UNIVERSITY OF TECHNOLOGY SYDNEY

CANDIDATURE ASSESSMENT 1 REPORT

Active noise control using parametric array loudspeakers

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Abstract

Active noise control (ANC) systems are designed to mitigate the unwanted noise at the target locations by introducing secondary sound sources. Although the noise at the target locations can be reduced by ANC systems, the sound pressure in the other areas often increases due to the omni-directivity of the traditional loudspeakers. To address this issue, the traditional loudspeakers can be replaced by directional ones so that the secondary waves radiate only in the direction of the target region. The parametric array loudspeakers (PALs) have sharper directivity than existing traditional loudspeakers but the feasibility of using them in ANC systems remains to be investigated. PALs differ from traditional loudspeakers because audible sounds are generated by the nonlinear interactions of ultrasounds in air. The first topic in this report is a fast and accurate calculation method for predicting audio sounds generated by a PAL. The second topic is the reflection, transmission, and scattering of audio sounds generated by a PAL. With the above foundations and results, the final topic is ANC using PALs as secondary sources. Finally, the progress to date, future work, and research data management plan are presented.

List of Publications

The peer-reviewed publications during the PhD candidature are as follows.

Journal Articles

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.** (in press), (2020). *Related to* ***Research Question 2***
2. **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). *Related to* ***Research Question 1***
3. **J. Zhong**, B. Chen, J. Tao, and X. Qiu, "The performance of active noise control systems on ground with two parallel reflecting surfaces," **J. Acoust. Soc. Am.** 147(5), 3397-3407 (2020).
4. **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). *Related to* ***Research Question 1***
5. **J. Zhong**, J. Tao, and X. Qiu, "Increasing the performance of active noise control systems on ground with two vertical reflecting surfaces with an included angle," **J. Acoust. Soc. Am.** 146(6), 4075-4085 (2019).
6. S. Wang, **J. Zhong**, X. Qiu, and I. Burnett, "A note on using panel diffusers to improve sound field diffusivity in reverberation rooms below 100 Hz," **Appl. Acoust.** (in press), (2020).
7. **J. Zhong**, S. Wang, R. Kirby, and X. Qiu, "Reflection of audio sounds generated by a parametric array loudspeaker," **J. Acoust. Soc. Am.** (under review), (2020). *Related to* ***Research Question 2***

Conference Papers

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. *Related to* ***Research Question 3***
2. **J. Zhong**, J. Tao, and X. Qiu, "A numerical study on active noise radiation control systems between two parallel reflecting surfaces," **The 18th Asia-Pacific Vibration Conference**, Sydney, Australia, November 18-20, 2019.

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Nomenclature

Acronyms/Abbreviations

ANB	Active Noise Barrier
ANC	Active Noise Control
DFW	Difference Frequency Wave
GBE	Gaussian Beam Expansion
HATS	Head and Torso Simulator
IL	Insertion Loss
JASA	The Journal of the Acoustical Society of America
KZK	Khokhlov-Zabolotskaya-Kuznetsov
LDV	Laser Doppler Vibrometer
NR	Noise Reduction
PAA	Parametric Acoustic Array
PAL	Parametric Array Loudspeaker
PWE	Plane Wave Expansion
SHE	Spherical Harmonics Expansion
SPL	Sound Pressure Level
UTS	University of Technology Sydney
VSB	Virtual Sound Barrier

1 Introduction

1.1 Background and Motivation

The noise pollution becomes more and more serious nowadays due to the development of the transportation systems (e.g., cars, airplanes, ships, trains), manufacturing plants (e.g., transformer stations), electrical appliances (e.g., vacuum cleaners, refrigerators, air-conditioners), and so on. Noise can be mitigated at three different stages: at the noise source, in the wave propagation path, and near the person ear (receiver). Different noise control techniques have been proposed by researchers to control the noise at different stages.

The passive noise control techniques include building enclosures for noise sources, building barriers and insulation walls in the wave propagation path, and wearing earplugs and earmuffs around the person ears. Although the passive control techniques are effective over a wide frequency range, they are not practical for low frequency noise because of too much space occupied and high cost. To cope with these problems, the active noise control (ANC) techniques can be used as alternatives. At the noise source, the active enclosure consisting of arrays of loudspeakers can reduce the global sound power radiation from the noise sources [1,2]. In the wave propagation path, the active noise barriers (ANBs), where a number of loudspeakers are installed near the edge of the barriers, have been proposed to improve the insertion loss (IL) in the low frequency range [3,4]. Around the person ear, the virtual sound barrier (VSB) system can be used to actively control the sound field inside a closed region [5], and the ANC headrest system [6] and ANC headphones [7] work effectively in cancelling the noise at the person ears.

All ANC techniques employ additional loudspeakers (called secondary sources) to cancel the noise at the target (error) points. When a secondary source is used to cancel the noise at a single location, the quiet zone is created near the target point but the sound pressures in the other areas might increase due to the omni-directional sound generated by the traditional secondary loudspeakers [8,9]. Placing the secondary source close to the target point can mitigate the increase of total energy in the other areas [10,11], but it brings obstructions to the person.

Some studies have demonstrated the capabilities and potentials of using directional loudspeakers to avoid increasing sound pressure levels (SPLs) in the other areas [1,12,13], because directional secondary sources radiate only in the direction of the target region. Parametric array loudspeakers (PALs), where the highly directional audio sounds are generated due to the nonlinear interactions of ultrasonic carrier waves in air, have shaper radiation directivity than existing traditional loudspeakers as shown in Fig. 1-1 [14]. The advantage of using PALs in ANC systems has been demonstrated in recent studies [9,15-17]. However, the feasibility of using multiple PALs as secondary sources to generate a large quiet zone and cancel a broadband noise remains to be investigated.

