Active Noise Control (ANC) Using Parametric Array Loudspeakers (PAL)

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Outline

- Introduction
- Literature Review
- Research Questions
- Progress to Date and Future Work
- Research Data Management Plan
- Conclusions

- Active noise control (**ANC**): cancel the **noise (primary wave)** at **target (error) points** by introducing **secondary loudspeakers (sources)**
- Mechanism: cancellation (superposition) of sound waves
- Applications: ANC headphones, ANC headrest system, virtual sound barrier (VSB)

Figure 1: Bose QuietComfort 35

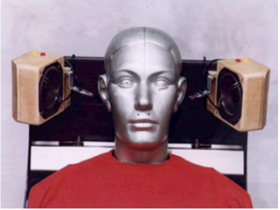


Figure 2: ANC headrest (Rafaely 1999)

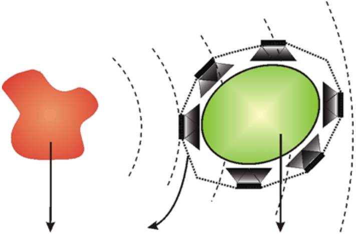


Figure 3: VSB system (Qiu 2019)

- Problem: the noise at the error point is reduced, but the noise in the other areas is increased!
- Reason: the **omni-directivity** of traditional loudspeakers (point source or point monopole)
- Solution: using **directional** loudspeakers

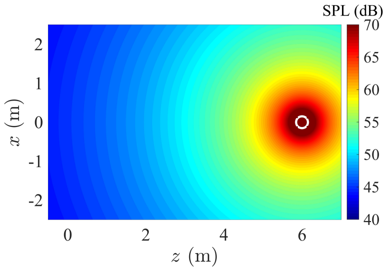


Figure 4: SPL distribution when ANC is off at 1 kHz. ○: noise source

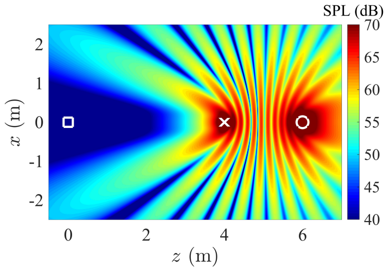


Figure 5: ANC on. □: error point; ×: secondary source

- PAL: **sharp directivity**
- **nonlinear interactions** of **intensive** ultrasonic waves (e.g., 130 dB)

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

- $f_1 = 61\,\text{kHz}, f_2 = 60\,\text{kHz}$, $\boxed{f_1 - f_2 = 1\,\text{kHz}}$

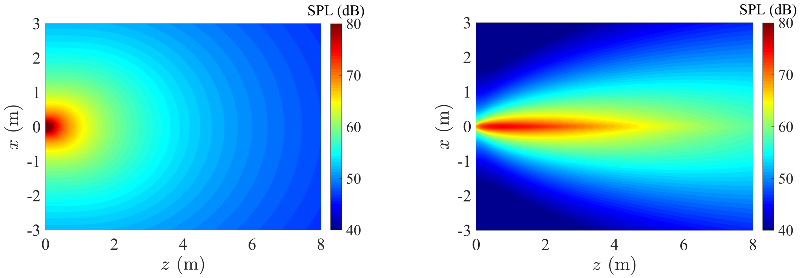


Figure 6: SPL distribution at 1 kHz: (left) a traditional loudspeaker; (right) a PAL

- museum exhibitions
- personal communications with a high level privacy
- measurements of the acoustic parameters of materials
- sound reproduction
- **ANC**

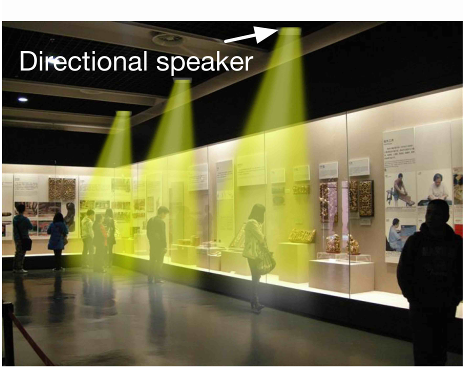


Figure 7: Listen narration in museum

- PAL: an application of **parametric acoustic array (PAA)** in air (Bennet 1975)
- The concept of PAA (Westervelt 1963)
  - primary beam: exponentially attenuated $\longrightarrow$ end-fire **virtual** array
  - end-fire array: a linear loudspeaker array
- The PAL prototype (Yoneyama 1983)
- The commercial PAL: e.g., Holosonics AudioSpotlight (Pompei 2002)
- Signal processing techniques $\longrightarrow$ improve sound quality (reviewed in Gan 2012)

