Parametric Array Loudspeakers (PALs) and Applications in Active Noise Control (ANC)

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Outline

- Introduction
  - Background
  - Motivation
  - Research question
- Part I: Improved prediction models for PALs
- Part II: Physical properties of audio sound generated by PALs
- Part III: ANC using PALs
- Conclusions & Future work

Introduction of ANC

- Active noise control (**ANC**): cancel the **noise** at **target points** by introducing **secondary loudspeakers**
- Applications: ANC headphones, ANC headrest system
  - Dec 18 2021: **Tesla** rolls out Active Road Noise Reduction for new Model S and X

Figure 1: Bose QuietComfort 35

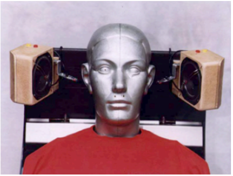


Figure 2: ANC headrest (Rafaely 1999)

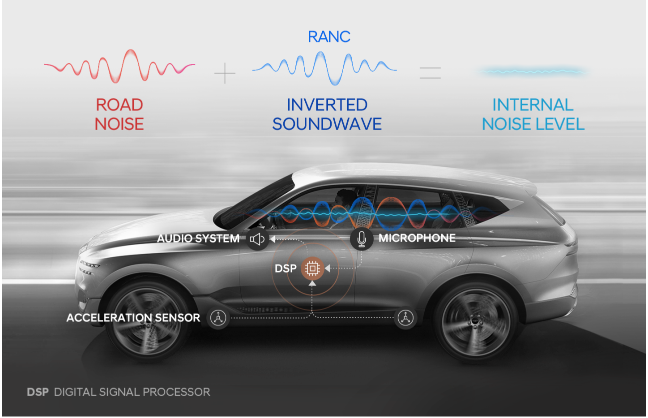


Figure 3: **Hyundai**'s Road Noise Active Control (RANC) technique (Feb 5 2020)

Traditional loudspeakers are usually omnidirectional

- For a traditional loudspeaker with a fixed **characteristic dimension** (Λ): **omnidirectional** at **low frequency**, **highly directional** at **high frequency**
- larger wavelength (λ) at lower frequency
- e.g.: $f = 1\,\text{kHz}, \quad \lambda = 0.34\text{m}, \quad \Lambda > 5\lambda = 1.7\text{m}$
- Issues: (1) large size; (2) large projection area

Figure 4: A traditional dynamic loudspeaker

Figure 5: Array

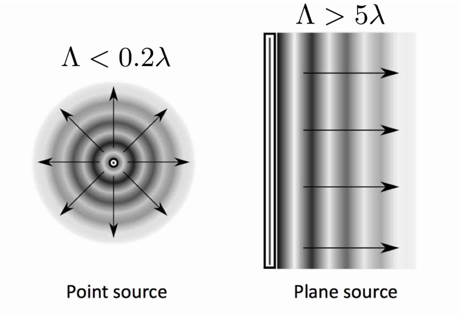
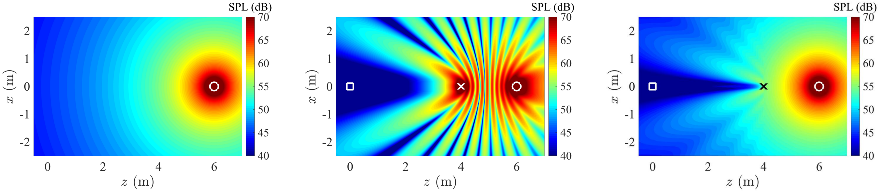


Figure 6: Radiation patterns of theoretical sound sources

Problem in ANC using traditional loudspeakers

- **Spillover effect**: the noise around the error (target) point is reduced (quiet zone), but **the noise in the other areas is amplified**!
- Reason: the **omni-directivity** of traditional loudspeakers
- Solution: using **directional** loudspeakers
- **Parametric Array Loudspeaker (PAL)**: sharp directivity
- Existing studies: ANC using **one** PAL (e.g., Tanaka and Tanaka 2010)



(a) Primary (noise) sound (b) Controlled by a **traditional loudspeaker** (c) Controlled by a **directional loudspeaker**

Figure 7: Sound pressure level (SPL) distributions at 1 kHz. ○: noise source; □: error point; ×: secondary source.

Overall research question

The feasibility of using **multiple PALs** in ANC systems to create a **large quiet zone** in various kinds of acoustic environments.

Issues in existing literatures

- **High computational cost** in calculating the audio sound generated by the PAL
- The **physical properties are still unclear** in complex acoustic environments (e.g., **reflection, transmission, and scattering**)
- No studies on the **ANC systems using multiple PALs** to create a **large quiet zone**

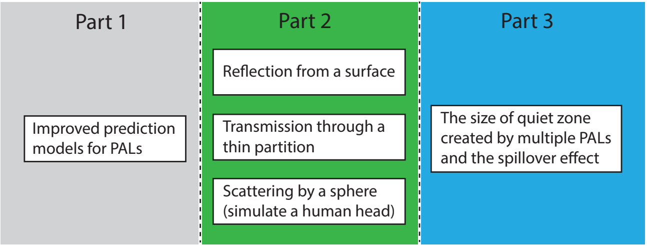


Figure 8: Outline of this thesis

- PAL: radiate only **ultrasound**!
- Mechanism: **nonlinear interactions** of **intensive** ultrasonic waves (e.g., 130 dB)

$$f_1, f_2 \xrightarrow{\text{second order}} \boxed{f_1 - f_2}, f_1 + f_2, 2f_1, 2f_2$$