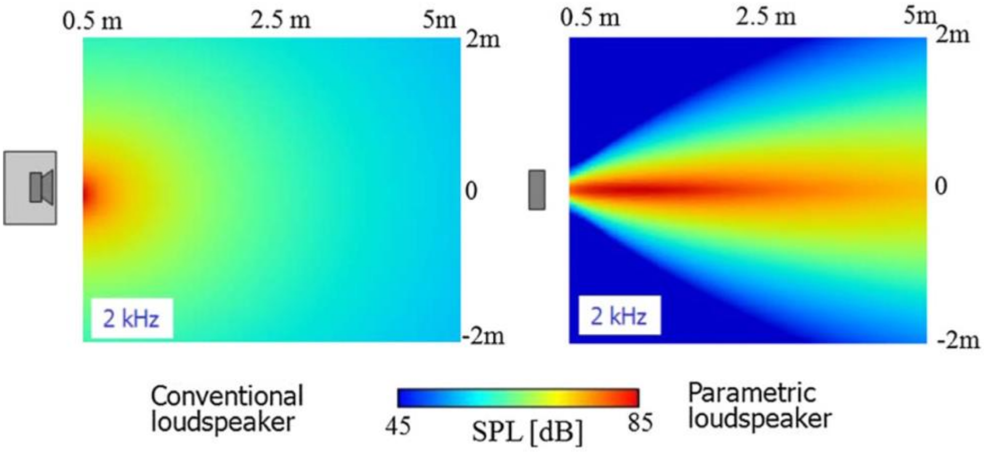

Figure 1-1 The sound pressure level distributions at 2 kHz generated by a traditional loudspeaker (left) and a PAL (right) with the same radiation surface size [14].

1.2 Research Questions

In this research, PALs will be used as the secondary sources in ANC systems to cancel the noise at target points. The audio sounds from PALs are generated by nonlinear interactions of ultrasonic waves in air, which is different from those from traditional loudspeakers. Therefore, the prediction model and physical properties of audio sounds generated by PALs need to be investigated first. The feasibility of using PALs in ANC systems can then be explored based on the above findings. The following questions are addressed in this research, where questions 1 and 2 focus on the PAL itself and question 3 is related to its applications in ANC.

Question 1. The accurate calculation of audio sounds generated by PALs is rather time-consuming due to the evaluations of five-fold integrals. The existing method employs the paraxial (Fresnel) approximation to simplify the calculations which is inaccurate at wide angles from the radiation axis of the PAL [18]. Therefore, it is worth investigating whether it is possible to simplify the calculation without additional approximations. The existing method is based on a baffled model; however, it has been reported that audio sounds can be heard behind a PAL in free field (non-baffled model). The question is how to develop a theoretical model to predict the sounds on both front and back sides of a non-baffled PAL?

Question 2. The audio sounds generated by PALs can be treated as the superposition of the sounds generated by infinitely many virtual sources in space with the source density proportional to the product of the sound pressure of ultrasounds. Therefore, the formation of the audio sound is accumulated before the ultrasound being totally absorbed in air. There would be interesting phenomena if the accumulation process is truncated by a reflecting surface, blocked by a partition, or scattered by a sphere (approximating a human head), and this will be explored in this research as the second topic.

Question 3. It has been reported that PALs can be used in ANC systems to create a quiet zone around the target point without affecting the sound levels in the other areas. However, the existing studies focus only on the control of the pure tone or narrow band (the upper limit is less than 2.5 kHz) noise [9,15-17]. The feasibility of applying PALs to reduce broader band noise up to 6 kHz will be investigated, as well as the possibility of creating a large quiet zone with multiple PALs.

1.3 Objectives

To answer the research questions, the corresponding objectives are set as follows.

Objective 1. Simplify the existing theoretical model of a baffled PAL and propose a non-baffled model.

- For a baffled PAL installed in an infinitely large baffle, we expect to simplify the five-fold integral in the quasilinear solution of the Westervelt equation without additional approximations.
- For a non-baffled PAL in free field, we expect to develop a calculation model to predict the audio sounds on the back size of the PAL.
- Conduct experiments using commercial PALs to verify the proposed model.

Objective 2. Investigate the physical properties of audio sounds generated by PALs, including sound reflection, transmission, and scattering.

- Investigate the reflection of audio sounds generated by the PAL if an infinitely large reflecting surface is placed near the PAL.
- Develop a theoretical model to predict the transmitted sound generated by the PAL through a thin partition.
- Investigate the scattering effects of a rigid sphere (approximating a human head) on the audio sounds generated by a PAL.
- Study the reflection, transmission, and scattering mechanisms of audio sounds generated by PALs and compare them to the traditional loudspeakers.
- Conduct experiments to observe the above phenomena and verify the proposed models.

Objective 3. Explore ANC using PALs.

- Investigate the feasibility of using a PAL to reduce the broadband (up to 6 kHz) noise at the person ear.
- Investigate the feasibility of using multiple PALs to create a large quiet zone.
- Explore the physical limitations of ANC systems using PALs.
- Optimize physical configuration of the noise source, secondary source, the reference sensor, and the error sensor.
- Conduct experiments to verify the findings.

1.4 Report Outline

Chapter 1 has presented the introduction of the report, which consists of the background and motivations of this research, the research questions and the corresponding objectives. Chapter 2 reviews the existing studies for the prediction models of audio sounds generated by a PAL, the reflection, transmission, and scattering of PALs, and their applications in ANC systems. Chapter 3 presents the methods used in this research. The progress to date and the planned future work are presented in Chapter 4. The research data management plan is described in Chapter 5. Chapter 6 draws the conclusions.

2 Literature Review

2.1 Parametric Array Loudspeakers (PALs)

Enlightened by the theoretical studies on the scattering of sound by sound [19-22], Westervelt proposed the concept of parametric acoustic array (PAA) in 1963 [23]. When a PAA radiates two collimated primary sound waves at frequencies f_1 and f_2 ($f_1 > f_2$) as shown in Fig. 2-1, the secondary sound waves with frequencies $2f_1$, $2f_2$, $f_1 - f_2$, and $f_1 + f_2$ are generated considering the second-order nonlinearity. Among them, the difference frequency wave (DFW), i.e., $f_1 - f_2$, is of the greatest interest because it is the lowest frequency. The virtual sources of the DFW are generated along the propagation path of the primary wave to form an end-fire array. Therefore, the DFW is highly directional even though its frequency is low [24].