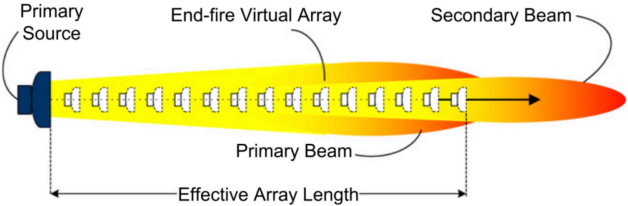


Figure 8: Model of parametric acoustic array (Gan 2012)

Figure 9: A PAL prototye (Yoneyama 1983)

Literature Review — PAL prediction models

Existing research: different models subject to different approximation levels

- **general second-order nonlinear equation** (Aanonsen 1983)
  - Pros: accurate in full field
  - Cons: very time consuming; almost impossible to use
- **Westervelt equation** (Červenka 2019)
  - Pros: accurate except at the points close to PAL
  - Cons: time consuming (**evaluation of five-fold integral**)
- **non-paraxial model** based on Westervelt equation (Červenka 2013)
  - Pros: faster calculation
  - Cons: paraxial approximation is assumed for ultrasonic waves
- **Khokhlov-Zabolotskaya-Kuznetsov (KZK) equation** (Hamilton 2008)
  - Pros: even faster
  - Cons: paraxial approximation is assumed for both ultrasonic and audio waves
- **collimated model** and its variants (Westervelt 1963, Shi 2015)
  - Pros: very fast
  - Cons: ultrasounds are assumed to be collimated; limited accuracy

Research question

- Simplify the calculation without too many approximations?

Existing research

- Focus on the **baffled PAL** — the PAL is installed on an infinitely large baffle
- Detection of audible sounds on the back side of a **non-baffled PAL** (Sugahara 2017)

Research question

- Predict the sound on the back side of a non-baffled PAL?

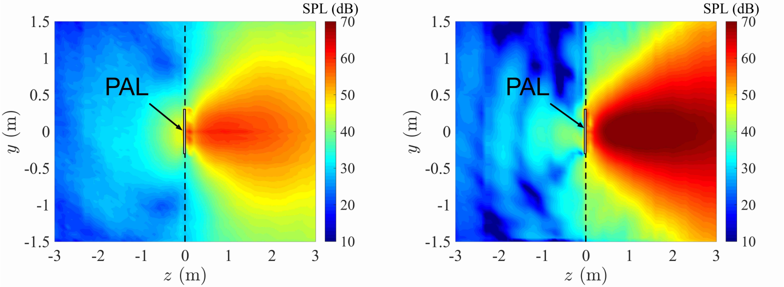


Figure 10: Measured SPL distribution at: (left) 315 Hz; (right) 800 Hz

Existing research

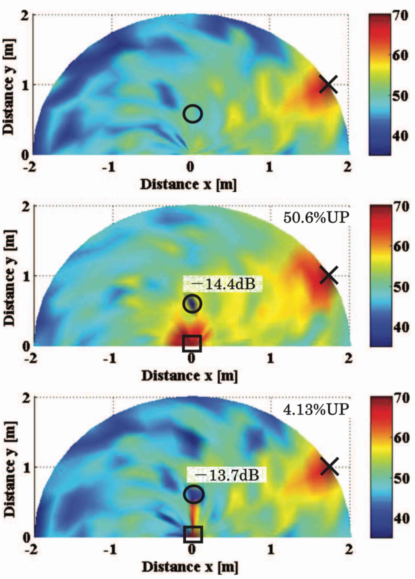
- Reflecting surfaces affect the noise reduction performance of ANC systems (Tao 2017, Zhong 2019, Zhong 2020)
- Problem: reflection of audio sounds generated by PALs is different compared to that generated by traditional loudspeakers
- Reason: the formation of audio sounds is an **accumulation process**
- **Reflection of ultrasounds**

Research question

- What would happen if the **process is truncated** by a reflecting surface?