- $f_1 = 61\,\text{kHz}, f_2 = 60\,\text{kHz}$, $\boxed{f_1 - f_2 = 1\,\text{kHz}}$
- Feature: **sharp directivity**

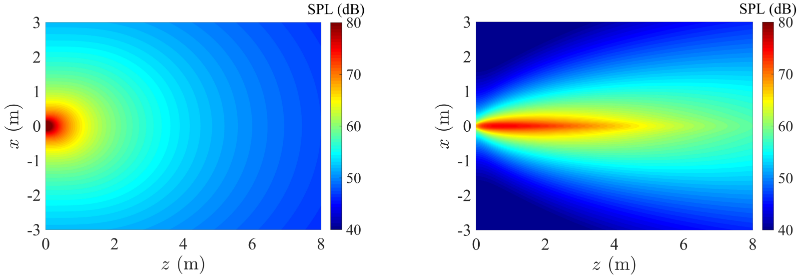


Figure 9: SPL distribution at 1 kHz with **a same size radiation surface**: (left) a traditional dynamic loudspeaker; (right) a PAL

- Audio sound originated from the ultrasound
- **Source density** $\propto$ **ultrasound pressure amplitude**
- Ultrasonic (primary) beam: **exponentially attenuated** due to atmospheric absorption
- Long end-fire **virtual** array $\Longrightarrow \Lambda \uparrow \Longrightarrow$ high directivity

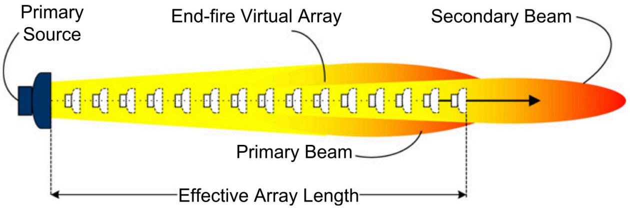


Figure 10: Model of parametric acoustic array (Gan 2012)

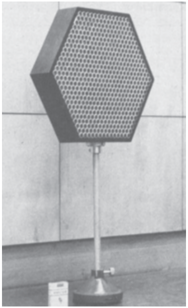


Figure 11: First PAL prototye (Yoneyama et al. 1983)

Research questions in Part I

Part I: Improved prediction models for PALs

Research question 1

- **Prediction accuracy** is important in predicting the noise reduction performance of ANC systems.
- Q: **How accurate** the current prediction (simulation) models are for audio sound generated by PALs?

Research question 2

- **Requirement of heavy computations** in multi-channel ANC systems due to large numbers of PALs.
- Q: Is it possible to **reduce the computational cost**?

Research question 3

- **Phased array PAL** provides a **steerable directional sound source**.
- Q: How to develop a fast and accurate prediction model for a **phased array PAL**?

Part I

- **Governing equations** and the framework of calculation
  - **Westervelt equation**
  - **Kuznetsov equation**
- The **spherical wave expansion (SWE)** method for a **circular PAL**
- The **sound fields** generated by a PAL
- The **cylindrical wave expansion (CWE)** method for a **phased array PAL**

Modeling methods for PALs

- **Kuznetsov equation**
  - Second-order nonlinear equation
  - Most accurate, slowest computational speed
- **Westervelt equation**
  - Neglecting Lagrangian density
  - Accurate only for high audio frequencies (Červenka and Bednarik 2019)
- **Inverse-law (far field) approximation**
  - Most inaccurate; **large differences between predictions and measurements** continue to be observed (Shi and Kajikawa 2015)
  - Fastest computational speed

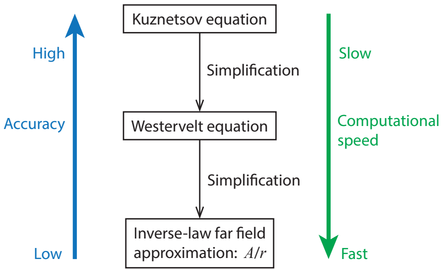


Figure 12: Modeling methods for PALs

Calculation of audio sound generated by a PAL

- second-order nonlinear equation $\xrightarrow{\text{quasilinear approximation}}$ two linear and coupled equations

$$\begin{cases} \nabla^2 p_i + k_i^2 p_i = 0, i = 1, 2 & \text{(ultrasound)} \\ \nabla^2 p_\mathrm{a} + k_\mathrm{a}^2 p_\mathrm{a} = q \propto p_1 p_2^*, & \text{(audio sound)} \end{cases}$$

- p_1, p_2 — ultrasound pressure; Rayleigh integral (**two-fold**)
- p_a — audio sound pressure; volume source (**three-fold**)

$$p_i(\mathbf{r}) \propto \iint_S g(\mathbf{r}|\mathbf{r}')\mathrm{d}^2\mathbf{r}'$$

$$p_\mathrm{a}(\mathbf{r}) \propto \iiint_V q(\mathbf{r}') g(\mathbf{r}|\mathbf{r}')\mathrm{d}^3\mathbf{r}'$$

- $g(\mathbf{r}|\mathbf{r}')$ — Green function
- **five-fold integral** in total
- Existing method: **Gaussian beam expansion** (Červenka 2013)
  - paraxial approximation
  - inaccurate: near field, low audio frequencies (**important in ANC**)