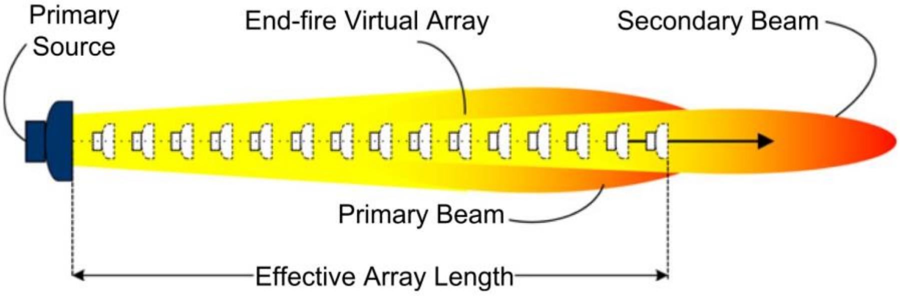

Figure 2-1 Demonstration of the generation of audible sound beam by using the PAA [14].

The PAA has been used in both underwater and airborne applications. The application of PAA in air is called parametric array loudspeaker (PAL), where the primary sound and DFW correspond to ultrasonic and audio waves, respectively [25,26]. The PAL has attracted much attention because of its high directivity in the low frequency range, small size, and very small sidelobes compared to the traditional loudspeakers [14]. Due to these advantages, PALs have been widely used in applications including ANC systems [9,15-17], personal communications [27], museum exhibitions and service and multimedia booths [28], measurements of the acoustic parameters of materials [29], mobile robotic navigation [30], stand-off concealed weapons detection [31], and so on. Thus, there have been many commercial PALs available in the market, such as Holosonics Audio Spotlight [32], HyperSound HSS300 [33], Acouspade [34], and SoundLazer [35]. Other techniques based on the PAL, such as the length-limited PAL [30,36] and remote playing PAL [37,38], also receive some attention.

2.1.1 Prediction Model

The fast and accurate prediction of audio sounds generated by a PAL is important. The fundamental model is a baffled circular PAL installed on an infinitely large reflecting surface as shown in Fig. 2-2 [18]. When a PAL radiates two intensive ultrasonic waves at different frequencies, a secondary wave containing the DFW (the audio sound in air) is generated due to the nonlinearity [23]. The nonlinear interactions of primary waves are rather complex, and some approximations and simplifications have to be made in the mathematical modelling [39].

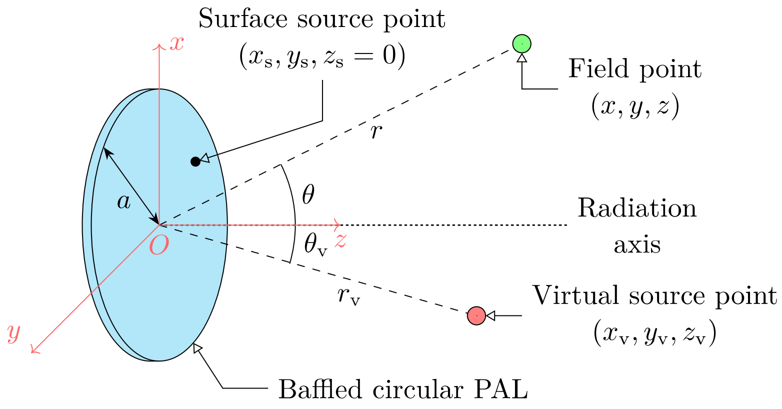

Figure 2-2 Sketch of a baffled circular PAL.

The simplest model assumes that the ultrasonic waves are highly collimated and fully attenuated in the nearfield and the audio sound is generated by a line array of virtual audio sources with the source strength exponentially decreased along the radiation axis of the PAL [23]. The most widely used model is based on the Khokhlov-Zabolotskaya-Kuznetsov (KZK) equation which considers the diffraction, absorption and nonlinearity of both the primary and secondary waves under the parabolic approximation [40]. Many methods have been proposed to solve the KZK equation analytically and numerically in frequency domain [41-43] or time domain [44,45]. However, the results are usually only valid within the paraxial region about 20° from the transducer axis [40].

The sound pressure at wide angles from the radiation axis of the PAL can be predicted based on the Westervelt equation [18,39], and it is discussed in this research. Besides, the quasilinear approximation, which is valid for weak nonlinearity, is assumed because the ultrasound level generated by a PAL is limited for safety concerns [14,46,47]. In this model, the ultrasounds are calculated first with the Rayleigh integral, i.e., a two-fold integral over the area of the transducer surface. Then, an infinitely large volume source is constructed with its source density function being proportional to the product of the sound pressure of ultrasounds. Finally, the audio sound is calculated by integrating the sound pressure generated by the volume source over the whole space. This solution is a five-fold integral and hard to compute, so it was rarely used by researchers. To simplify the calculation, the Gaussian beam expansion (GBE) method is usually used to transform the two-fold integral for the ultrasounds into a one-fold summation [48].

The GBE method approximates the vibration velocity profile of the transducer surface as N Gaussian ones to simplify the ultrasound expression thanks to the simplicity of Gaussian beams under the paraxial (Fresnel) approximation [49]. It has been found that many velocity profiles can be approximated by Gaussian beams using the optimization theory [48,50-55]. For the circular piston (uniform) source considered in this research, the GBE coefficients have been calculated for N = 10, 15, 25, and 40, where larger N provides more accurate results [48,49,56,57]. Although the GBE method consumes less calculation time than the direct integration approach, it is not an exact solution of the Westervelt equation under the quasilinear approximation. Furthermore, Gibbs oscillations occur for a uniform piston source no matter how many Gaussian beams are used [48,49], and the calculation of the off-axis audio sound is still time consuming due to the triple-integral over the whole space. Therefore, it is important to find a way to simplify the five-fold integral without additional approximations.

The most accurate existing theoretical models of PALs assume that a PAL is placed on an infinitely large baffle, which means that no audio sounds propagate to the back side of the PAL. However, one can hear audible audio sounds in the back side of a PAL in practice because the audio sounds can diffract to the back side especially at low frequencies [58]. Unfortunately, there is no analytical model for non-baffled PALs at present. The sound scattered by a finite size disk can be calculated analytically [59], so the disk-shaped PAL can be considered in this research.

2.1.2 Physical Properties

Reflection from a Surface

Existing analytical models of the PAL consider the sound radiation in free space, but do not pay much attention to its reflection, which is important in some applications [60]. For example, PALs have been used to measure the sound absorption coefficients of materials in air [29,61,62] and the reflection and transmission coefficients of elastomeric materials underwater [63,64], and to actively control the binaural noise at human ears [15], where the reflection exists on the material surface or human skin and hair.