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?

Existing research: Tanaka 2017

- noise reduction at ear: 10.4 dB
- frequency range: **600 Hz – 2 kHz**

Research question

- Cancel broader band noise up to 6 kHz using PALs?

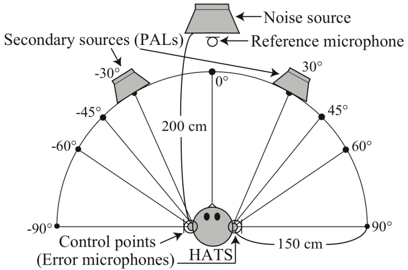


Figure 11: Binaural ANC using PALs

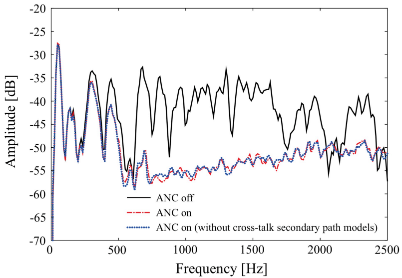


Figure 12: ANC performance at the ear of the head and torso simulator (HATS)

Research Questions — summary

Topic 1: PAL prediction models

- Reduce the computational load (five-fold integral)?
- Predict the sound on the back side of a non-baffled PAL?

Topic 2: PAL physical properties

- Reflection?
- Transmission?
- Scattering by a sphere (simulating a human head)?

Topic 3: ANC using PAL

- Cancel the borad band noise up to 6 kHz?
- Create a large quiet zone using multiple PALs?

Progress to Date — Topic 1: prediction model of a baffled PAL

- 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

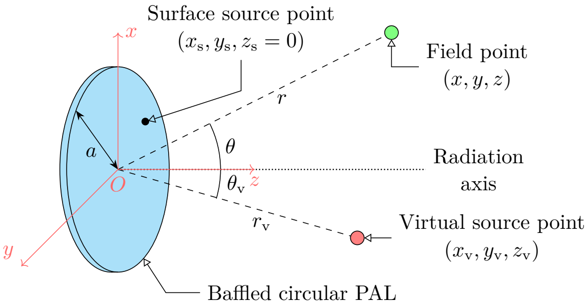


Figure 13: A baffled circular PAL

Progress to Date — Topic 1: prediction model of baffled PAL

Introduction

- Model: Westervelt equation
- Problem: **five-fold integral**
- Existing method: Gaussian beam expansion (Wen 1988)
  - vibration velocity profile $\longrightarrow$ Gaussian profiles
  - Pros: **two-fold integral** $\longrightarrow$ **one-fold summation**
  - Cons: paraxial approximation is assumed for ultrasonic waves
- Proposed method: spherical harmonic expansion
  - **five-fold integral** $\longrightarrow$ **three-fold summation + one-fold integral**
  - Pros: **no additional approximations; at least 15 times faster**
  - Cons: limited to circular PAL

Publication

1. **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).

Introduction

- Problem: existing methods cannot predict audio sounds on the back side of a non-baffled PAL
- Solution: **disk scattering model** for audio sounds

Publication

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

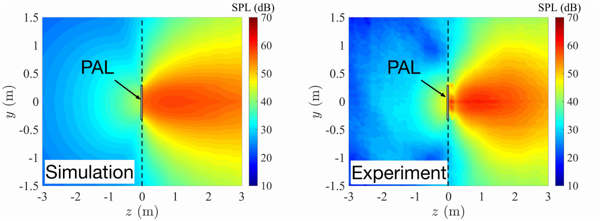


Figure 14: Validation of the proposed model for a non-baffled PAL at 315 Hz

Introduction

- Problem: the reflection of audio sounds generated by a PAL is different
- Reason: audio sounds are formed by ultrasounds
- Key: the reflection of ultrasonic waves
- 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)

