ACTIVE NOISE CONTROL SYSTEMS FOR OPEN WINDOWS: CURRENT UPDATES AND FUTURE PERSPECTIVES

Bhan Lam, Chuang Shi, and Woon-Seng Gan

Nanyang Technological University, School of Electrical & Electronic Engineering, Digital Signal Processing Lab, Singapore.
email: blam002@e.ntu.edu.sg

Active noise control (ANC) is currently being explored as a potential solution for controlling noise that propagates through an open window. The main motivation of this technique is to provide acoustic insulation via active means, while preserving the natural ventilation properties of the open window. The feasibility of such an open-window ANC system is first discussed using numerical methods. To validate the numerical studies, we developed a full-scale model of a small bedroom with a two-panel sliding window, which is identical to those installed in public housing apartments in Singapore. The ANC system is installed at the opening of the sliding window. From the experimental results, the limitations of the current system and potential solutions are discussed. Lastly, the practical implementation challenges and suggested solutions of the proposed open-window ANC system are also highlighted.

Keywords: active noise control, finite element methods, open window noise control

1. Introduction

There is a growing interest in developing active noise control (ANC) systems for domestic windows. Motivation behind such systems stem from rising concerns due to noise pollution in densely populated urban areas. Moreover, trends toward urban sustainability stresses the importance of natural ventilation via open windows. Not only does traditional noise insulation methods through multilayer glazing not provide enough natural ventilation, they are also impractical for tropical climates.

Due to geographical and cultural differences, active noise control systems have been developed on various window types, which can be classified into: (1) partially-opened windows, (2) ventilation windows, and (3) fully open windows.

Firstly, partially-opened windows are commonly found around temperate zones and usually have a maximum gap and are unable to open fully. Noticeably, Pàmies et. al. has demonstrated an ANC system built onto a side-hung window that targets aircraft fly-by noise [1]. Also, two ANC systems have been demonstrated on European single-hung windows, but are based on different control strategies (local [2] and global [3]) to control traffic noise. For similar reasons, Carme et. al. has retrofitted a modern sliding window (maximum of 13 cm gap) with an ANC system [4].

Secondly, ventilation windows are passive fixtures that are usually not adjustable and exist in various forms. Implementation of active control systems on a louvre-type window was investigated by Qin and Qiu using numerical methods [5]. Although there are no reported experimental systems on louvre-type windows, several studies have successfully implemented ANC systems on ventilation windows with staggered panels. Huang et al. constructed an experimental system in the laboratory [6] and further extended the concept to a model window [7]. An ANC systems have also been developed for a similar 'plenum' window design that has staggered glass panels [8]. The staggered panel systems are analogous to the acoustic duct systems, which simplifies the active control system implementation by limiting the total number of control sources.

The third category of fully-open windows is plausibly the most challenging implementation due to a larger aperture and absence of duct-like acoustic features that can simplify the control strategies. Due to the highest ventilation characteristics of fully-open windows, ANC systems for such windows are desired for tropical regions. Kwon and Park has demonstrated an active control system capable of broadband, global attenuation using 8 sources uniformly distributed around the edges of the aperture [9]. Murao and Nishimura achieved similar outcomes with an acoustic shielding system that arranged control sources evenly across the aperture [10]. However, the existing attempts at implementing active control systems on open apertures have been limited to less than 0.1 m^2.

To implement ANC systems on full-scale open windows, the active acoustic shielding methodology from Murao and Nishimura is adopted and scaled. The Huygens principle-based method of Murao and Nishimura has been shown to outperform the edge method of Kwon and Park in initial investigations when the aperture is increased. Although in [11] the feasibility of scaling Murao and Nishimura's method has been demonstrated in numerical simulations for a fully open window, it is also worth looking at scenarios with the inclusion of windows. The setup of the simulations will be similar to the actual full-scale model used for experimentation, which is a 16-channel ANC system mounted on a window with two sliding panels. As the development of the complete system is still on-going, the performance of the ANC system will only be briefly discussed.

2. Simulation methodology

The purpose of the simulations is to firstly demonstrate the expected attenuation from a single-glazed window under the fully-glazed scenario (closed window). Subsequently, the degradation in attenuation with increasing opening size – mimicking a sliding operation – establishes a baseline for active control to be evaluated against. The attenuation benefits of multi-glazed window will not be discussed as these windows are not common in urban areas with tropical climates.