When there is a reflecting surface near a PAL, both primary and secondary sound waves are reflected by the surface. The reflection by a pressure-release surface has been studied for underwater applications [65]. This model assumed that the primary fields were plane waves within the Rayleigh distance and spherical waves afterwards, and the analysis was based on the weak shock wave theory. It was found that the DFW generated by the incident primary waves was anti-phase with itself after the pressure-release reflection, while the DFW generated by the reflected primary waves was in-phase with the incident DFW. Therefore, the DFW suffered from a phase cancellation effect and this phenomenon has been observed in experiments [65]. The studies have been extended to the finite size planar targets with the weak nonlinearity by using a more accurate model [66].

The reflection by the water-air (pressure-release) interface with a small grazing angle has been modeled to investigate its effects on acoustic communication in shallow-water channels [67]. Two theoretical models have been proposed: a simplified Westervelt model where the primary waves are highly attenuated within the collimated zone, and a spherical spreading model where the interaction of primary waves is significant in the far field spherically spreading beam. Experiments were conducted at 5.4° and 7.7° grazing angles and only the spherical spreading model was shown to agree well with the experiments.

The experiments were conducted underwater with a pressure-release surface in all the studies aforementioned, and little research can be found regarding the reflection sound of PAL in air. When a PAL radiates sound in air in the presence of a reflecting surface, additional audio sound components are generated by the reflected ultrasound waves. The two models proposed in Ref. [67] are only valid in the far field while the model in Ref. [66] is valid in the near field but limited to the paraxial region. The non-paraxial model in Refs. [18] and [68] is more accurate at wide-angle field but has not considered reflections. In this research, the model in Ref. [18] will be extended to investigate the reflection of audio sound generated by a PAL.

Transmission through a Partition

It was found in experiments that the directivity of audio sounds generated by a PAL deteriorates significantly after introducing a thin and homogeneous partition; however, existing analytical models of PALs pay little attention to its transmission through a partition. The transmission of an audio plane wave through a thin partition is well known and the mass law is widely used to predict the insertion loss (IL) [69]; however, things are different for audio sounds generated by PALs because of the nonlinear interactions of ultrasounds are affected by the partition.

Understanding the IL of the partition for audio sounds generated by a PAL is important in applications. For example, with the capability of producing quasi-plane waves, PALs have been used to measure the acoustic parameters of materials in situ by measuring the sound pressure on the transmission side of the specimen [29]. The sharp directivity of PALs is attractive to mobile phone designers [27,70-72]. However, the size of the effective radiation surface should be as large as possible to generate considerable sound levels. A natural way is to install a PAL under the phone screen, so the effects of the thin screen on the generated audio sound need to be known. In research, one may need a circular PAL in experiments for verifying the analytical model, but there are only square/rectangular commercial PALs. It is questionable whether a circular PAL can be constructed by covering a square one with a thin panel with a hole.

The thin partition considered in this research implies that the thickness of the partition is small compared with the audio wavelength and the effective absorption length of the PAL. The effects of a thin partition on spherical waves radiated by a point monopole has been studied where the transmission loss and the IL are derived analytically using the plane wave expansion (PWE) method [73]. The transmission of a diffuse incident sound through a partition has also been well studied [74]. However, there is little research reported on the transmission of audio sounds generated by a PAL through a thin partition.

Scattering by a Sphere

In some applications where humans are exposed to the sound, the sound generated by a PAL will be scattered by human heads [27]. The human head can be approximately modeled as a rigid sphere and its effects on audio sound generated by traditional loudspeakers have been well studied [75]. The effect of a sphere on the audio sound generated by a PAL is different because it is originated from nonlinear interactions of ultrasonic waves.

There has been some work reported on sphere scattering of sound generated by a PAA [76,77]. Based on the Westervelt equation and quasilinear approximations, an analytic expression for the sound pressure of the DFW has been obtained when plane primary waves were interacted with a rigid sphere [76]. However, the expression in Ref. [76] is inaccurate because the scattered waves do not follow the plane wave assumption and the higher modes of spherical harmonics are neglected. A more accurate theoretical model was proposed later in Ref. [77] where the Westervelt equation is modified considering the Lagrangian density of waves (see Chap. 3 in Ref. [40] for more details). Both work shows that the total sound pressure of the DFW are contributed by the nonlinear interactions of incident primary waves (incident-with-incident), scattered primary waves (scattered-with-scattered), and incident and scattered primary waves (incident-with-scattered) among which the last one is generally negligible. However, both theories are limited to the plane incident waves and solutions are only valid in the far field.

2.2 Applications of PALs in Active Noise Control (ANC)

It has been demonstrated that directional sources can be used as secondary sources in multiple channel ANC systems to improve the performance, and much work has reported their applications in ANC. For example, tripole secondary sources with a cardioid radiation pattern have been used to reduce the primary source radiation [1], the directional sources consisting of two closely located loudspeakers with pre-adjusted phase difference have been used to increase the performance of an ANC barrier [12], and the directional sources consisting of a central circular core enclosed within an annulus have been used to reduce the noise generated by finite length coherent line sources [13]. The reason for the improvement is that these directional secondary sources radiate only in the direction of the target region and have less effects on the other areas.

The PAL has a sharper directivity than traditional loudspeakers. The advantage of using PALs in ANC has been shown in a single-channel system where the 1.5 kHz sound wave at the target point is reduced without affecting sound fields in other areas [9]. A two-channel ANC system using PALs have been examined in the application of reducing the binaural factory noise from 500 Hz to 2.5 kHz at human ears [15].

2.2.1 Cancelling a Broadband Noise

An ANC system can be designed to cancel the unwanted noise at a person's ears. Recent studies have investigated the error sensing strategies, where various remote error sensing techniques have been used to estimate the sound pressures at the person's ears accurately [6,78]. However, the secondary sources have received little attention to date. The feasibility of using PALs to reduce the noise with a broader bandwidth remains to be investigated.

In a recent study, a remote acoustic sensing apparatus has been proposed, which placed a custom-made membrane pick-up at the point of interest, and the membrane vibration measured by a laser Doppler vibrometer (LDV) was used to determine the acoustic information at the point from a remote location [79]. The membrane pick-up was placed in the person's ear and the estimated signal from the LDV was used as the error signal in the ANC system. It has been demonstrated the upper limit frequency of effective control can be significantly improved to 6 kHz [80], which is much higher than 1 kHz achieved by the traditional sensing techniques [6,81]. This research will investigate the feasibility of applying this technique to broaden the effective frequency range of ANC with a PAL as the secondary source.