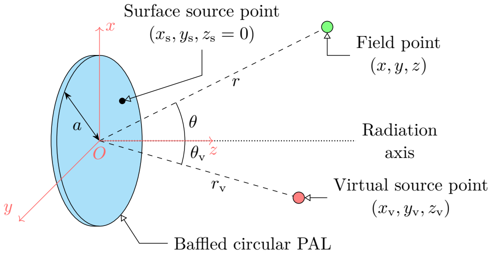


Figure 13: A baffled circular PAL

Spherical Wave Expansion (SWE)

- Utilizing the **spherical harmonics expansion** of Green's functions
- Pros:
  - available for **both Westervelt and Kuznetsov equations**
  - **no additional approximations** $\Longrightarrow$ accurate in the full range frequency
  - **100 $\sim$ 550 times faster**
- Cons:
  - limited to the **circular PAL** with an axisymmetric excitation profile

$$\text{Existing method:} \qquad p(\mathbf{r}) = \iiiint\!\!\int \cdots \mathrm{d}^2\mathbf{r}' \mathrm{d}^3\mathbf{r} \tag{1}$$

$$\text{Proposed SWE method:} \qquad p(\mathbf{r}) = \sum\sum\sum\sum\int \cdots \mathrm{d}r \tag{2}$$

Publications:

- **J. Zhong**, R. Kirby, and X. Qiu, "The near field, Westervelt far field, and inverse-law far field of the audio sound generated by parametric array loudspeakers," **J. Acoust. Soc. Am.** 149(3), 1524-1535 (2021).
- **J. Zhong**, R. Kirby, and X. Qiu, "A spherical expansion for audio sounds generated by a circular parametric array loudspeaker," **J. Acoust. Soc. Am.** 147(5), 3502-3510 (2020).
- **J. Zhong** and X. Qiu, "On the spherical expansion for calculating the sound radiated by a baffled circular piston," **J. Theor. Comput. Acoust.**, 2050026 (2020).

Sound fields generated by a PAL

- Front side
  - **Near field**: Kuznetsov equation (local effects are strong)
  - **Westervelt far field**: Westervelt equation (local effects are negligible)
  - **Inverse-law far field**: $p_a \propto 1/r$
  - R_1: **transition distance** from near field to Westervelt far field (0.1 m)
  - R_2: **transition distance** from Westervelt far field to inverse-law far field (30 m)
- Back side
  - Exist when the PAL is not baffled

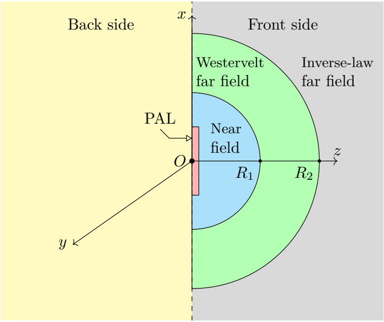


Figure 14: Sound fields generated by a PAL

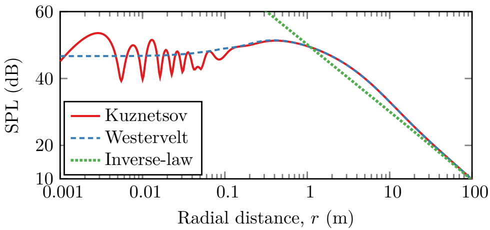


Figure 15: Audio SPL as a function of the propagating distance at 1 kHz. PAL radius is 0.05 m.

- The **location** depends on the **ultrasound** and the **aperture size**
  - a: radius of the circular PAL
  - λ_u: wavelength of the ultrasound

$$R_1 = \frac{a^2}{\lambda_\mathrm{u}} - \frac{\lambda_\mathrm{u}}{4} \tag{3}$$

- The **magnitude** of the SPL difference denpends on the **audio sound**
  - f_a: audio frequency

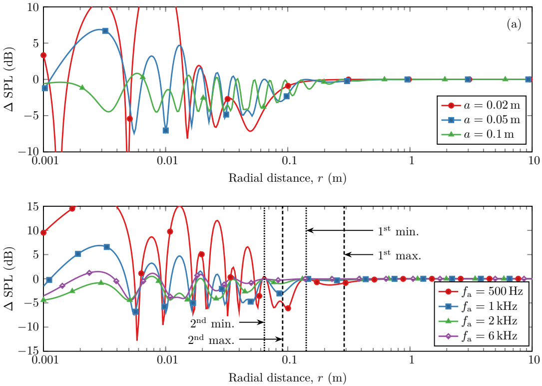


Figure 16: SPL difference calculated using Kuznetsov and Westervelt equations

- $R_2 \uparrow$ as $a \uparrow$
- $R_2 \uparrow$ as $f_a \downarrow$
- $R_2 \uparrow$ as $f_u \downarrow$ since absorption is weaker at low frqeuencies
- e.g., $a = 0.1$ m, $f_u = 40$ kHz, $f_a = 1$ kHz $\implies R_2 = 31.8$ m when ΔSPL< 1 dB
- Inverse-law far field is usually **far away from the PAL**!
- **Inverse-law approximate is inaccurate** in most applications
    - large differences between measurements and predictions in literatures

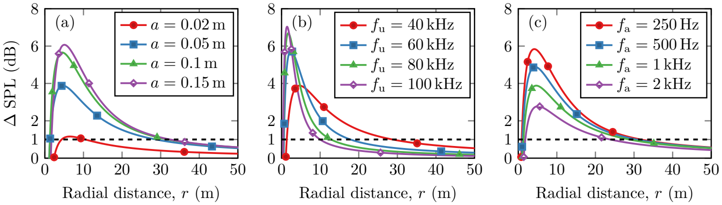


Figure 17: The audio SPL difference calculated with the Westervelt equation and the inverse-law property. Dashed lines, SPL = 1 dB.