The finite-element method (FEM) simulations are run using COMSOL Multiphysics 5.2a, with a minimum element size of one-sixth the wavelength of 1 kHz. The simulation plane is adopted from [11] as shown in Figure 1, and enclosed in a perfectly matched layer to imitate a free-field scenario. A glass panel of width $L_w = 3$ mm, and length L_g, is positioned at the edge of the walls nearest to the noise source. The glass panel has a density set at 2180 kgm^{-3} and Young's Modulus of 68 GPa.

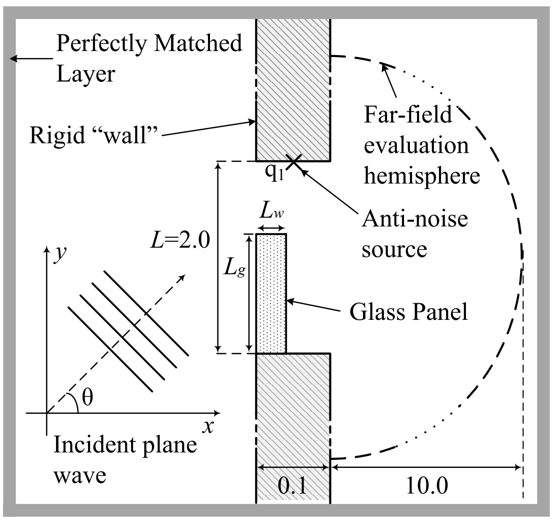

Figure 1: Finite-element method simulation plane in 2D to represent an aperture fitted with a glass panel to mimic a sliding window. The active control system is represented by a line source q_1 similar to [4].

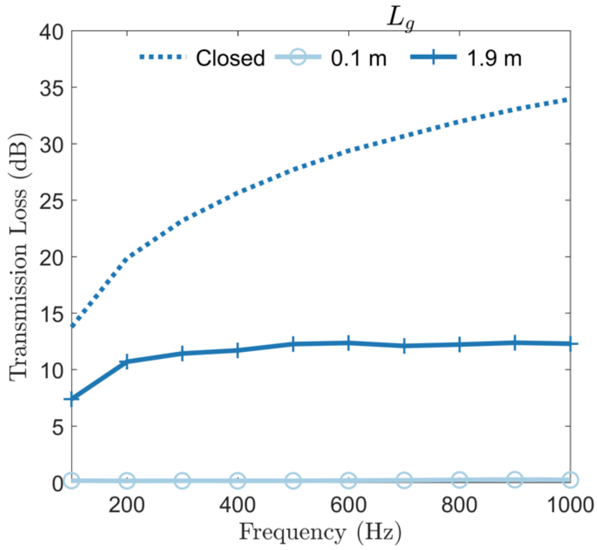

Figure 2: Transmission loss in dB for (1) fully-closed window ($L_g = 2.0$ m), (2) Partially-open ($L_g = 1.9$ m), and (3) almost fully-open ($L_g = 0.1$ m).

By varying L_g, the passive attenuation provided a single-panel sliding window is profiled and shown in Figure 2. The case with the window fully-closed ($L_g = 2.0$) closely matches the performance of measurements [12]. When a 10 cm gap is present (i.e., $L_g = 1.9$) the attenuation performance plummets significantly and interestingly, plateaus after 200 Hz. The results in Figure 2, forms the benchmark for active control, implying that the ANC system must perform better than the passive attenuation of the window to be useful at the respective L_g.

To draw a comparison to existing systems, the 'Active Window' system [4] described by Carme et. al. will be examined via FEM simulations, as depicted in Figure 1. The single line source q_1, located at the edge of the wall where the window gap will be, emulates the column of control sources in the 'Active Window' system.

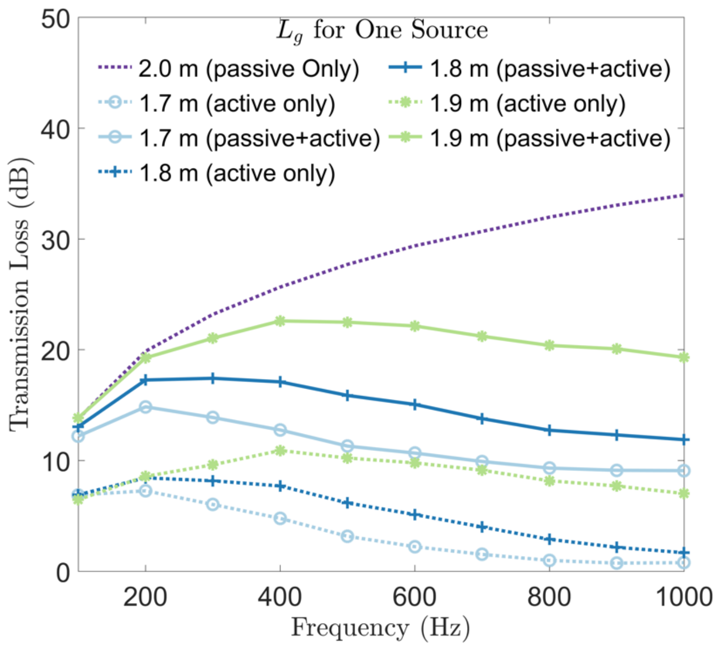

Figure 3: Transmission loss in dB for fully-glazed window without ANC is shown in dotted purple lines ($L_g = 2.0$ m).