2.2.2 Creating a Large Quiet Zone

Generating a quiet zone in a noisy environment by using ANC systems has been a research focus for several decades [82,83]. Much progress has been made in recent years on reducing the number of microphones [84] and loudspeakers [85], and enlarging the quiet zone size using traditional loudspeakers [86]. As a highly directional loudspeaker, PALs can be used in ANC to create large quiet zones, but the feasibility remains to be investigated.

It is easy to use one secondary source to mitigate the noise at a single location [87], and the quiet zone in a diffuse sound field is found to be centered at the location with a size of about one tenth of the wavelength [88]. Placing the secondary source close to the target point can mitigate the total energy increase in other areas [10,11]. For ANC headrest systems where the noise at two ears needs to be reduced, one loudspeaker and one microphone can be installed near each ear [6]. Because the quiet zone size is small at middle and high frequencies and it is inconvenient to place a sensor at the ear, virtual sensing algorithms such as the virtual microphone arrangement [89] and remote microphone technique [81] have been proposed to estimate the pressures near the ears remotely. Additional head tracking systems can be used if the human head moves [6].

A larger quiet zone can be created by using multiple secondary sources surrounding the target region if the spacing between the secondary sources is sufficiently small [90,91]. In free field, it was found the quiet zone size is proportional to the number of secondary sources [8], and the experiment results showed that more than 20 dB noise reduction (NR) can be obtained inside a sphere with a radius of 0.3 m from 100 Hz and 500 Hz by using 30 secondary sources on a spherical surface [92]. In an ordinary room, the experiment results with 16 secondary sources on a cylindrical surface demonstrate that a cylindrical quiet zone with 0.2 m height and 0.2 m radius can be obtained below 550 Hz [93]. However, the sound field outside the target region might increase due to the sound generated by the omni-directional secondary sources [8,9].

3 Methodology

The research methods are presented as three parts, each part corresponding a research question.

Part 1. This part corresponds to research question 1. To simplify the expression of audio sounds generated by a baffled circular PAL, we used the spherical harmonics expansion (SHE) of the Green function in free field. The proposed method is denoted as the SHE method and it can rigorously transform the five-fold integral into a three-fold summation with a one-fold integral using the orthogonality of the spherical harmonics. The calculation results and computation load of the SHE method were compared to the ones using the GBE method. For a non-baffled circular PAL, we used the disk scattering model [94] to calculate the audio sounds behind the PAL. The solution consists of the so-called spheroidal wave functions derived from the oblate spheroidal coordinate system [59,94]. Although the computation of spheroidal wave functions is complicated, some software or codes are available [95,96]. The validity of the proposed method was demonstrated by experiments at UTS.

Part 2. This part corresponds to research question 2. To study the physical properties of PALs, we adopted the quasilinear solution of the Westervelt equation which has been found to be accurate enough for the problems investigated in this research. The reflection, transmission, and scattering of ultrasounds and audio sounds can then be calculated. A custom-made 60-channel microphone array was designed to measure the spatial sound field and the results were compared to the predicted ones.

Part 3. This part corresponds to research question 3. To investigate the feasibility of cancelling a broadband noise at the listener ear, an ANC system using a PAL and an LDV sensing system has been developed. The experiments in a semi-anechoic room at UTS have been conducted, where the listener ear is the ear simulator of a head and torso simulator (HATS). To create a large quiet zone by multiple PALs, the theoretical model has been established based on the quasilinear solution of the Westervelt equation. The experiment plan has been designed and will be conducted in the future.

4 Progress to Date and Future Work

In the first three months after I enrolled at UTS (*March 2019 to June 2019*), I continued some previous work during my Master candidature at Nanjing University. The work includes the ANC experiments in the presence of reflecting surfaces, and the writing of manuscripts. I submitted two manuscripts to a top journal in Acoustics (JASA) on this work, and both of them have been published. A peer-reviewed conference paper was also published on this topic.

From *June 2019 to April 2020*, I started working on PALs. After understanding the fundamentals in this area, I started the research on the prediction models and physical properties of audio sounds generated by PALs. Some experiments were conducted in UTS acoustics labs to validate the simulation results. I have submitted 4 manuscripts to JASA based on the findings and three of them have been published and the other one is under review.

From *April 2020 to date*, I focused on the ANC systems using PALs. The feasibility of using multiple PALs to create a large quiet zone was investigated first. I have finished the establishment of the theoretical model and prepared a manuscript for JASA on this research. I also studied the ANC system using a PAL and an LDV sensing system to cancel the noise at the ear simulator of a HATS. The work has been submitted to as a peer-reviewed conference paper.

Besides, I have already completed Research Integrity Modules on UTS Online (https://online.uts.edu.au). I also finished the subjects TRP (Technology Research Preparation) and TRM (Technology Research Methods) in Autumn and Spring 2019, respectively.

Future work has been scheduled as follows:

- *July 2020 to August 2020*. Finish the establishment of the theoretical model of audio sounds generated by a PAL scattered by a rigid sphere. Prepare a manuscript and submit it to JASA.
- *August 2020 to December 2020.* Conduct experiments on creating large quiet zones using multiple PALs. Prepare a manuscript and submit it to JASA.
- *December 2020 to March 2021*. Investigate the feasibility of using PALs and LDV sensing systems to effectively control the broadband noise at person’s ears. Hopefully I can prepare a manuscript and submit it to JASA.
- *April 2021 to December 2021*. Other possible explorations and investigations on ANC systems using PALs, such as improving the noise reduction performance of the system.

5 Research Data Management Plan

In this research, all of the data are gathered and managed by me, which include:

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

I have already created a project on UTS Stash as suggested by GRS (Graduate Research School). The important data of this research will be uploaded, stored, and managed on both UTS Stash and Microsoft OneDrive. The data will also be stored on my personal computer to lower the risks of data loss. The data contain no health records, classified documents, and culturally and commercially sensitive information, so they can be shared to anyone who is interested in this research. All data are numbers obtained from simulations and experiments, so no special facilities and equipment are required to use these data.

