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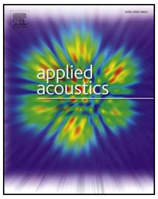

# Physical limits on the performance of active noise control through open windows

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ABSTRACT

Active noise control through open windows is a noise mitigation technique that preserves natural ventilation in dwellings. Designing a practical open window active noise control system requires the knowledge of the physical limits on the attenuation performance. Of the numerous variables to be optimised, it is the control source configuration (quantity and position) that ultimately defines the maximum attenuation attainable by an active noise control system. The physical limits are characterised here by systematically investigating the performance of different physical arrangements of control sources, using a two-dimension simulation model based on the finite-element method, which includes the diffraction effects of the window. The simulations reveal that the best attenuation is achieved by placing the control sources away from the edges of the window. It also shows that the plane of control sources can be placed centrally with respect to the depth of the walls, for practical implementation with minimal performance degradation. The simulated attenuation as a function of frequency and window width, for different angles of noise incidence, can be used to provide an estimate of the number of control sources, based on the desired level of attenuation. This estimate helps to determine the configuration with the minimum number of control sources required for different scenarios, before a more detailed system design is undertaken.

## 1. Introduction

Common noise mitigation measures such as double-glazed windows and the installation of noise barriers have been somewhat effective, however, these techniques do not translate well for densely populated high-rise urban areas. As barriers only mitigate noise in the shadow zone, upper floors of a high-rise building are typically not shielded from noise [1]. Although integration of active noise control technology on the top of the noise barriers can increase the effective height of the barriers [2,3], land scarcity, cost, and visual aesthetics are several factors that restrict noise barrier implementation. For regions with hot and humid weather, natural ventilation is a priority, as this requirement is usually mandated by local Governments. Thus, in these areas, noise mitigation measures must be effective in a high-rise scenario whilst also maintaining adequate natural ventilation.

Modified ventilation windows have been developed based on the benefits of double-glazing to achieve acoustical shielding while providing some degree of air flow into buildings. The plenum window design proposed by Tong and Tang [4,5], achieved up to 9.5 dBA of noise reduction in a full-scale study. Active noise control systems have also been integrated with 'double-glazed' ventilation systems to achieve better low frequency attenuation [6,7]. Whilst modified ventilation windows can provide significant noise insulation, the air flow rate can be reduced by up to 2–4 times [6]. Installation of such ventilation windows also requires existing windows and their supporting structures to be replaced, increasing the cost of implementation and inconvenience to residents.

To retain the full natural ventilation properties of conventional windows, active control methods have emerged as potential solutions. Emms and Fox demonstrated the feasibility of sound attenuation through a square aperture based on the active sound absorption method, an application of the Huygens principle [8,9]. Realization of active sound absorption, however, requires a continuous distribution of monopole and dipole sources that are susceptible to instability due to uncertainties in calibration [9]. Active noise control (ANC) methods – increasingly found in consumer headphones – can potentially reduce noise in the entire room by controlling the total sound power transmitted through the windows [1]. Although ANC systems for window applications require numerous transducers, sensors and digital processors, the advent of cheaper and more advanced electronics have

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increased its cost-effectiveness. Scale-model ANC systems (built on open apertures) can achieve wide-band noise reduction of up to 10 dB [10,11], which is similar to modified ventilation windows. ANC systems have also been employed to reduce noise through a partially-opened window [12–14].

The effectiveness of ANC systems is evaluated by how well the 'anti-noise' field minimises the noise in the desired area (e.g., a room). Total or global minimisation of noise in a room can be achieved by (1) controlling all unwanted acoustic modes in the room, or (2) by minimising the acoustic power of the noise source [15,16]. Controlling room modes is considered the least practical solution, as large numbers of control sources would have to be installed in the room. If the source of noise is assumed to be transmitted into a building primarily through the windows, global noise attenuation can be attained if the active noise control system succeeds in controlling the total acoustic power transmitted through the windows.

Noise incident at the façade of the building can be assumed to be plane waves, as surface transportation noise (e.g., busy highway) is usually modelled as an incoherent line source in the far-field [17]. Plane waves through a rectangular aperture exhibit frequency-dependant scattering patterns [9,18,19], and thus the open window ANC systems must also control scattering to achieve global attenuation. However, theoretical studies of the open window ANC systems have only been conducted in free-field conditions [10] and have not considered the physical effects due to the scattering behaviour of the window. Moreover, placement of secondary sources in experiments have been motivated by Huygens principle in the free-field [10] and by boundary control [11], without taking into consideration the effects of scattering by the window.

The effects of scattering on the attenuation performance of the open window ANC system are investigated here using numerical methods. Control source positions are investigated for various incidence angles and frequencies to establish guidelines for optimal noise attenuation in the frequency domain. The study is performed using the 2D finite element method (FEM), with a maximum element size of one-sixth the wavelength at 4 kHz. The 2D model has about 1 million elements and is reasonably quick to run for a variety of geometrical conditions, whereas the corresponding 3D model would need about 120 million elements and it would be too time consuming to run all the cases required to provide physical insight and practical guidelines, of the maximum separation between sources for example, which is the purpose of this study. These guidelines can aid in the design of large scale ANC platforms for the active control of noise through open windows for a range of frequencies and incidence angles. The motivation for this initial study is to investigate the control limit set by the position and the number of secondary sources, for a given set of error sensors, which is in line with the hierarchical method of practical active control system design [20] to determine the fundamental physical limitation of the ANC system [21].