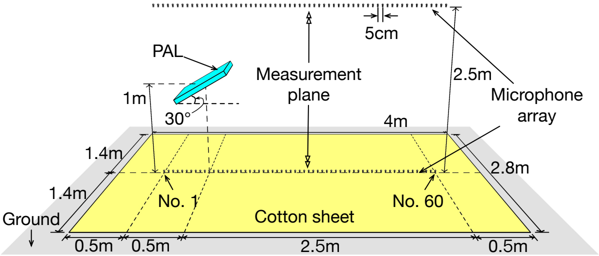


Figure 15: Experiment setup when a PAL radiates toward ground covered with a cotton sheet

Publication

1. **J. Zhong**, S. Wang, R. Kirby, and X. Qiu, “Reflection of audio sounds generated by a parametric array loudspeaker,” **J. Acoust. Soc. Am. (Accept subject to minor revisions)**, (2020).

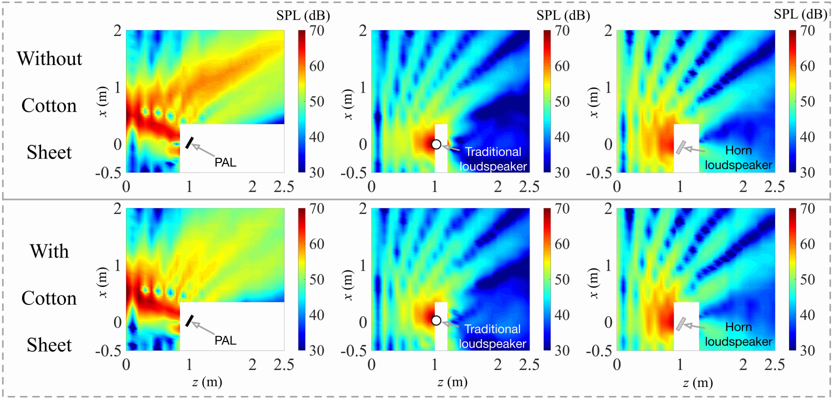


Figure 16: Measured SPL distribution: (left) PAL; (middle) traditional omni-directional loudspeaker; (right) traditional directional horn loudspeaker

Introduction

- Model: transmission of sounds generated by a PAL through a **thin** partition
- Significance: (1) measure the acoustic parameters *in situ* (Castagnède 2008); (2) mobile phones (Ahn 2019); (3) construction of a circular PAL by a rectangular PAL (Zhong 2020)
- Transmission side: transmitted audio sounds generated by incident ultrasonic waves; audio sounds generated by transmitted ultrasonic waves

Publication

1. **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).

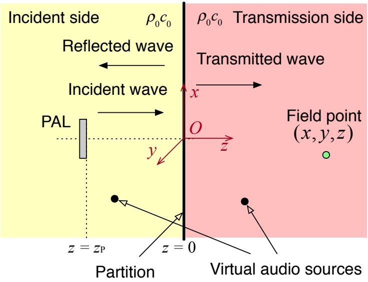


Figure 17: A PAL near a thin partition

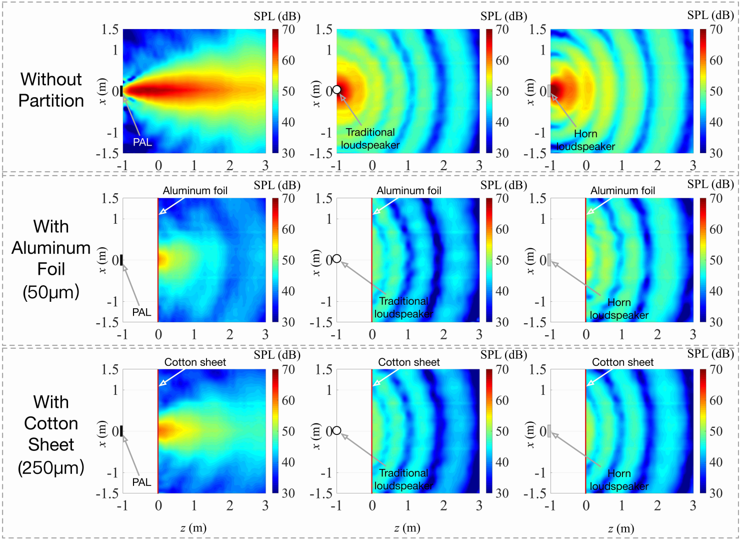


Figure 18: Measured SPL distribution: (left) PAL; (middle) traditional omni-directional loudspeaker; (right) traditional directional horn loudspeaker