Sound field on the back side

- No studies in existing literatures
- Theory: SWE + disk scattering
- **Measurements** validated the proposed model
- The audio sound is audible especially at **low frequencies**
  - Reason: diffraction is more significant

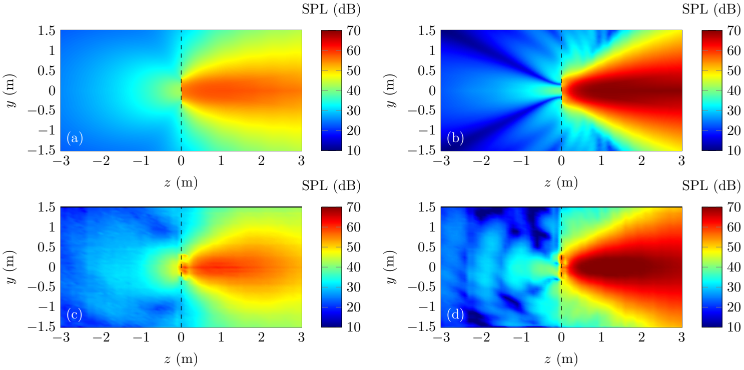


Figure 18: Audio SPL. Left column, 315 Hz; right column, 800 Hz; top row, simulations; bottom row, measurements.

Publication:

- **J. Zhong**, R. Kirby, and X. Qiu, "A non-paraxial model for the audio sound behind a non-baffled parametric array loudspeaker" **J. Acoust. Soc. Am.** 147(3), 1577-1580 (2020).

CWE (Cylindrical Wave Expansion) for a phased array PAL

- **Phased array PAL**: a **steerable** directional source
- Utilizing **cylindrical expansions** of Green's functions
  - 2D version of CWE
- original **fivefold integral** $\xrightarrow{\text{simplified into}}$ **twofold summation** + **onefold integral**
- **Assumption**: PAL is infinitely long along z axis
  - Inaccurate at low frequencies

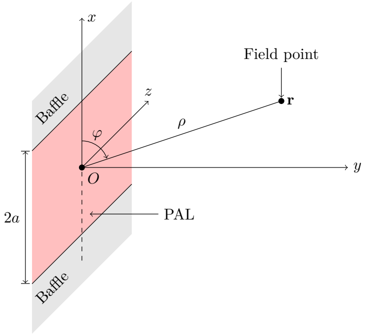


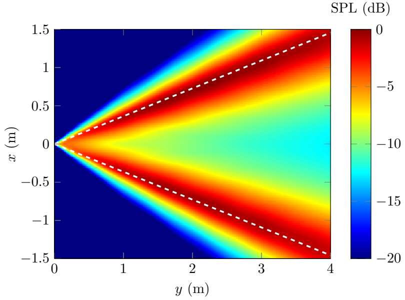
Figure 19: Sketch of a phased array PAL

$$\text{Existing method:} \quad p(\mathbf{r}) = \iiiint\!\!\int \cdots \mathrm{d}^2\mathbf{r}'\mathrm{d}^3\mathbf{r} \tag{4}$$

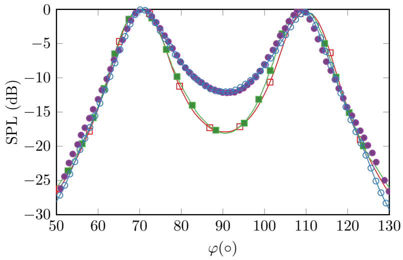
$$\text{Proposed SWE method:} \quad p(\mathbf{r}) = \sum\sum\int \cdots \mathrm{d}r \tag{5}$$

CWE (Cylindrical Wave Expansion) for a phased array PAL

- Existing popular method: the **convolution model** (Shi and Kajikawa 2015)
  - only applicable in the **inverse-law far field**
- the proposed CWE
  - fast; accurate in the **full field**



(a) 2D sound fields



(b) Directivity. Red hollow square, convolution model; blue hollow circle, cylindrical expansion at 4m; green solid square, convolution model from Shi and Kajikawa 2015; and purple solid circle, measurement from Shi and Kajikawa 2015.

Figure 20: Audio SPL at 4 kHz generated by a steerable PAL generating dual beams at 70° and 110° (denoted by dashed lines).

Publication:

- **J. Zhong**, R. Kirby, M. Karimi, and H. Zou, "A cylindrical expansion of the audio sound for a steerable parametric array loudspeaker" **J. Acoust. Soc. Am.** 150(5), 3797-3806 (2021).

Research questions in Part I

- Resarch question 1: How accurate are the current prediction models for audio sound generated by PALs?
  - Depend on the observation point
  - Near field: Kuznetsov equation
  - Westervelt far field: Westervelt equation
  - Inverse-law far field: inverse-law approximations
- Research question 2: Is it possible to reduce the computational cost of existing calculation methods?
  - Proposed a SWE method for a circular PAL
  - 100 times faster without loss of accuracy
  - Both Westervelt and Kuznetsov equations
- Research question 3: How to develop a fast and accurate prediction method for a phased array PAL?
  - Proposed a CWE method

Part II: Physical properties of audio sound generated by PALs

- **Reflections, tranmissions, and scattering** affect the noise reduction performance of ANC systems, but these properties for PALs are still **unclear**

Research question 1

- What would happen if the audio sound generated by a PAL is **reflected from a reflecting surface**?

