UNIVERSITY OF TECHNOLOGY SYDNEY

# Laser Doppler Vibrometry Based Remote Sensing for Active Noise Control

by Tong Xiao

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of

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November 2022

# Author's declaration

I, *Tong Xiao* declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the *Centre for Audio, Acoustics and Vibration* (*CAAV*), *School of Mechanical and Mechatronic Engineering*, *Faculty of Engineering and Information and Technology* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

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DATE: November 7, 2022

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# Abstract

Demands for active noise control/cancellation (ANC) to provide a quiet environment have grown significantly over the past few decades. Notably, many ANC headphones and earphones have emerged and gained much success in the market due to their excellent performance and robustness. There are also other ANC applications, such as ANC headrests and ANC windows. However, developments for such applications have been slow due to their relative complexity and cost of implementation. Particularly, the physical presence and the number of required sensors, typically condenser microphones, severely limit the performance of many ANC applications.

Laser Doppler vibrometry, which works on the principle of optical interferometry, has been widely used in to measure vibrations in many vibro-acoustic applications. Yet, the developed instrument, laser Doppler vibrometer (LDV), has little been studied in the published literature in the context of sound/noise measurement and control. The main advantage of such a technique is that it is often considered to be non-contact and non-invasive. For ANC headrests and windows, which prohibit the use of passive acoustic absorption materials and limit the installation of physical microphones for noise control, an LDV can be favourable by providing acoustic information remotely and inherently non-invasively.

This thesis, therefore, investigates and develops LDV-based remote acoustic sensing techniques for ANC applications, particularly ANC headrests and windows. The first part of the thesis studies how to use an LDV together with customised retro-reflective membranes to acquire acoustic information at discrete locations from a remotely positioned LDV. Then, such a configuration is used for remote error sensing in an ANC headrest scenario. The experimental results show significant improvements over the state-of-the-art systems. The reference signals are also investigated in ANC systems. Results show that a non-minimum-phase secondary path may require reference microphones to be installed at a considerable distance away from the secondary sources to have an adequate control performance, especially for the low frequencies. This is impractical in many applications. Remote acoustic sensing can also be applied for the reference signal. Results show that the proposed remote reference sensing can achieve a comparable result without the need for physical connections like those required for conventional microphones.

The second part of the thesis is concerned with measuring and controlling noise over a large area, e.g., at a window or a similar opening. Instead of measuring at a series of discrete points as with a microphone array, refracto-vibrometry can serve as an alternative method to measure the sound field, quasi-continuously, over an area and then utilise the measurements for control. The major advantage of this technique is that it enables sound pressure measurement at all points of interest without disturbing the sound field and with high spatial resolution. Such a technique is preferable for noise control at windows and openings where ventilation and access are prioritised over the introduction of physical sensors. The sound field at an enclosure opening is measured in the experiment and used for the error signals for ANC. Results show that using refracto-vibrometry to measure a sound field can give a much finer resolution than using a microphone array and an ANC system as a consequence can have the optimal performance for a given secondary source arrangement.

# Acknowledgments

I would like to express my deepest gratitude to my supervisors, Dr. Ben Halkon, A/Prof. Sebastian Oberst and Dr. Guoqiang Zhang, for all the guidance and support during my research. Without them, this thesis would not be possible. I take this opportunity to sincerely acknowledge their guidance, help and encouragement.

Special thanks to my previous supervisor, Prof. Xiaojun Qiu, who gave me the chance and guided me throughout my candidature. The discussions with him have deepened my understanding of acoustics and provided insights into my research.

I would like to thank everyone at the Centre of Audio, Acoustics and Vibration. In particular, my colleagues and co-authors, Dr. Sipei Zhao, Dr. Shuping Wang and Mr. Jiaxin Zhong. Discussions with them have broadened my knowledge of acoustics. It is also my pleasure to acknowledge the help from Dr. Qiaoxi Zhu, who gave me technical support and encouraged me through my dark days. I am also grateful to Dr. Somanath Pradhan for going through many difficulties at the beginning of our candidatures.

I would like to thank Dr. Buye Xu and Dr. Chuming Zhao during my internship at Facebook (Meta). They have given me many insights and supports throughout the journey.

I would like to acknowledge the support by the Research Training Program scholarship from the Australian Government.

Finally, I would like to thank my parents and my families for their selfless support throughout many different stages of my life.

# List of Publications

Much of this work has either been published or submitted for publications as journal articles and conference proceedings. The following is a list of the manuscripts that formed the basis for the thesis.

**Peer-reviewed International Journals:**

1. **Xiao, T.**, Zhao, S., Qiu, X. and Halkon, B.: 2021, Using a retro-reflective membrane and laser doppler vibrometer for real-time remote acoustic sensing and control, *Sensors* **21**(11).

2. **Xiao, T.**, Qiu, X. and Halkon, B.: 2020, Ultra-broadband local active noise control with remote acoustic sensing, *Scientific reports* **10**(1), 1-12.

**Peer-reviewed Conference Proceedings:**

3. **Xiao, T.**, Halkon, B., Oberst, S., Wang, S. and Qiu, X.: 2022, Sound field measurement at an enclosure opening using refracto-vibrometry, *Proceedings of the 28th International Congress on Sound and Vibration, ICSV*, 2022.

4. **Xiao, T.**, Qiu, X. and Halkon, B.: 2021, Using a laser doppler vibrometer to estimate sound pressure in air, *in* S. Oberst, B. Halkon, J. Ji and T. Brown (eds), *Vibration Engineering for a Sustainable Future*, Springer International Publishing, Cham, pp. 371-377.

5. Zhong, J., **Xiao, T.**, Halkon, B., Kirby, R. and Qiu, X.: 2020, An experimental study on the active noise control using a parametric array loudspeaker, *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, Vol. 261, Institute of Noise Control Engineering, pp. 662-668.

6. **Xiao, T.** and Qiu, X.: 2019, A comparison of using sound pressure and particle velocity as error signals for local active noise control, *Proceedings of the 26th International Congress on Sound and Vibration, ICSV* 2019.

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