# Active noise control applied to open windows

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## ABSTRACT

Active opening windows are a set solutions developed by TechnoFirst (initiated in 2011 by a partnership with the French Environment and Energy Management Agency, ADEME) to cope with noise disturbances while your window is opened to a noisy environment. Indeed, opening your window reduces the acoustic insulation. That is why TechnoFirst designed an Active Noise Reduction-based solution for windows (ANR). The first one is related to sliding windows: the active window. A loudspeakers line integrated in the window joinery generates a counter-noise facing the opening, to minimize the noise between 100 and 500 Hz measured by microphones integrated in the window opening. The latter is covered with passive materials coping with middle and high frequencies. Thus the sound transmission through the window opening is reduced up to 25 dB. The second application proposed by TechnoFirst, based on the same ANR principle, enables natural ventilation of a room while minimizing the intrusion of pollution (noise and air) from outside: the active labyrinth. The opened area that allows ventilating is divided into ducts by a labyrinth. Each of these ducts includes an ANR electronic processing and an anti-pollution filter. The electronic processing system is composed of an ultra-compact loudspeaker (designed by the Fraunhofer Institute for Building Physics) and sensors connected to a controller producing the mirror noise which will attenuate low and medium frequencies ([100 - 1700] Hz). The system is thus able to reduce the noise level up to 30 dB compared to a typical window ajar.

Keywords: Active noise control, Sound insulation I-INCE Classification of Subjects Number(s): 51.3

## 1. INTRODUCTION

Over past decades, noise pollution has progressively become a major environmental issue as it has adverse effects on human health. More than 10 000 case of premature death in Europe are related to environmental noise exposure every year (1).

Three distinct approaches are commonly considered to protect living areas from external noise pollution. The first one aims at reducing noise directly at source. This approach mainly concerns the road, railway and aircraft industries, and has the strongest positive impact at the global level. The second one consists in preventing noise from reaching living areas, by inserting sound barriers along the propagation paths or through the implementation of appropriate urban planning. The last one, which is the subject of this paper, focus on office and residential buildings by improving acoustic isolation of facades.

The weakest component of a building façade is usually the window, which tends to exhibit a lower sound transmission loss. Acoustic isolation performances of multiple glazed windows has been extensively investigated through theoretical and experimental approaches (2). Despite the progress achieved in sealing and frame design, windows still present some weaknesses, especially in the low frequency range and at some specific isolated frequencies.

Active control approaches have been carried out by the use of different methods, such as panel control (3) and cavity control (4). Cavity control showed better performances than panel control, but industrialization of this kind of solution would require the integration of the loudspeakers in the window frame. Jakob and Möser used a set of small low-cost standard loudspeakers, integrated in a double-glazing in which the two glass panes are separated by 40mm (5). For the smaller pane separation distance, which is typically 10 to 20 mm, it would require a specially designed loudspeaker, like the linear loudspeaker (6, 7).On that topic, TechnoFirst has partnered with the French Environment and Energy Management Agency (ADEME) to develop an active double-glazed window

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and a window with actively controlled openings for natural ventilation (8).

Research has also been conducted on open windows to enable both natural ventilation of a room and isolation from external noise. Huang et al. investigated both analytically and experimentally the use of active noise control (ANC) techniques applied to ventilation windows (9). Attenuation of 10 dB has been obtained up to 400 Hz with a single channel ANC system applied to a 1:2 scale experimental setup. Tang et al. performed an MIMO ANC experiment on a full scale ventilation window (10), where they obtained 4 dB attenuation up to about 500 Hz.

Ventilation window is particularly well suited for ANC implementation because the large ventilation path facilitates the integration of the system. However, this type of window is not the most commonly used in the construction industry.

This paper presents two ANC systems dedicated to standard sliding windows, which aim at enabling natural ventilation as well as protection against external noise when the window is partially open.