The attenuation as a result of both the active control and passive insulation due to the glass panel is shown in Figure 3 as solid lines. The theoretical performance of the active system only, is represented in dotted lines. With the exception for the dotted purple line, which is the said benchmark of the fully-glazed window without active control. It is evident that a single line source (or column of sources) located at the edge of the wall, is unable to perform as well as the fully-glazed window. Therefore, the ANC setup of Murao and Nishimura should be adopted for improved noise attenuation instead.

The simulation results presented in Figure 3 exhibits a similar downward trend in attenuation as frequency increases as shown in Figure 6 of [4]. From cross-referencing, there seems to be greater attenuation in the 'Active Window' system reported by Carme et. al. than predicted by the FEM simulations and could be attributed to: (1) scaled-down window gap of 60 cm by 13 cm, and (2) a non-planar primary noise source. However, it is difficult to explain the large attenuation attained in the 100 – 200 Hz region in [4], given that small speakers will not reproduce with efficiency close to the line source in FEM and the nature of the acoustic limits determined by FEM simulations. This warrants further investigation by means of a full-scale window setup.

3. Experimental validation

3.1 Experimental setup

The full-scale model is constructed with 30 mm thick plywood measuring $2 \times 2 \times 2$ m^3. One side of the model is fitted with a 1×1 m^2 single-glazed sliding window, built to the specifications of the housing authority in Singapore, as shown in Figure 4.

The active noise control system consists of 8 control sources mounted on a grille structure that is typically installed for child safety purposes. Remainder of the 8 sources depicted in Figure 4 are not in use. The control sources are custom designed with aluminium drivers, measuring 4.5 cm in diameter, mounted in a 3D printed housing. The primary source is a calibrated speaker (GENELEC 8351A) capable of generating large wave fronts to mimic plane waves. Reference and error microphones in the ANC setup are basic electret microphones connected to 16-bit analog-to-digital converters.

Due to the high computation demand of the 8-channel multiple error Least Mean Squared (LMS) control algorithm [13], the co-located variant introduced by Murao and Nishimura is adopted [10]. The algorithm is deployed on a National Instruments PXI platform running a real-time operating system.

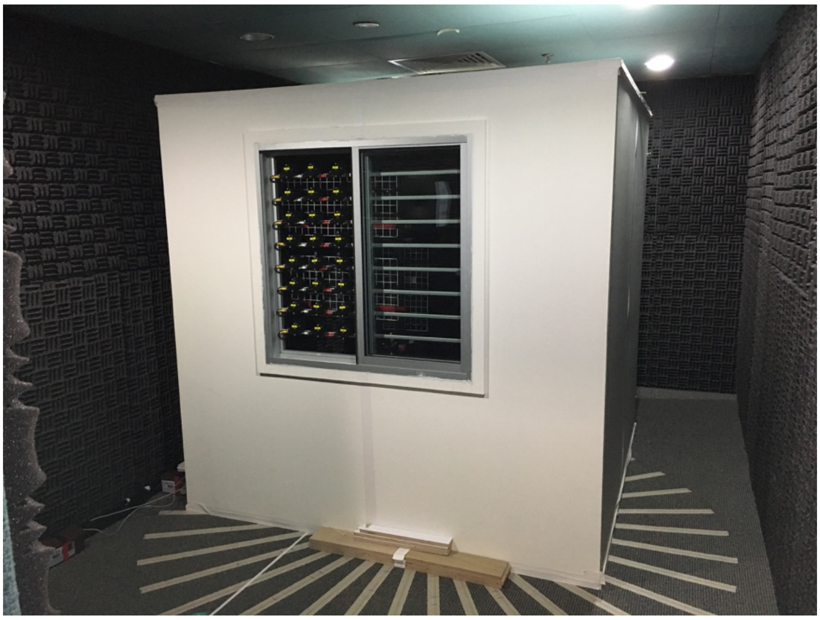

Figure 4: A full scale test chamber measuring $2 \times 2 \times 2$ m^3, located in a recording studio. The sliding window installed on one side of the chamber measures 1×1 m^2.