Research question 2

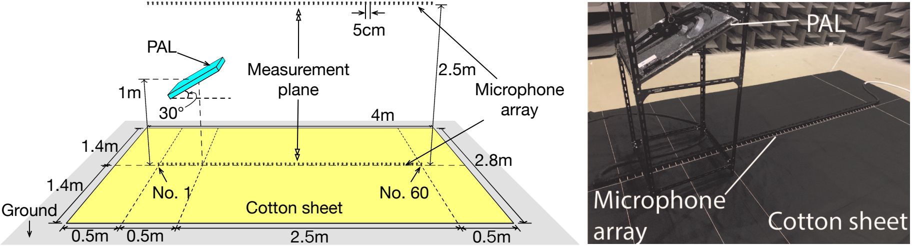
- How **transmissions through a thin partition** affect the audio sound generated by a PAL?

Research question 3

- How **scattering by a rigid sphere (simulating a human head)** affect the audio sound generated by a PAL?

Reflection from a reflecting surface (1/2)

- Theory: **SWE** + **image source method**
  - Reflections of ultrasonic waves are considered
- Cotton sheet (thick: 250 μm; surface density: 0.12 kg/m^2)
  - Audio sound at 1 kHz: **low** absorption coefficient (about 0.05)
  - Ultrasound at 64 kHz: **high** absorption coefficient (more than 0.8)



(a) Sketch (b) Photo

Figure 21: Experiment setup when a PAL radiates toward ground covered with a cotton sheet

Reflection from a reflecting surface (2/2)

- Results: the reflection audio sound is less focused for PALs
- Reason: audio sound are formed by ultrasound which is absorbed

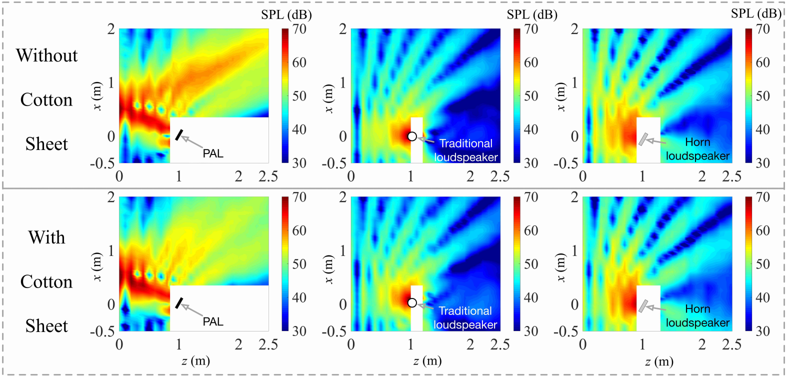
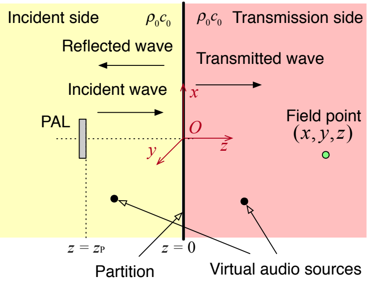


Figure 22: Measured SPL distribution: (left) PAL; (middle) traditional omni-directional loudspeaker; (right) traditional directional horn loudspeaker

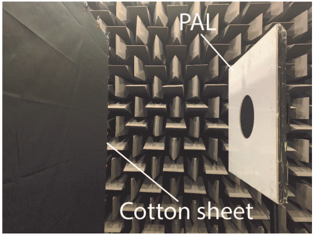
Publication:

- **J. Zhong**, S. Wang, R. Kirby, and X. Qiu, "Reflection of audio sounds generated by a parametric array loudspeaker," **J. Acoust. Soc. Am.** 148(4), 2327-2336 (2020).

- Model: transmission of sound generated by a PAL through a **thin** partition
  - **thin**: the thickness is much less than the audio wavelength
- Transmission side:
  - transmitted audio sound generated by **incident ultrasonic waves on the incident side**
  - audio sound generated by **transmitted ultrasonic waves on the transmitted side**



(a) Sketch



(b) Photo

Figure 23: A PAL near a thin partition

Publication:

- **J. Zhong**, S. Wang, R. Kirby, and X. Qiu, "Insertion loss of a thin partition for audio sounds generated by a parametric array loudspeaker," **J. Acoust. Soc. Am.**, 148(1), 226-235 (2020).

Transmission through a thin partition (2/2)

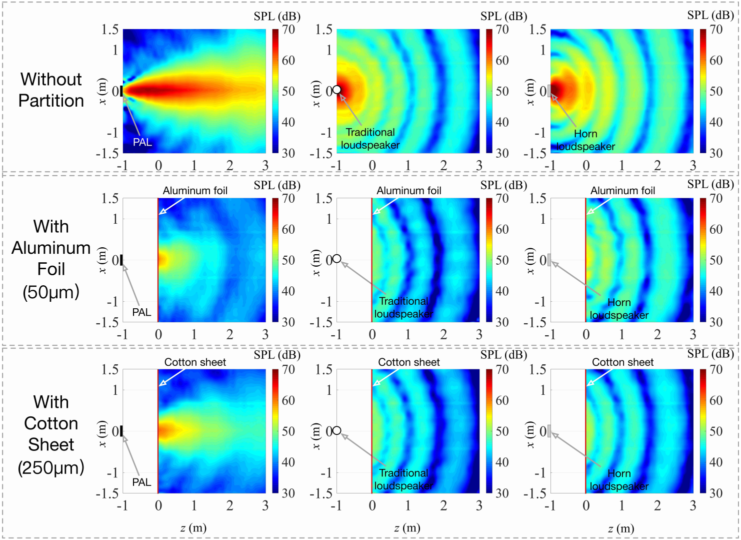


Figure 24: Measured SPL distribution: (left) PAL; (middle) traditional omni-directional loudspeaker; (right) traditional directional horn loudspeaker