## 2. PRESENTATION OF THE ANC SYSTEMS

Active Window and Active Labyrinth are the name of the two concepts that are depicted on Figure 1. Both concepts rely on an ANC system integrated into the frame of a standard sliding window.

Figure 1 - Overview of Active Window (left) and Active Labyrinth (right)

The reduction of constraints linked to integration of the system is currently being investigated through the use of compact loudspeakers developed by Fraunhofer Institute of Building Physics (IBP) for ANC applications (11).

### 2.1 The Active Window

The Active Window is based on several ANC modules arranged in a line, placed in the vicinity of the window aperture. A module is composed of a loudspeaker and its enclosure, a microphone and control electronics. A layer of absorbing material is located in front of the modules and attached to the sliding part of the window, as depicted on Figure 2.

When the loudspeaker is not controlled, it acts as band-pass filter of a passive resonator with a resonant frequency being dependent of the mass-spring-damper parameters. When the loudspeaker is controlled by a feedback loop using the microphone, it acts as an active resonator. The frequency bandwidth of the band-pass filter and attenuation performances are increased. The layer of absorbing material provides a complementary attenuation at medium and high frequencies, where ANC cannot perform, as depicted on Figure 2 (c).

The Active Window can also be implemented in a feedforward configuration (Figure 2 (b)). The error microphone can either be located in the vicinity of the loudspeaker, as for the feed-back configuration, or remotely at the layer of absorbing material, in front of the loudspeaker. The feedforward configuration also requires the use of an additional reference microphone to pick up the incoming noise before it reaches the window aperture. This microphone is located in the vicinity of the aperture on the outside. Optionally, the reference signal can go through a signal conditioning stage in order to optimize coherence between error and reference signals.

In this study, the loudspeakers are distributed along the whole aperture height. The aperture width has been limited to 13 cm, which provided a good trade-off between ANC performances and natural ventilation.

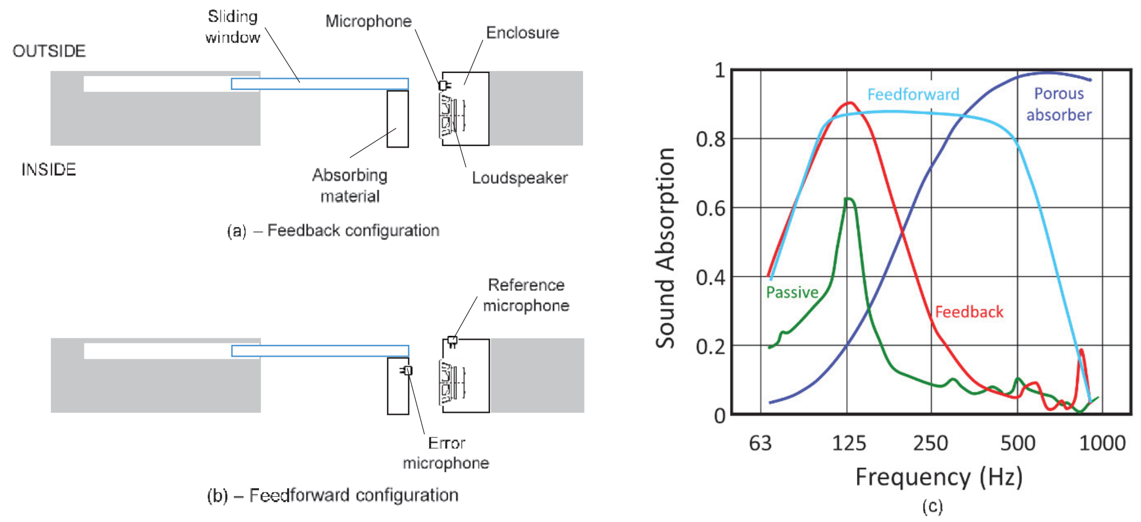


Figure 2 - Active Window feedback (a) and feedforward (b) configurations. Typical sound absorption (c)

The feedback configuration is based on a SISO architecture, each module is working independently from the others. The feedforward configuration is based on a MIMO architecture, which tend to provide better performances than SISO because it takes into account the potential contributions of cross-talk secondary paths between ducts

Regarding control electronics, the NoVACS™ controller (12) has been used, which enables multi-channel digital feedback and feedforward configurations based on FxLMS algorithm.