3.2 Tonal performance

To evaluate the attenuation performance of the full-scale setup, the sound pressure level from 8 observation microphones arranged in a plane parallel to the window is averaged. Position of the microphones reflect the position of an averaged-height human standing 0.4 m from the window gap. The results are normalised with the SPL recorded with the windows fully closed as a method of comparison, and is given by,

$$Attenuation = -20\log_{10}\left(\frac{\mathbf{p}_o^{\mathrm{H}}\mathbf{p}_o}{\mathbf{p}_c^{\mathrm{H}}\mathbf{p}_c}\right), \tag{1}$$

where $\mathbf{p}_o$ is the vector of SPL values from the eight observation microphones and $\mathbf{p}_c$ represents the vector of SPL values at the observation microphones when the window is fully closed. Thus, attenuation values above 0 dB indicates that insulation is greater than that of the fully closed window scenario.

With an 18 cm gap, the passive insulation as compared to that of the fully-closed window is shown in the solid line in Figure 5. The attenuation performance when the 8-channel ANC system is introduced can be seen from the dashed line. Even though the ANC system clearly provides additional attenuation from 500 to 1700 Hz, it does not yield the same levels of attenuation one would expect from the closed window (> 0 dB in Figure 5).

The non-linear nature of the plots also suggests the presence of acoustic modes that may limit the effectiveness of the ANC system. In addition, the speaker housing also experiences resonances at specific frequencies.

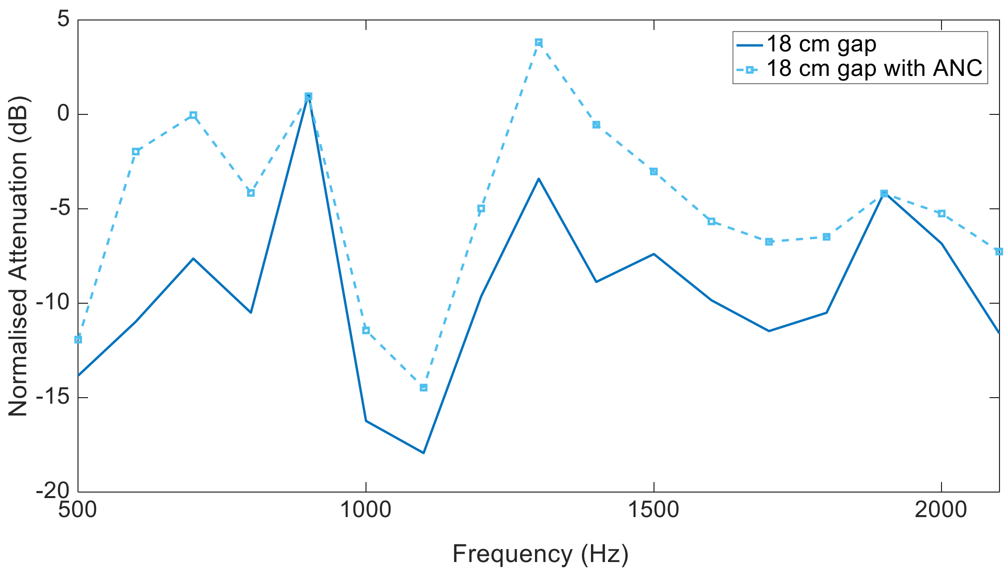

Figure 5: Attenuation performance normalised with respect to the fully-glazed scenario when the window gap is 18 cm. Solid line represents the attenuation only considering the passive insulation and the dashed line takes into account both the passive and active performances.

4. Discussion and future work

To justify the usefulness of an ANC system in an open window scenario, the attenuation performance could be benchmarked against a fully-glazed window's passive insulation performance. From the FEM simulations, it is clear that only installing a single column of sources at the edge of the wall, as in [4], is insufficient to attain desirable levels of attenuation. Thus, the scaled-up system of Murao and Nishimura is introduced and installed on a full-scale model for evaluation. Although the experiment results indicate real potential for an effective noise mitigation solution, there are several hurdles in scalability.

Firstly, the increasing complexity of the algorithm implementation must be addressed. Strategic de-centralisation of the multi-channel ANC system could help to reduce the computational complexity [14], albeit at the cost of attenuation performance. However, implementing the algorithm in parallel streams on field-programmable gate arrays (FPGA) is another promising method, which will not sacrifice attenuation performance [15], [16].