6 Conclusions

Three major research questions have been proposed in this report to study the feasibility of using PALs in ANC systems. The first research topic is to investigate fast and accurate calculation methods for predicting audio sounds generated by a baffled or non-baffled PAL. The second topic is to study the reflection, transmission, and scattering of audio sounds generated by a PAL. With the above foundations and results, the final topic is ANC using PALs as secondary sources, which include cancelling a broadband (up to 6 kHz) noise at a target point and creating large quiet zones using multiple PALs. The existing literatures have been comprehensively reviewed and the methods used in this research were identified. Finally, the progress to date, future work, and research data management plan were presented.

References

[1] G. A. Mangiante, “Active sound absorption,” J. Acoust. Soc. Am. **61**(6), 1516-1523 (1977).

[2] X. Qiu, X. Li, Y. Ai, and C. H. Hansen, “A waveform synthesis algorithm for active control of transformer noise: implementation,” Appl. Acoust. **63**(5), 467-479 (2002).

[3] N. Han and X. Qiu, “A study of sound intensity control for active noise barriers,” Appl. Acoust. **68**(10), 1297-1306 (2007).

[4] J. Guo and J. Pan, “Increasing the insertion loss of noise barriers using an active-control system,” J. Acoust. Soc. Am. **104**(6), 3408-3416 (1998).

[5] X. Qiu, *An Introduction to Virtual Sound Barriers* (CRC Press, New York, 2019).

[6] S. J. Elliott, W. Jung, and J. Cheer, “Head tracking extends local active control of broadband sound to higher frequencies,” Sci. Rep. **8**(1), 1-7 (2018).

[7] L. Y. L. Ang, Y. K. Koh, and H. P. Lee, “The performance of active noise-canceling headphones in different noise environments,” Appl. Acoust. **122**, 16-22 (2017).

[8] J. Guo, J. Pan, and C. Bao, “Actively created quiet zones by multiple control sources in free space,” J. Acoust. Soc. Am. **101**(3), 1492-1501 (1997).

[9] N. Tanaka and M. Tanaka, “Active noise control using a steerable parametric array loudspeaker,” J. Acoust. Soc. Am. **127**(6), 3526-3537 (2010).

[10] P. Joseph, S. J. Elliott, and P. A. Nelson, “Near field zones of quiet,” J. Sound Vib. **172**(5), 605-627 (1994).

[11] A. David and S. J. Elliott, “Numerical studies of actively generated quiet zones,” Appl. Acoust. **41**(1), 63-79 (1994).

[12] W. Chen, W. Rao, H. Min, and X. Qiu, “An active noise barrier with unidirectional secondary sources,” Appl. Acoust. **72**(12), 969-974 (2011).

[13] Q. Hu and S. K. Tang, “Active cancellation of sound generated by finite length coherent line sources using piston-like secondary source arrays,” J. Acoust. Soc. Am. **145**(6), 3647-3655 (2019).

[14] W. S. Gan, J. Yang, and T. Kamakura, “A review of parametric acoustic array in air,” Appl. Acoust. **73**(12), 1211-1219 (2012).

[15] K. Tanaka, C. Shi, and Y. Kajikawa, “Binaural active noise control using parametric array loudspeakers,” Appl. Acoust. **116**, 170-176 (2017).

[16] K. Tanaka, C. Shi, and Y. Kajikawa, “Multi-channel active noise control using parametric array loudspeakers,” in *Signal and Information Processing Association Annual Summit and Conference (APSIPA), 2014 Asia-Pacific*, (2014), pp. 1-6.

[17] N. Tanaka and M. Tanaka, “Mathematically trivial control of sound using a parametric beam focusing source,” J. Acoust. Soc. Am. **129**(1), 165-172 (2011).

[18] M. Červenka and M. Bednařík, “Non-paraxial model for a parametric acoustic array,” J. Acoust. Soc. Am. **134**(2), 933-938 (2013).

[19] P. J. Westervelt, “Scattering of sound by sound,” J. Acoust. Soc. Am. **29**(2), 199-203 (1957).

[20] U. Ingard and D. C. Pridmore-Brown, “Scattering of sound by sound,” J. Acoust. Soc. Am. **28**(3), 367-369 (1956).

[21] P. J. Westervelt, “Scattering of sound by sound,” J. Acoust. Soc. Am. **29**(8), 934-935 (1957).

[22] J. L. S. Bellin and R. T. Beyer, “Scattering of sound by sound,” J. Acoust. Soc. Am. **32**(3), 339-341 (1960).

[23] P. J. Westervelt, “Parametric acoustic array,” J. Acoust. Soc. Am. **35**(4), 535-537 (1963).

[24] H. O. Berktay and J. A. Shooter, “Nearfield effects in end-fire line arrays,” J. Acoust. Soc. Am. **53**(2), 550-556 (1973).

[25] M. B. Bennett and D. T. Blackstock, “Parametric array in air,” J. Acoust. Soc. Am. **57**(3), 562-568 (1975).

[26] M. Yoneyama, J.-i. Fujimoto, Y. Kawamo, and S. Sasabe, “The audio spotlight: An application of nonlinear interaction of sound waves to a new type of loudspeaker design,” J. Acoust. Soc. Am. **73**(5), 1532-1536 (1983).

[27] Y. Nakashima, T. Ohya, and T. Yoshimura, “Prototype of parametric array loudspeaker on mobile phone and its acoustical characteristics,” Audio Engineering Society Convention 118, Barcelona, Spain, 1-6 (2005).

[28] K. J. Kortbek and K. Grønbæk, “Communicating art through interactive technology: new approaches for interaction design in art museums,” in *Proceedings of the 5th Nordic Conference on Human-Computer Interaction: Building Bridges*, (2008), pp. 229-238.

[29] B. Castagnède, A. Moussatov, D. Lafarge, and M. Saeid, “Low frequency in situ metrology of absorption and dispersion of sound absorbing porous materials based on high power ultrasonic non-linearly demodulated waves,” Appl. Acoust. **69**(7), 634-648 (2008).

[30] E. Skinner, M. Groves, and M. K. Hinders, “Demonstration of a length limited parametric array,” Appl. Acoust. **148**, 423-433 (2019).

[31] K. Rudd and M. Hinders, “Simulation of incident nonlinear sound beam and 3D scattering from complex targets,” Journal of Computational Acoustics **16**(03), 427-445 (2008).

[32] Holosonics, “Audio Spotlight 24i,” Available at https://www.holosonics.com/audio-spotlight-24i, Accessible on 2019-6-11.