- Rigid sphere: simulate a **human head** in applications
- Theory: **SWE** + **sphere scattering**

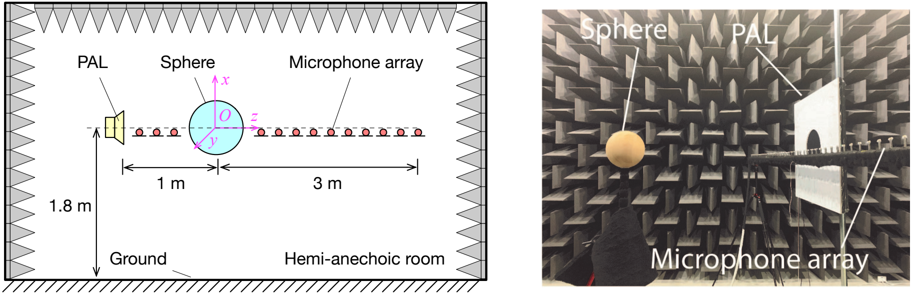


Figure 25: Experiment setup: (left) sketch; (right) photo

- Measurments validated the proposed model
- **Directivity is deteriorated**
- **Audio sound is amplified** on the back side of the sphere

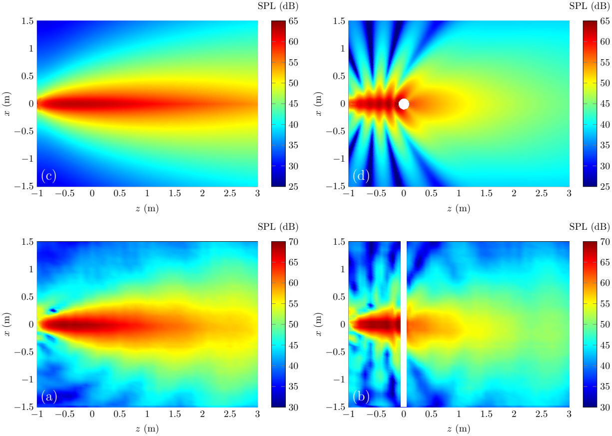
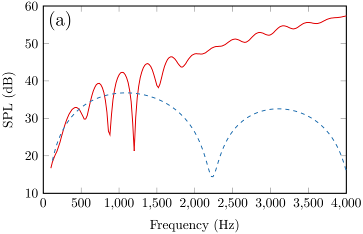
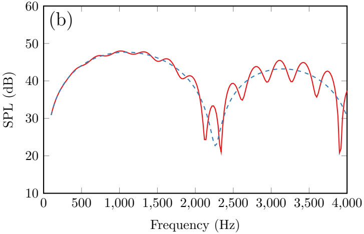


Figure 26: Sound fields generated by a PAL at 1 kHz. (left) no sphere; (right) with a sphere; (top) simulations; (bottom) measurements.

- More significant at **high frequencies**
- Reason: sphere size is much larger than the ultrasonic wavelength



(a) PAL



(b) Traditional loudspeaker

Figure 27: Audio SPL at the zenith angle $\theta = 135^\circ$ and the radius of 1.0 m from 100 Hz to 4 kHz. Solid line, with sphere; dashed line, without sphere.

Publication:

- **J. Zhong**, R. Kirby, M. Karimi, H. Zou, and X. Qiu, "Scattering by a rigid sphere of audio sound generated by a parametric array loudspeaker" **J. Acoust. Soc. Am.** Under Review (2021).

Research questions in Part II

Part II: Physical properties of audio sound generated by PALs

Research questions

1. What would happen if the audio sound generated by a PAL is **reflected from a reflecting surface**?
2. How **transmissions through a thin partition** affect the audio sound generated by a PAL?
3. How **scattering by a rigid sphere (simulating a human head)** affect the audio sound generated by a PAL?

Answers

- Directivity is deteriorated
- Sharp directivity is not guaranteed as expected in complex acoustic environments

Part III: ANC using PALs

Research question 1

- Is it possible to **cancel the broad band noise using PALs**?

Research question 2

- Can we **predict the quiet zone size** when using multiple PALs in ANC systems?

Research question 3

- Can PALs provide a **good alternative** to cancel the noise compared to traditional loudspeakers?