## 2. Active noise control formulation

### 2.1. Design of the active acoustic window model

The 2D FEM computation model illustrated in Fig. 1 is a 10 m by 10 m vertical cross-section containing a solid wall with a $L = 2$ m wide aperture, bounded by a perfectly-matched layer to emulate a free-field condition. Two rectangular blocks with rigid boundary conditions represent the walls and form the cross-section of the opened window, indicated by the shaded regions in Fig. 1. The thickness of the wall is set to 0.1 m, since it was found that changing the wall thickness from 0.05 m to 0.3 m had a minimal effect on the sum of squared pressures in the far-field for frequencies of interest (⩽ 4 kHz). $N$ secondary sources, arranged symmetrically $w$ m apart in the $L$ m wide aperture, are optimised to reduce the sum of squared pressures evaluated at the semi-circular boundary in the far-field. The $N$ secondary sources are modelled as line sources producing cylindrical waves as defined in the FEM software used [22].

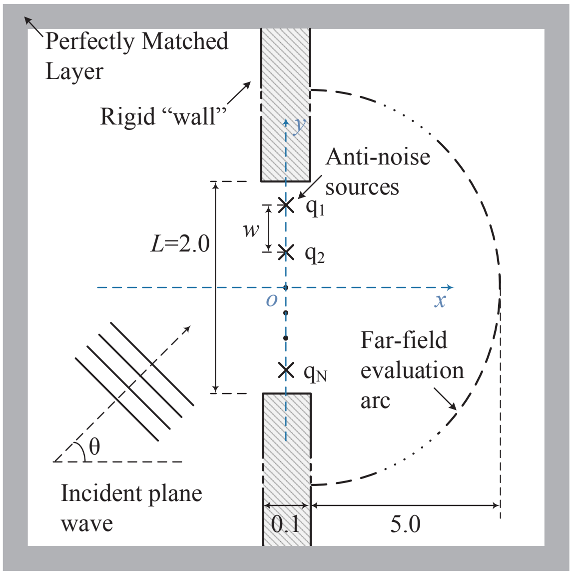

**Fig. 1.** 2D FEM model of the active acoustic window (in m). The axes and origin of the computation plane is depicted in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Owing to complexities of the large computational model, the FEM simulations were performed on a high-performance workstation with a XEON E5-2699 processor (18 cores, 2.3 GHz) and 128 GB of memory. The density of the mesh was set to provide a minimum of six elements per wavelength at 4 kHz for all frequencies tested (⩽ 4 kHz) to ensure consistency and accuracy, giving a 2D mesh consisting of approximately 1 million elements and solved for 2 million degrees of freedom.

### 2.2. Global control formulation

The active acoustic window concept achieves global attenuation in the building interior by treating the open window as the noise source and minimising its total power output [11,23]. The active noise control system is thus formulated to minimise the sum of squared pressures on the far-field semi-circular array that encompasses the entire open window and all secondary sources. Since the focus of this study is to understand the effects of diffraction on the performance of the active control system, the area to be controlled is assumed to be a free-field.

In the simulations presented here, the acoustic pressures were measured at 1100 positions at a distance of 5 m from the centre of the window as shown in Fig. 1, so that the separation between the measurement points was less than one-sixth of a wavelength at the highest frequency of interest.

The vector of complex pressures at all the evaluation positions on the far-field arc can be expressed as

$$\mathbf{e} = \mathbf{d} + \mathbf{G}\mathbf{q}_s, \tag{1}$$

where $\mathbf{d}$ is the vector of complex pressures at the evaluation positions due to the scattered incident plane waves through the window, $\mathbf{q}_s$ is the vector of source strengths of all the secondary sources, and $\mathbf{G}$ is the matrix of complex plant responses between the secondary sources and the evaluation positions on the far-field arc. Both $\mathbf{d}$ and $\mathbf{G}$ were obtained through the FEM simulation. The sum of squared pressures at the evaluation positions is minimised using the exact least squares method with the cost function given by

$$J = \mathbf{e}^{\mathrm{H}}\mathbf{e} = \mathbf{q}_s^{\mathrm{H}}\mathbf{A}\mathbf{q}_s + \mathbf{q}_s^{\mathrm{H}}\mathbf{b} + \mathbf{b}^{\mathrm{H}}\mathbf{q}_s + \mathbf{d}^{\mathrm{H}}\mathbf{d}, \tag{2}$$

where $\mathbf{A} = \mathbf{G}^{\mathrm{H}}\mathbf{G}$ and $\mathbf{b} = \mathbf{G}^{\mathrm{H}}\mathbf{d}$.

By setting the derivative of the cost function in (2) with respect to