[33] Turtle Beach Corporation, "HyperSound HSS300," Available at http://hypersound.com/pro/products/, Accessible on 2020-6-11.

[34] Ultrasonic Audio Technologies, "ACOUstic SPAce DElimiter - Directional Speaker," Available at https://ultrasonic-audio.com/products/acouspade-directional-speaker/, Accessible on 2020-6-11.

[35] Soundlazer, "Soundlazer introduction," Available at https://www.soundlazer.com/, Accessible on 2020-6-11.

[36] H. Nomura, C. M. Hedberg, and T. Kamakura, "Numerical simulation of parametric sound generation and its application to length-limited sound beam," Appl. Acoust. **73**(12), 1231-1238 (2012).

[37] P. Ji, J. Yang, and W.-S. Gan, "The investigation of localized sound generation using two ultrasound beams," IEEE transactions on ultrasonics, ferroelectrics, and frequency control **56**(6), 1282-1287 (2009).

[38] R. Iijima, S. Minami, Y. Zhou, T. Takehisa, T. Takahashi, Y. Oikawa, and T. Mori, "Audio hotspot attack: An attack on voice assistance systems using directional sound beams and its feasibility," IEEE Transactions on Emerging Topics in Computing, (2019).

[39] M. Červenka and M. Bednařík, "A versatile computational approach for the numerical modelling of parametric acoustic array," J. Acoust. Soc. Am. **146**(4), 2163-2169 (2019).

[40] M. F. Hamilton and D. T. Blackstock, *Nonlinear Acoustics* (Acoustical Society of America, New York, 2008).

[41] S. I. Aanonsen, T. Barkve, J. N. Tjøtta, and S. Tjøtta, "Distortion and harmonic generation in the nearfield of a finite amplitude sound beam," J. Acoust. Soc. Am. **75**(3), 749-768 (1984).

[42] T. Kamakura, N. Hamada, K. Aoki, and Y. Kumamoto, "Nonlinearly generated spectral components in the nearfield of a directive sound source," J. Acoust. Soc. Am. **85**(6), 2331-2337 (1989).

[43] T. Kamakura, M. Tani, Y. Kumamoto, and K. Ueda, "Harmonic generation in finite amplitude sound beams from a rectangular aperture source," J. Acoust. Soc. Am. **91**(6), 3144-3151 (1992).

[44] Y.-S. Lee, "Numerical solution of the KZK equation for pulsed finite amplitude sound beams in thermoviscous fluids," The University of Texas at Austin, (1993).

[45] M. A. Averkiou, Y. S. Lee, and M. F. Hamilton, "Self-demodulation of amplitude-and-frequency-modulated pulses in a thermoviscous fluid," J. Acoust. Soc. Am. **94**(5), 2876-2883 (1993).

[46] B. W. Lawton, *Damage to human hearing by airborne sound of very high frequency or ultrasonic frequency* (Health & Safety Executive, 2001).

[47] F. J. Pompei, “Sound from ultrasound: The parametric array as an audible sound source,” Massachusetts Institute of Technology, Cambridge, MA, USA (2002).

[48] J. J. Wen and M. A. Breazeale, “A diffraction beam field expressed as the superposition of Gaussian beams,” J. Acoust. Soc. Am. **83**(5), 1752-1756 (1988).

[49] M. Červenka and M. Bednařík, “On the structure of multi-Gaussian beam expansion coefficients,” Acta Acust. united Ac. **101**(1), 15-23 (2015).

[50] D. Ding, “A simplified algorithm for the second-order sound fields,” J. Acoust. Soc. Am. **108**(6), 2759-2764 (2000).

[51] D. Ding, “A simplified algorithm for second-order sound beams with arbitrary source distribution and geometry (L),” J. Acoust. Soc. Am. **115**(1), 35-37 (2004).

[52] D. Ding, Y. Shui, J. Lin, and D. Zhang, “A simple calculation approach for the second harmonic sound field generated by an arbitrary axial - symmetric source,” J. Acoust. Soc. Am. **100**(2), 727-733 (1996).

[53] D. Ding, X. Tong, and P. He, “Supplementary notes on the Gaussian beam expansion,” J. Acoust. Soc. Am. **118**(2), 608-611 (2005).

[54] D. Ding and Y. Zhang, “Notes on the Gaussian beam expansion,” J. Acoust. Soc. Am. **116**(3), 1401-1405 (2004).

[55] D. Ding, Y. Zhang, and J. Liu, “Some extensions of the Gaussian beam expansion: Radiation fields of the rectangular and the elliptical transducer,” J. Acoust. Soc. Am. **113**(6), 3043-3048 (2003).

[56] D. Huang and M. A. Breazeale, “A Gaussian finite-element method for description of sound diffraction,” J. Acoust. Soc. Am. **106**(4), 1771-1781 (1999).

[57] H.-J. Kim, L. W. Schmerr Jr, and A. Sedov, “Generation of the basis sets for multi-Gaussian ultrasonic beam models—An overview,” J. Acoust. Soc. Am. **119**(4), 1971-1978 (2006).

[58] A. Sugahara, H. Lee, S. Sakamoto, and S. Takeoka, “A study on the measurements of the absorption coefficient by using a parametric loudspeaker,” INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Hongkong, China, **255**(4), 3743-3751 (2017).

[59] C. Flammer, *Spheroidal Wave Functions* (Dover Publications, Mineola, New York, 2014).

[60] Holosonic Research Labs, “User’s manual of Audio Spotlight,” (2016),

[61] A. Sugahara, H. Lee, S. Sakamoto, and S. Takeoka, “Measurements of acoustic impedance of porous materials using a parametric loudspeaker with phononic crystals and phase-cancellation method,” Appl. Acoust. **152**, 54-62 (2019).

[62] A. Romanova, K. V. Horoshenkov, and A. Hurrell, “An application of a parametric transducer to measure acoustic absorption of a living green wall,” Appl. Acoust. **145**, 89-97 (2019).

[63] V. F. Humphrey, "The measurement of acoustic properties of limited size panels by use of a parametric source," J. Sound Vib. **98**(1), 67-81 (1985).

[64] V. F. Humphrey, S. P. Robinson, J. D. Smith, M. J. Martin, G. A. Beamiss, G. Hayman, and N. L. Carroll, "Acoustic characterization of panel materials under simulated ocean conditions using a parametric array source," J. Acoust. Soc. Am. **124**(2), 803-814 (2008).