Introduction

- Primary noise: 1 kHz – 6 kHz
- Secondary loudspeaker: PAL
- Error sensor: optical microphone using laser Doppler vibrometer (LDV)
- Evaluation points: 9 microphones randomly located in front of a head and torso simulator (HATS)

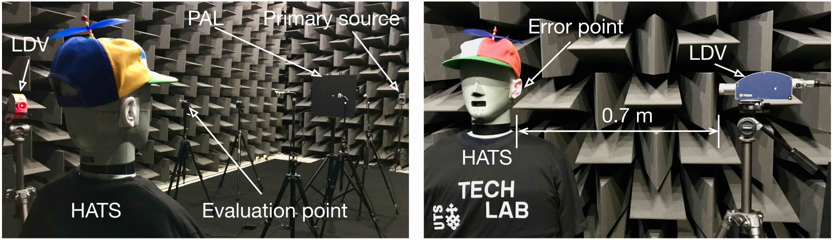


Figure 19: (left) Experiment setup in the semi-anechoic room; (right) LDV error sensing system

Experiment results

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

Publication

1. **J. Zhong**, T. Xiao, B. Halkon, R. Kirby, and X. Qiu, "An experimental study on the active noise control using a parametric array loudspeaker," **Inter-Noise 2020**, Seoul, Korea, August 23-26, 2020.

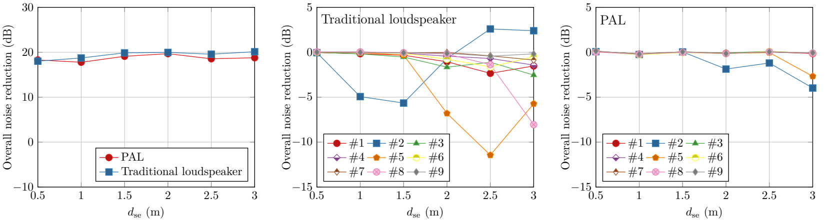


Figure 20: Overall noise reductions from 1 kHz to 6 kHz: (left) at the **ear**; and at the **9 evaluation points** using (middle) a traditional loudspeaker and (right) a PAL

- N_p primary sources, N_s secondary sources, N_e error points
- 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

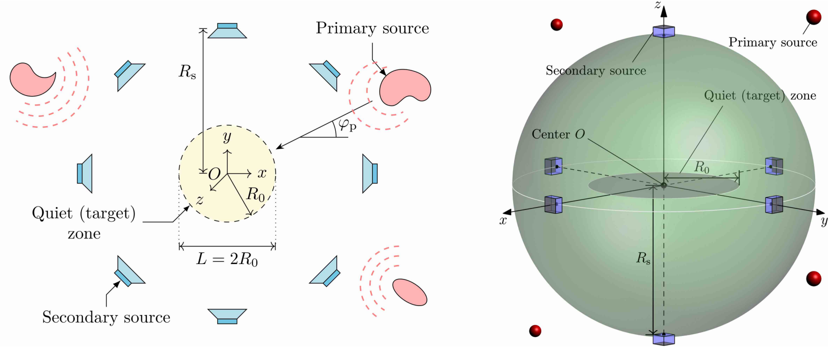


Figure 21: (left) 2D configuration; (right) 3D configuration

Progress to Date — Topic 3: create a large quiet zone using multiple PALs

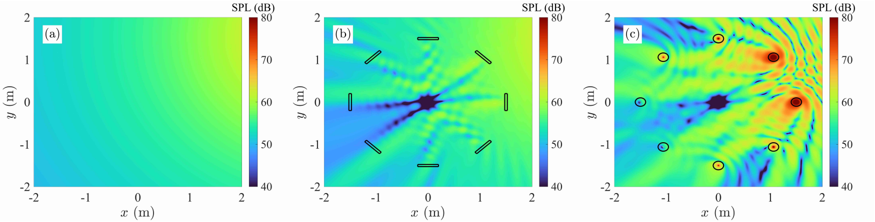


Figure 22: Sound fields at 1 kHz (a) for the primary noise comes from 22.5°, (b) under the optimal control with 8 PALs, and (c) under the optimal control with 8 point monopoles