## 2.2 The Active Labyrinth

The Active Labyrinth is composed of multiples ducts located at the window aperture. These ducts act as acoustic waveguides when the external noise goes through the window aperture. The main advantage of this configuration compared to the previous one is that it falls into the classical acoustic wave propagation in ducts, which relies on well-known theoretical foundations. In particular, the control bandwidth is inversely related to characteristic dimension of the cross-section. It is thus possible to get a broader bandwidth of attenuation by carefully sizing the cross-section area of the ducts.

As depicted on Figure 1 (right), the ducts are opened at both ends only when the window is open, thus forcing the acoustic disturbance to follow these paths. When the window is closed, both duct ends are also closed. Each duct has its own loudspeaker and associated enclosure, two microphones and absorbing material, as depicted on Figure 3.

The whole duct setup is controlled by a MIMO feedforward algorithm connected to all microphones and loudspeakers. Reference microphones are located at the outside end of the ducts to pick up the external noise. Reference microphones are preferably unidirectional in order to avoid the unwanted contribution of the acoustic feedback (i.e. the reference microphone that picks up the sound produced by the control loudspeaker). Error microphones are located at the inside end of the ducts and measure the residual noise after control. All microphone signals are fed to the NoVACS™ controller, allowing it to define the optimal loudspeakers outputs that will minimize the residual noise at the error microphone locations. As for the Active Window, the reference signal can go through a signal conditioning stage in order to optimize coherence between error and reference signals.

This feedforward configuration aims at controlling the acoustic plane wave propagating in the duct up to its cut-off frequency. For a duct with a rectangular cross-section $(L, l)$, with $L > l$, the cutoff frequency is given by:

$$f = \frac{c}{2L} \tag{1}$$

where $c$ is the speed of sound in air. Experimental study presented in section 3 has been performed with a cross-section area of 100x100 mm² which theoretically enables active control performances up to 1.7 kHz.

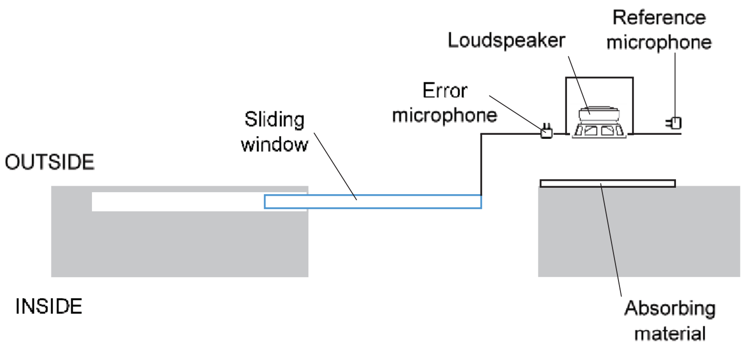


Figure 3 - Active Labyrinth feedforward configuration

Layers of absorbing material can be applied on the inner walls of the ducts in order to get additional attenuation performance beyond the plane wave bandwidth, as well as a better stability of the control algorithm.

This ducts configuration enables natural ventilation of a room as well as providing a protection against external noise pollution. Additionally, ducts can also be equipped with anti-pollution filters to prevent the ingress of pollutant particles.