[65] T. Muir, L. Mellenbruch, and J. Lockwood), "Reflection of finite‐amplitude waves in a parametric array," J. Acoust. Soc. Am. **62**(2), 271-276 (1977).

[66] G. S. Garrett, J. N. Tjøtta, R. L. Rolleigh, and S. Tjøtta, "Reflection of parametric radiation from a finite planar target," J. Acoust. Soc. Am. **75**(5), 1462-1472 (1984).

[67] L. S. Wang, B. V. Smith, and R. Coates, "The secondary field of a parametric source following interaction with sea surface," J. Acoust. Soc. Am. **105**(6), 3108-3114 (1999).

[68] 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), In production (2020).

[69] A. D. Pierce, *Acoustics: An Introduction to Its Physical Principles and Applications* (Springer Nature, Cham, Switzerland, 2019).

[70] H. Ahn, K. Been, I.-D. Kim, C. H. Lee, and W. Moon, "A critical step to using a parametric array loudspeaker in mobile devices," Sensors **19**(20), 4449 (2019).

[71] X. Li, L. Xu, and L. Xu, "Micro audio directional system for portable multimedia devices," International Journal of Mechatronics and Automation **2**(3), 178-184 (2012).

[72] X. Li, L. Xu, and L. Xu, "Audio near-distance directional loudspeaker technology for portable multimedia devices," in *2011 IEEE International Conference on Mechatronics and Automation*, (2011), pp. 727-731.

[73] X. Shi, J. Tao, and X. Qiu, "Sound insulation of an infinite partition subject to a point source incidence [in Chinese]," Acta Acustica **33**(3), (2008).

[74] A. Pellicier and N. Trompette, "A review of analytical methods, based on the wave approach, to compute partitions transmission loss," Appl. Acoust. **68**(10), 1192-1212 (2007).

[75] Z. Lin, J. Lu, C. Shen, X. Qiu, and B. Xu, "Active control of radiation from a piston set in a rigid sphere," J. Acoust. Soc. Am. **115**(6), 2954-2963 (2004).

[76] I. B. Abbasov and N. P. Zagrai, "Sphere scattering of nonlinearly interacting acoustic waves," Fluid dynamics **30**(2), 158-165 (1995).

[77] G. T. Silva and A. Bandeira, "Difference-frequency generation in nonlinear scattering of acoustic waves by a rigid sphere," Ultrasonics **53**(2), 470-478 (2013).

[78] D. Moreau, B. Cazzolato, A. Zander, and C. Petersen, "A review of virtual sensing algorithms for active noise control," Algorithms **1**(2), 69-99 (2008).

[79] T. Xiao, X. Qiu, S. Zhao, and B. Halkon, "A remote acoustic sensing apparatus based on a laser Doppler vibrometer," Sensors (under review), (2020).

[80] T. Xiao, X. Qiu, and B. Halkon, "Ultra-broadband active noise cancellation at the ears via optical microphones," arXiv:1909.03377v2, (2020).

[81] W. Jung, S. J. Elliott, and J. Cheer, "Estimation of the pressure at a listener's ears in an active headrest system using the remote microphone technique," J. Acoust. Soc. Am. **143**(5), 2858-2869 (2018).

[82] S. J. Elliott, P. A. Nelson, I. M. Stothers, and C. C. Boucher, "In-flight experiments on the active control of propeller-induced cabin noise," J. Sound Vib. **140**(2), 219-238 (1990).

[83] P. N. Samarasinghe, W. Zhang, and T. D. Abhayapala, "Recent advances in active noise control inside automobile cabins: Toward quieter cars," IEEE Signal Processing Magazine **33**(6), 61-73 (2016).

[84] Y. Maeno, Y. Mitsufuji, and T. D. Abhayapala, "Mode domain spatial active noise control using sparse signal representation," in *2018 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, (2018), pp. 211-215.

[85] J. Zhang, T. D. Abhayapala, P. N. Samarasinghe, W. Zhang, and S. Jiang, "Multichannel active noise control for spatially sparse noise fields," J. Acoust. Soc. Am. **140**(6), EL510-EL516 (2016).

[86] D. Shi, B. Lam, S. Wen, and W.-S. Gan, "Multichannel active noise control with spatial derivative constraints to enlarge the quiet zone," in *ICASSP 2020 - 2020 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, (2020).

[87] J. Guo and J. Pan, "Effects of reflective ground on the actively created quiet zones," J. Acoust. Soc. Am. **103**(2), 944-952 (1998).

[88] S. J. Elliott, P. Joseph, A. J. Bullmore, and P. A. Nelson, "Active cancellation at a point in a pure tone diffuse sound field," J. Sound Vib. **120**(1), 183-189 (1988).

[89] J. Garcia-Bonito, S. J. Elliott, and C. C. Boucher, "Generation of zones of quiet using a virtual microphone arrangement," J. Acoust. Soc. Am. **101**(6), 3498-3516 (1997).

[90] S. J. Elliott, J. Cheer, L. Bhan, C. Shi, and W.-S. Gan, "A wavenumber approach to analysing the active control of plane waves with arrays of secondary sources," J. Sound Vib. **419**, 405-419 (2018).

[91] J. Zhang, T. D. Abhayapala, W. Zhang, and P. N. Samarasinghe, "Active noise control over space: A subspace method for performance analysis," Applied Sciences **9**(6), 1250 (2019).

[92] N. Epain and E. Friot, "Active control of sound inside a sphere via control of the acoustic pressure at the boundary surface," J. Sound Vib. **299**(3), 587-604 (2007).

[93] H. Zou, X. Qiu, J. Lu, and F. Niu, “A preliminary experimental study on virtual sound barrier system,” J. Sound Vib. **307**(1-2), 379-385 (2007).

[94] J. Zhong, J. Tao, F. Niu, and X. Qiu, “Effects of a finite size reflecting disk in sound power measurements,” Appl. Acoust. **140**(1), 24-29 (2018).

[95] S. Zhang and J. Jin, *Computation of Special Functions* (John Wiley & Sons, New York, 1996).

[96] A. L. Van Buren, “Accurate calculation of oblate spheroidal wave functions,” arXiv:1708.07929, (2017).