text{for} \quad x < x_v
\end{array} \right. \]

What we can control (excitation function)

What to manipulate (reproduced field)

Propagation (transfer function)
Reproduction of Interior Virtual Source in 1D Case

- But time-reversed propagation of *omni-directional virtual source* generates left going wave as well.

Since the left going wave is an *artifact*, it must be removed!
Time-reversed propagation of the directional virtual source can excite the left-side control source to reproduce only right going wave.

Control sources can be selectively excited for reproducing a directional virtual source.
**2D Reproduction of Interior Virtual Source**

- *Time-reversed radiation of the directional virtual source* can selectively excite the control sources.

- \( N_{spk} = 64 \) (circular array), Control source at \( 2\lambda \) from center