- Noise: **broad band up to 6 kHz**
- Secondary loudspeaker: PAL or traditional loudspeaker
- Error sensor: optical microphone using a **laser Doppler vibrometer (LDV)**
- Evaluation points: **9 microphones** randomly located in front of a head and torso simulator (HATS)

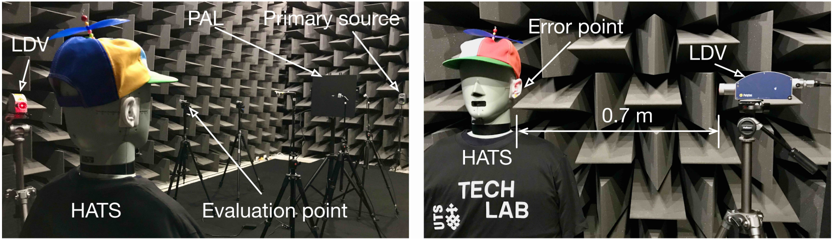


Figure 28: (left) Experiment setup in the semi-anechoic room; (right) LDV error sensing system

Cancel a broad band noise using PALs (2/2)

- Ear: $\sim 20\,\text{dB}$ noise reduction from 1 kHz to 6 kHz for both loudspeakers
- Evaluation points: noise levels ↑ using traditional loudspeaker

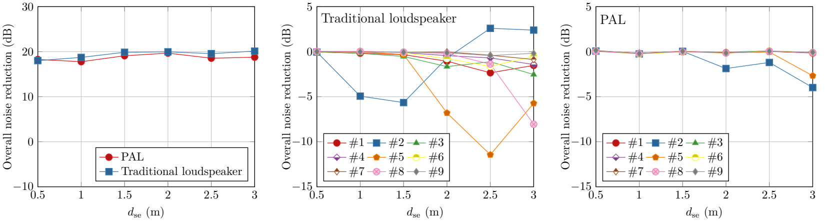


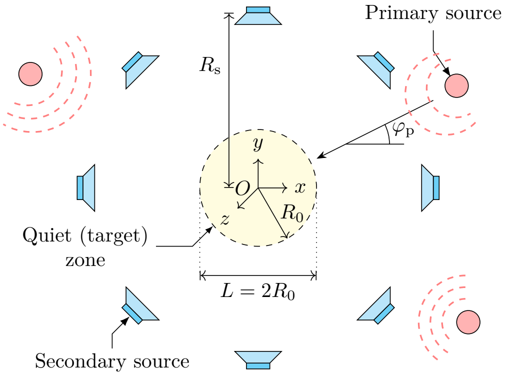
Figure 29: Overall noise reductions from 1 kHz to 6 kHz: (left) at the **ear**; and at the **9 evaluation points** using (middle) a traditional loudspeaker and (right) a PAL

Publication

- **J. Zhong**, T. Xiao, B. Halkon, R. Kirby, and X. Qiu, "An experimental study on the active noise control using a parametric array loudspeaker," **InterNoise 2020**, Seoul, Korea, (2020). Awarded the **Young Professional Grant**.

Create a large quiet zone using multiple PALs

- $N_{\mathrm{p}} > 1$ primary (noise) sources, $N_{\mathrm{s}} > 1$ secondary sources
- R_0 — the maximum radius of **the circular quiet zone** (noise reduction > 10 dB)
- **2D configuration**: all elements are located on the same plane; secondary sources are on a circle
- **3D configuration**: all elements are located in the space; secondary sources are on a spherical surface



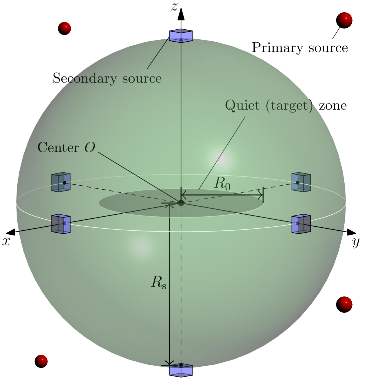


Figure 30: (left) 2D configuration; (right) 3D configuration

Create a large quiet zone using multiple PALs

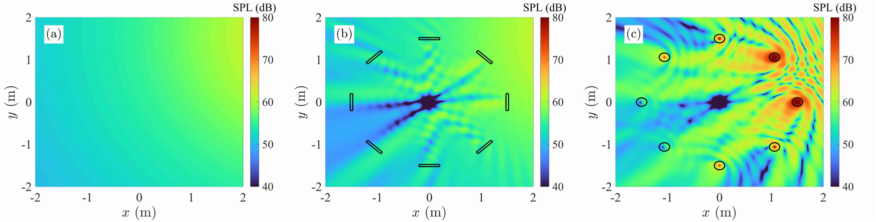


Figure 31: Sound fields at 1 kHz (a) for the primary noise comes from 22.5°, (b) under the optimal control with **8 PALs**, and (c) under the optimal control with **8 monopoles (traditional loudspeakers)**

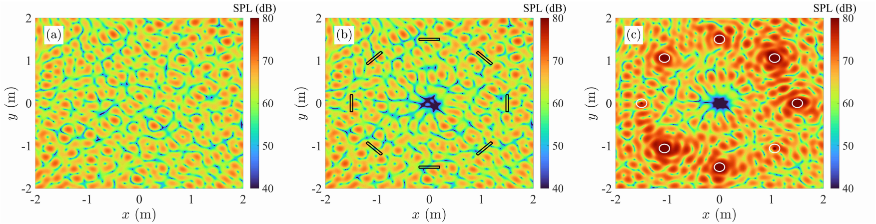


Figure 32: Sound fields at 1 kHz (a) generated by 8 primary sources, (b) under the optimal control with **8 PALs**, and (c) under the optimal control with **8 monopoles (traditional loudspeakers)**

- **Size of the quiet zone** L (m): the diamter of the circular quiet zone

$$L = 0.19\lambda N_\mathrm{s} \tag{6}$$

- **Energy gain** G (dB): the level of the summation of the squared sound pressure at all points with and without ANC
  - quantify the **spillover effect**
  - $G > 0$: the total acoustic energy is **increased** with ANC
  - $G < 0$: the total acoustic energy is **reduced** with ANC