### 2.3 Integration constraints

The industrialization of such ANC system for windows requires addressing the major issue of integration constraints. Conventional loudspeakers usually require enclosures that are too large to allow a realistic integration of the system in a window frame. The Fraunhofer Institute for Building Physics (IBP) brought a promising solution into the project. Indeed, they have developed compact loudspeaker module (depicted on Figure 4) dedicated to ANC applications. With its small form factor of 50x50x50 mm3, they are able to provide a satisfactory sound pressure level as well as a better match with integration constraints.

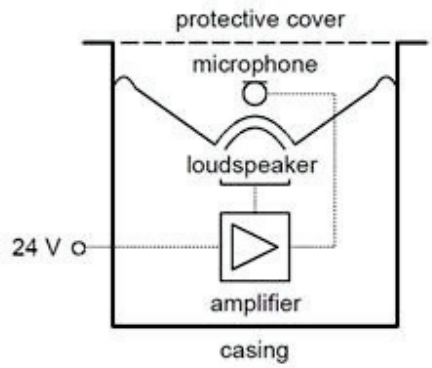


Figure 4 - ASCa module schematics (left) and picture (right) designed by

the Fraunhofer Institute for Building Physics

The Fraunhofer IBP initially developed this loudspeaker module for feedback configurations with a microphone located in the vicinity of the membrane. In this project, microphone location has been subjected to change in order to match feedforward requirements.

The experimental study presented in the next section is however based on a homemade loudspeaker module with a larger form factor of 150x150x170 mm3. The solution brought by the Fraunhofer IBP is currently under investigation and testing, and already showed encouraging results. It may significantly contribute to develop a system that will be compatible with industrialization constraints.

## 3. EXPERIMENTAL STUDY

### 3.1 Test setup

A prototype, depicted in Figure 5, has been developed to test the two configurations described in section 2. It is made of a large wood enclosure containing the primary loudspeaker producing a noise disturbance (road traffic). This test bench is reversed: the inside simulates an outdoor environment, whereas the outside represents a room. A sliding window is mounted on one side of the enclosure, allowing the different ANC setups.

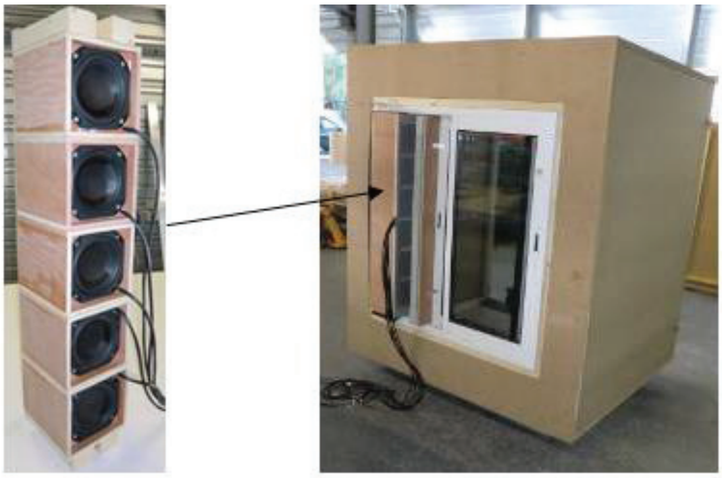

Figure 5 - Picture of the test bench with Active Window configuration

Either the Active Labyrinth or the loudspeaker modules of the Active Window are installed inside the enclosure, at the edge of the open window, as depicted in Figure 5. The modules are connected to an amplifier linked to the NoVACS™ controller. The controller implements a 1x5x5 feedforward configuration (1 reference, 5 error microphones and 5 loudspeakers). The five error microphones are installed as follows:

- For Active Window, they are located in front of each secondary source, on the absorbing material, as depicted on Figure 2 (b).
- For Active Labyrinth, they are located in the ducts between the secondary loudspeaker and the ducts end toward the window, as depicted on Figure 3.

Three observation microphones pick up the noise inside the enclosure, in the window aperture, and outside the box at 1 m of the aperture.

