

Thesis Title

Active control of noise through open windows

Thesis Abstract

Active noise control (ANC) is a noise mitigation technique that preserves natural ventilation in dwellings when applied on domestic windows. ANC systems for open windows mitigates noise at the receivers' end, which augment solutions that are less effective for urban noise in high-rise cities. The target of the ANC system is to reduce noise that propagates through an open aperture, such as a window, into the interior of a room. This thesis presents a systematic approach to the open window ANC system design to address the complex practical implementation challenges.

Firstly, the fundamental limits of the ANC system in controlling noise through an open aperture are determined by numerical simulations. Investigation into the performance of different physical arrangements reveal that the upper limit frequency limit of control is determined by the separation distance between the sources of the planar array, distributed evenly in the aperture. As a result, the minimum number of sources required to achieve good control is generalized for an arbitrary aperture size and the dominant noise incidence angles.

Next, an experimental setup with a full-sized domestic window is designed and installed on a room model. A total of 24 control sources of the multiple-input multiple-output (MIMO) ANC system are implemented on a fully opened sliding window. To determine the upper limit of control system performance, different active control algorithms are investigated using measured transfer functions from the 24 channel ANC system. The performance of the real-time 24-channel ANC system in attenuating road traffic noise is determined by the energy-averaged sound pressure levels from 27 microphones in the room interior.

Lastly, strategies for practical implementation are discussed. Namely, omission of error microphones from the final design, dealing with residual high frequency noise, and high computational complexity of coupled MIMO ANC systems.

List of Publications

Journals (To be included in Thesis)

- Elsevier Applied Acoustics (5Y IF:1.98)
 - Authors: **B Lam**, SJ Elliott, J Cheer, W-S Gan
 - Title: Physical limits on the performance of active noise control through open windows
 - Submitted in: 30 May 2017 (Under review)
 - Revised and re-submitted: 1 Dec 2017
- Elsevier Building & Environment (5Y IF: 4.464)
 - Authors: **B Lam**, C Shi, D Shi, W-S Gan
 - Title: Active control of sound through full-sized open windows
 - To be submitted 2nd Week Dec 2017
- Elsevier Journal of Sound and Vibration (5Y IF:2.955)
 - Authors: SJ Elliott, J Cheer, **B Lam**, W-S Gan
 - Title: A wavenumber approach to the active control of plane waves with arrays of secondary sources
 - Submitted in: 9 Jun 2017 (Under review)
 - Revised and re-submitted: 22 Nov 2017

Magazine Articles (To be included in Thesis)

- **B. Lam**, W.-S. Gan, Active Acoustic Windows: Towards a Quieter Home, IEEE Potentials. 35 (2016) 11–18. doi:10.1109/MPOT.2014.2310776.

Conference Papers (To be included in Thesis)

- **B. Lam**, S.J. Elliott, J. Cheer, W. Gan, The Physical Limits of Active Noise Control of Open Windows, in: 12th West. Pacific Acoust. Conf., Singapore, 2015: pp. 184–189.
- **B. Lam**, J. He, T. Murao, C. Shi, W.S. Gan, S.J. Elliott, Feasibility of the Full-Rank Fixed-filter Approach in the Active Control of Noise Through Open Windows, in: INTER-NOISE NOISE-CON Congr. Conf. Proc., Hamburg, Germany, 2016: pp. 3548–3555.
- **B. Lam**, C. Shi, W.-S. Gan, Active noise control systems for open windows: Current updates and future perspectives, in: 24th Int. Congr. Sound Vib. ICSV 2017, 2017.
- S. Fasciani, J. He, **B. Lam**, T. Murao, W.S. Gan, Comparative study of cone-shaped versus flat-panel speakers for active noise control of multi-tonal signals in open windows, in: INTER-NOISE NOISE-CON Congr. Conf. Proc., San Francisco, CA, USA, 2015: pp. 1109–1120.
- J. He, **B. Lam**, T. Murao, R. Ranjan, W.S. Gan, Symmetric design of multiple-channel active noise control systems for open windows, in: INTER-NOISE NOISE-CON Congr. Conf. Proc., 2016.
- T. Murao, M. Nishimura, J. He, **B. Lam**, R. Ranjan, C. Shi, W.-S. Gan, Feasibility study on decentralized control system for active acoustic shielding, in: INTER-NOISE NOISE-CON Congr. Conf. Proc., 2016.

- R. Ranjan, J. He, T. Murao, **B. Lam**, W.S. Gan, Selective Active Noise Control System for Open Windows using Sound Classification, in: INTER-NOISE NOISE-CON Congr. Conf. Proc., 2016: pp. 482–492.
- C. Shi, T. Murao, D. Shi, **B. Lam**, W.-S. Gan, Open loop active control of noise through open windows, J. Acoust. Soc. Am. 140 (2016) 3313–3313. doi:10.1121/1.4970553.
- J.-Y. Hong, **B. Lam**, Z.-T. Ong, R. Gupta, W.-S. Gan, S.H. Chong, J. Feng, Suitability of natural sounds to enhance soundscape quality in urban residential areas, in: 24th Int. Congr. Sound Vib. ICSV 2017, 2017.
- S. Elliott, J. Cheer, **B. Lam**, C. Shi, W.-S.W. Gan, Controlling Incident Sound Fields With Source Arrays in Free Space and Through Apertures, in: Proc. 24th Int. Congr. Sound Vib., London, UK, 2017: pp. 1–7.
- J. Hong, **B. Lam**, Z. Ong, R. Gupta, W. Gan, S.H. Chong, J. Feng, Appropriate levels of natural sounds to enhance soundscapes in urban areas, in: INTER-NOISE NOISE-CON Congr. Conf. Proc., Hong Kong SAR, China, 2017: pp. 49–53.

Journal Papers (Not Included in Thesis)

- J. Hong, J. He, **B. Lam**, R. Gupta, W.-S. Gan, Spatial Audio for Soundscape Design: Recording and Reproduction, Appl. Sci. 7 (2017) 627. doi:10.3390/app7060627.

Conferences Papers (Not Included in Thesis)

- R. Gupta, **B. Lam**, J.-Y. Hong, Z.-T. Ong, W.-S. Gan, S.H. Chong, J. Feng, 3D audio AR/VR capture and reproduction setup for auralization of soundscapes, in: 24th Int. Congr. Sound Vib. ICSV 2017, 2017.
- K. Ooi, J. Hong, **B. Lam**, Z.T. Ong, W. Gan, Validation of binaural recordings with head tracking for use in soundscape evaluation, in: INTER-NOISE NOISE-CON Congr. Conf. Proc., Hong Kong SAR, China, 2017: pp. 63–71.
- Z.T. Ong, J.Y. Hong, **B. Lam**, K. Ooi, R. Gupta, Effect of masker orientation on masking efficacy in soundscape applications, in: INTER-NOISE NOISE-CON Congr. Conf. Proc., Hong Kong SAR, China, 2017: pp. 55–61.