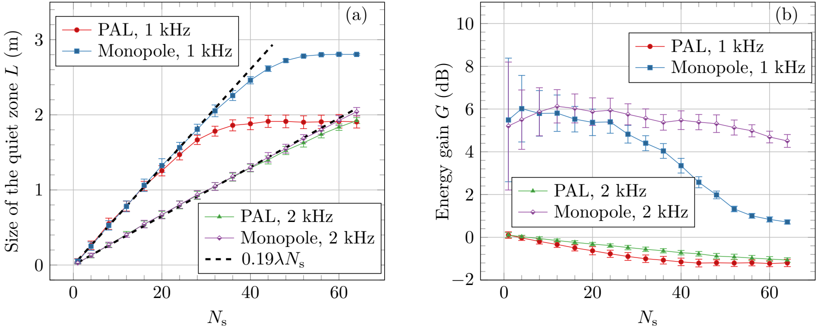


Figure 33: **2D configuration**: (a) the quiet zone size and (b) the energy gain as a function of secondary source number, where λ is the wavelength

- **Size of the quiet zone** L (m): PAL $\sim$ monopole

$$L = 0.55\lambda\sqrt{N_s} \quad (7)$$

- **Energy gain**: PAL $<$ monopole

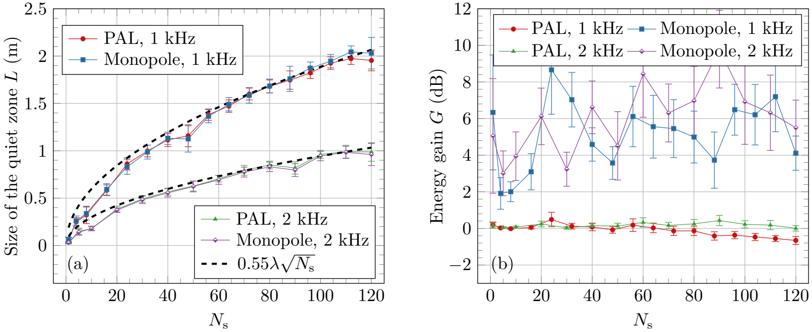


Figure 34: **3D configuration**: (a) the quiet zone size and (b) the energy gain as a function of secondary source number, where λ is the wavelength

- Experiment setup: 2 or 4 PALs
- Prediction validated by the measurements

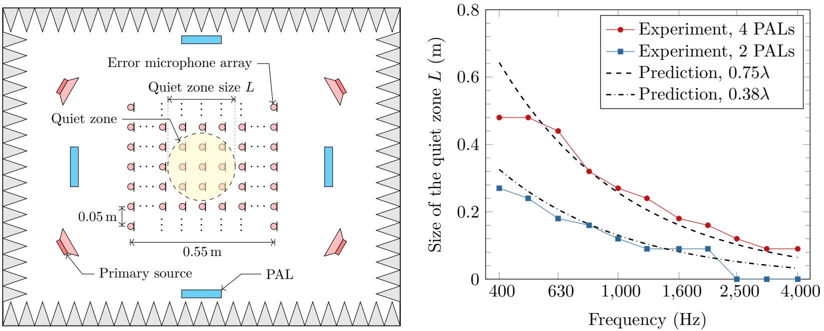


Figure 35: (left) Experiment setup; (right) predicted and measured quiet zone size

Publication:

- **J. Zhong**, T. Zhuang, R. Kirby, M. Karimi, H. Zou, and X. Qiu, "Quiet zone generation in a free field with multiple parametric array loudspeakers," **J. Acoust. Soc. Am.** Under Review (2021).

Part III: ANC using PALs

Research questions

1. Is it possible to **cancel the broad band noise using PALs**?
2. Can we **predict the quiet zone size** when using multiple PALs in ANC systems?
3. Can PALs provide a **good alternative** to cancel the noise compared to traditional loudspeakers?

Answers

- PALs can be used to cancel **a broad band noise up to 6 kHZ**.
- **Simple empirical formulae** are provided to **predict the quiet zone size** of two typical configurations.
- PALs can create a quiet zone with the **comparable size** as that created by traditional loudspeakers, but the **spillover effect is insignificant**

Conclusions

Part I: improved prediction models

- SWE for a circular PAL
- CWE for a phased array PAL
- Sound fields generated by a PAL

Part II: physical properties

- Reflection
- Tranmission
- Scattering

Part III: ANC using PALs

- Broad band noise
- Quiet zone size is the same
- Spillover effect is insignificant

Future Work

- Fast and accurate prediction models in the **time domain**
- How to **improve the directivity** in complex acoustic environments
- The effects of **physical properties** (reflection, transmission, and scattering) on the **noise reduction performance**
- Propagation of audio sound in other acoustic environments, such as **an enclosed cabin with reverberations**
- **Reducing the error sensors** in multi-channel ANC systems using multiple PALs

Thank you.
Any questions?

Existing research: Tanaka 2010

- Figure
  - top: ANC off
  - middle: ANC on with a traditional loudspeaker
  - bottom: ANC on with a PAL
- single-channel; 1.5 kHz
- the noise at the error poitn is reduced without affecting sound fields in the other areas
- **size of queit zone: 1/10 wavelength**
  - 1 kHz, wavlength: 34 cm, 1/10 wavlength: 3.4 cm

Research question

- Create a large quiet zone using multiple PALs?