For the Active Labyrinth, each duct is 500 mm long and has a cross-section of 100x100 mm². A loudspeaker module is located at half the length of each duct. Five identical ducts are stacked in the vicinity of the window aperture. Error microphones are set on the inner wall at the downstream end of each duct. When used, reference microphone is placed on the other end of the duct. The results presented in section 3.2 are based on an electrical reference (i.e. signal from primary source) in order to limit the effects of non-optimal experimental conditions.

For each concept, several configurations were tested, placing error microphones differently or changing secondary source orientation. With the Active Window particularly, three orientations for the ANC modules were tested: directed toward the aperture, toward the primary noise source, and toward the outside of the enclosure. The best results, presented in section 3.2, were obtained for the secondary source oriented toward the aperture.

### 3.2 Main results

The test bench depicted on Figure 5 was used to perform measurements in several configurations. The Figure 6 depicts the typical performances that were obtained with the Active Window configuration. The blue line corresponds to the primary noise spectrum. The red one corresponds to the attenuation brought by passive material (foam): an attenuation of 3.6 dB (2.6 dBA) is measured. The cyan curve corresponds to both active and passive contributions: an attenuation of 15.5 dB (12 dBA) is measured.

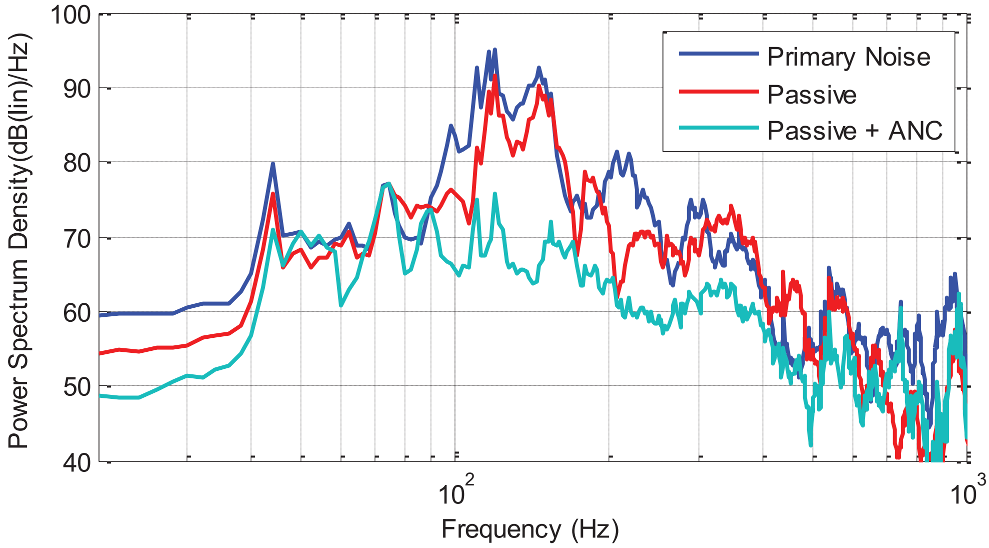


Figure 6 - Performances of the Active Window configuration

The Figure 7 depicts the typical performances obtained with the Active Labyrinth configuration. The blue line shows the primary noise spectrum. The red one shows the attenuation brought by passive material (foam and duct): an attenuation of 3.5 dB (5.5 dBA) is measured. The cyan curve shows both active and passive contributions: an attenuation of 16 dB (13.5 dBA) is measured.

The same observation can be made here about the ANC effect: the exceeding levels are lowered down to a more stable value. As expected, it can be noted that the Active Labyrinth configuration provides of broader control bandwidth, compared to Active Window configuration.