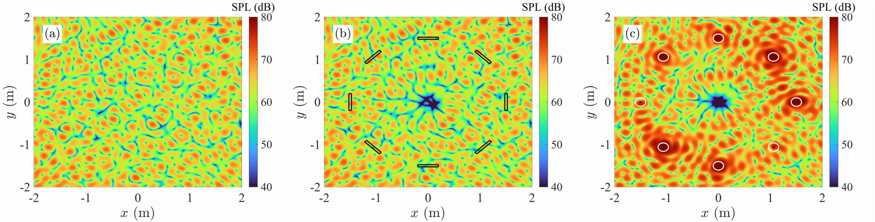


Figure 23: Sound fields at 1 kHz (a) generated by 8 primary sources, (b) under the optimal control with 8 PALs, and (c) under the optimal control with 8 point monopoles

Publication

1. **J. Zhong**, T. Xiao, R. Kirby, and X. Qiu, "Quiet zone generation in free field with multiple parametric array loudspeakers," **J. Acoust. Soc. Am. (to be submitted in August 2020)**.

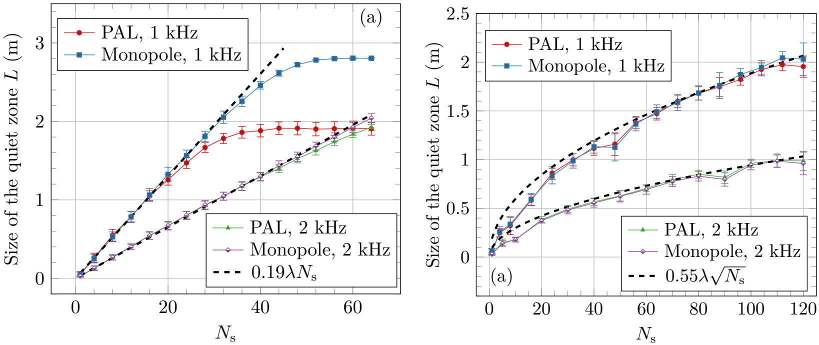


Figure 24: (left) 2D configuration; (right) 3D configuration. 8 primary sources; **the value and error bar are the mean value and standard deviation of 100 random trials**, and λ is the wavelength

Future Work

Topic 1: PAL prediction model

- Fast and exact calculation of nearfield audio sounds generated by a PAL based on general second-order nonlinear equation *present to Sept 2020*
    - Progress to date: built the theoretical model
    - Future work: conduct simulations

Topic 2: PAL physical properties

- PAL scattering by a rigid sphere (simulating a human head) *present to Oct 2020*
    - Progress to date: finished the experiments
    - Future work: build a theoretical model and conduct simulations

Topic 3: ANC using PAL

- Create a large quiet zone using multiple PALs *Aug 2020 – Dec 2020*
    - Progress to date: finished the theoretical model and simulations
    - Future work: validations by experiments
- Other possible explorations and investigations *Jan 2021 to Dec 2021*

Research Data Management Plan (RDMP)

Data source

1. Simulation data generated by the numerical calculations of the theoretical models
2. Experiment data measured by acoustical measurement hardware and software, such as Brüel & Kjær PULSE sound and vibration analyzers
3. Data obtained by post-processing of both simulation and experiment data

Data management

- Multiple manage platforms to lower the risks of data loss: personal computer, Microsoft OneDrive, and UTS Stash
- Sensitivity: the data contain no health records, classified documents, and culturally and commercially sensitive information
- No special facilities and equipment are required to use these data

Conclusions

- Problem in traditional ANC systems
  - Omni-directivity of traditional loudspeakers
  - PAL $\longrightarrow$ secondary source
- 3 topics
  - PAL prediction model
  - PAL physical properties (reflection, transmission, and scattering)
  - ANC using PAL
- Progress to date
- Future work and data mangement

Thank you.
Any questions?