Secondly, effect of feedback interference from reducing the size of the control sources. For primarily aesthetic reasons, reducing the size of the secondary sources is a desirable step. However, as the size of the source shrinks, the feedback interference to the reference microphone becomes significant. Although this feedback can be neutralised with a howling canceller [17], it further burdens the computation load. More importantly, reverberations through the housing and the associated resonances degrades the performance of the control sources as the control effort increases. Thus, the construct of the housing has to be engineered to minimise such spurious transmissions.

Lastly, for practical deployment, the removal of the error microphones must be addressed. To discard the error microphones, several strategies could be employed: (1) open-loop control [14], (2) fixed-filter [18], and also based on the type of noise [19]. However, the identified strategies are still in the preliminary stages of research.

ACKNOWLEDGEMENT

This material is based on research/work supported by the Singapore Ministry of National Development and National Research Foundation under L2 NIC Award No.: L2NICCFP1-2013-7.

REFERENCES

1 T. Pàmies, J. Romeu, M. Genescà, and R. Arcos, Active control of aircraft fly-over sound transmission through an open window, *Applied Acoustics*, **84**, 116–121, (2014).

2 D. Sachau, T. Kletschkowski, and K. Kochan, Active noise reduction in bedrooms, in *Proc of IMAC XXVI a conference and exposition on structural dynamics, Orlando, FL, USA, February*, 4–7, (2008).

3 J. Hanselka, S. Jukkert, and D. Sachau, Experimental Study on the Influence of the Sensor and Actuator Arrangement on the Performance of an Active Noise Blocker for a Tilted Window, in *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 3046–3057, (2016).

4 C. Carme, O. Schevin, C. Romerowski, and J. Clavard, Active opening windows, in *23rd International Congress on Sound and Vibration (ICSV23)*, (2016).

5 M. Qin and X. Qiu, The noise reduction performance of oblique slits and louvers with active noise control system, in *21st International Congress on Sound and Vibration (ICSV21)*, (2014).

6 H. Huang, X. Qiu, and J. Kang, Active noise attenuation in ventilation windows., *The Journal of the Acoustical Society of America*, **130** (1), 176–88, (2011).

7 X. Qiu, H. Huang, and Z. Lin, Progress in research on natural ventilation ANC windows, in *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 3189–3196, (2011).

8 S. K. Tang, Y. G. Tong, and K. L. Tsui, Sound transmission acrosss a plenum window with an active noise cancellation system, *Noise Control Engineering Journal*, **64** (4), 423–431, (2016).

9 B. Kwon and Y. Park, Interior noise control with an active window system, *Applied Acoustics*, **74** (5), 647–652, (2013).

10 T. Murao and M. Nishimura, Basic Study on Active Acoustic Shielding, *Journal of Environment and Engineering*, **7** (1), 76–91, (2012).

11 B. Lam, S. J. Elliott, J. Cheer, and W. Gan, The Physical Limits of Active Noise Control of Open Windows, in *12th Western Pacific Acoustics Conference*, 184–189, (2015).

12 J. D. Quirt, Sound transmission through windows I. Single and double glazing, *The Journal of the Acoustical Society of America*, **72** (3), 834–844, (1982).

13 S. Elliott, I. Stothers, and P. Nelson, A multiple error LMS algorithm and its application to the active control of sound and vibration, *IEEE Transactions on Acoustics, Speech, and Signal Processing*, **35** (10), 1423–1434, (1987).

14 C. Shi, T. Murao, D. Shi, B. Lam, and W.-S. Gan, Open loop active control of noise through open windows, *The Journal of the Acoustical Society of America*, **140** (4), 3313–3313, (2016).

15 D. Shi, C. Shi, and W.-S. Gan, A systolic FxLMS structure for implementation of feedforward active noise control on FPGA, in *2016 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA)*, 1–6, (2016).

16 D. Shi, J. He, C. Shi, T. Murao, and W.-S. Gan, Multiple parallel branch with folding architecture for multichannel filtered-x least mean square algorithm, in *2017 IEEE International Conference on Acoustics, Speech and Signal Processing*, (2017).

17 S. M. Kuo and D. R. Morgan, *Active noise control systems: algorithms and DSP implementations*. Wiley, (1996).

18 B. Lam, J. He, T. Murao, C. Shi, W. S. Gan, and S. J. Elliott, Feasibility of the Full-Rank Fixed-filter Approach in the Active Control of Noise Through Open Windows, in *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 3548–3555, (2016).

19 R. Ranjan, J. He, T. Murao, B. Lam, and W. S. Gan, Selective Active Noise Control System for Open Windows using Sound Classification AAS cell, in *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, (August), 482–492, (2016).