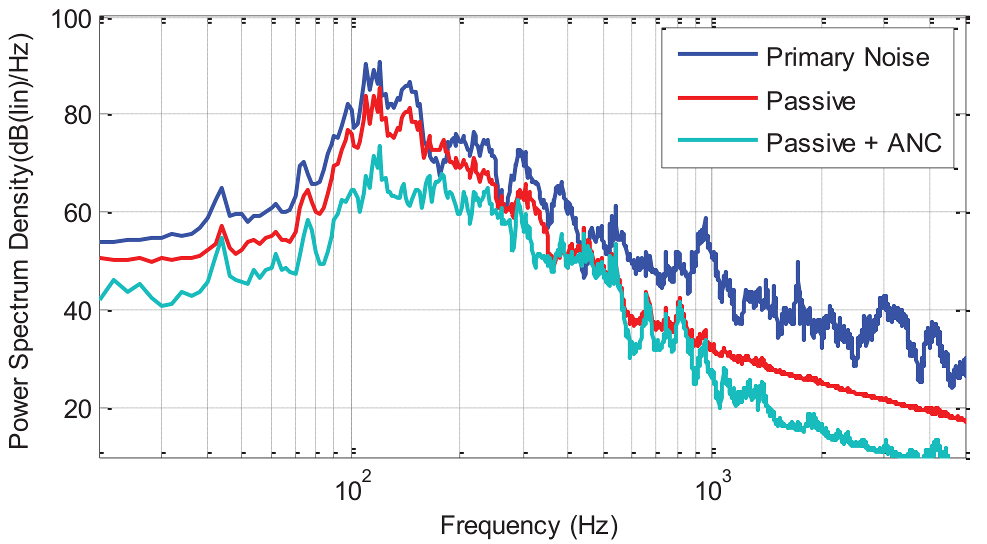


Figure 7 - Performances of the Active Labyrinth configuration

## 4. CONCLUSIONS

This paper presented two active noise control approaches applied to open windows, improving sound transmission loss, as well as enabling natural ventilation of a room. Both approaches exhibited significant noise attenuation performances.

Further investigations are currently on-going to validate the performances of compact loudspeaker solution brought by the Fraunhofer IBP and confirm that it could match the industrialization constraints of the ANC system (cost and integration). In parallel, theoretical and experimental studies are carried out in order to reduce the number of channels required.

## REFERENCES


1 Nugent C et al. Noise in Europe 2014. EAA Report No. 10/2014, European Environment Agency; 2014.
2 Tadeu AJB, Mateus DMR. Sound transmission through single, double and triple glazing. Experimental evaluation. Applied Acoustics 2001;62 (3):307-325.
3 Jakob A, Möser M. Active control of the cavity sound field of double panels with a feedback controller. 7th International Congress on Sound and Vibration; 4-7 July 2000; Garmish-Partenkirchen, Germany 2000.
4 Yu X et al. Active control of sound transmission through windows with carbon nanotube-based transparent actuators. IEEE Transactions on Control Systems Technology 2007;15 (4):704-714.
5 Jakob A, Möser M. An actively controlled double-glazed window with small pane distance. Forum Acusticum; Sevilla, Spain 2002.
6 Carme C, Montassier A, Rehfeld M. Active double-glazing: the solution is the transducer. Fifth International Congress on Sound and Vibration; 15-18 December 1997; Adelaide, South Australia 1997.
7 Carme C, Rehfeld M. Linear Loudspeaker. US6285773, 2001.
8 ADEME, The French Environment and Energy Management Agency. 2001. Available from: http://www.ademe.fr.
9 Huang H, Qiu X. Active noise attenuation in ventilation windows. J Acoust Soc Am. 2011;130 (1):176-188.
10 Tang SK, Tong YG, Tsui KL. The sound transmission loss across ventilation window under active noise cancellation. Proc INTER-NOISE 14; 16-19 November 2014; Melbourne, Australia 2014.
11 Bay K, Leistner P. Lean transducers for ANC applications, 21st International Congress on Sound and Vibration; 13-17 July 2014; Beijing, China 2014.
12 TechnoFirst SA; 2014. Available from: http://www.technofirst.com/fr/novacs/.