

**Active noise control using DSP :  
Experimental activities on advanced aircraft windows**

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**ABSTRACT**

Aircraft windows are a significant path for structure-borne and air-borne noise transmission in aircraft. Turbulent Boundary Layer noise is mainly transmitted into aircraft cabin by airborne paths, but structure-borne noise, associated with engine vibration, and interactions between aerodynamic wakes and aircraft structure, make a significant contribution to interior noise levels, especially at certain discrete frequencies. The heavy sidewall treatments, typically located behind the sidewall trim panels to reduce the amount of noise and vibration due to external sources, do not ensure an effective solution for cabin noise reduction if windows provide a weak link in noise transmission.

In this paper, an active noise control system applied to a triple-pane aircraft window prototype is presented. Piezo stacks actuators are integrated into the prototype to drive the system generating sound waves counteracting the primary noise to be canceled in a specific area (quiet zone). A suitable control algorithm based on a feed-forward strategy is developed and tested in a digital control system running in a DSP control board. The effectiveness of the proposed control architecture is validated by real-time experiments addressing the acoustic control of a reference enclosure subjected to tonal and narrow-band noise disturbances.

**Keywords:** active noise control, digital signal processing, interior noise experiments

**1. INTRODUCTION**

Active noise control (ANC) has recently attracted much attention from engineers and scientists. Using the additive property of sound propagation, ANC systems attempt to reduce the noise in a specific location or to block the noise from entering a specific area (quiet zone), by controlling a secondary sound source.

It is well known that traditional passive noise control methods are not effective for attenuating low-frequency noise due to the long wavelength. On the contrary, active control has the potential to overcome these limitations by utilizing smart materials such as piezoceramics sensors or actuators. Furthermore, the advancement in the low-cost digital signal processor and the fact that ANC offers benefits in terms of bulk and expenditure over the conventional utilization of passive dampers, make structural-acoustic control an attractive opportunity for reducing undesired levels of acoustic noise.

Active control approaches can be classed into two groups depending on whether the control objective emphasizes a structural metric or an acoustic metric. Structural control utilizes structural

actuators and sensors to enhance the structural damping or modify the sound transmission through the structure. In acoustic control, the actuators can be either acoustic speakers or structural actuators such as piezoceramic patches or stacks, and the sensors are a combination of structural and acoustic sensors. The focus of the acoustic control is to reduce interior sound field either by controlling the structural impedance (active boundary control) by feeding back structural and acoustic measurements to structural actuators, or by generating an anti-noise field able to reduce the primary acoustic field through the destructive interference of sound waves (speaker control). In both cases, acoustic sensors are distributed throughout the cavity.

Interior noise studies on general aviation aircraft have shown that windows are a privileged path for structure-borne and air-borne noise transmission into aircraft, [1]. This noise arises predominantly from turbulent boundary layer pressure fluctuations but engine vibrations and the interactions between aerodynamic wakes and aircraft fuselage make a significant contribution to the interior noise levels, especially at certain discrete frequencies.

Component-by-component testing and extensive ground and flight measurements would be highly desirable in order to isolate the contributions of all sources and paths by which the energy from a given source reaches the cabin. However, recent flight surveys [2] and dedicated experimental campaigns [3] produced consistent evidence that conventional windows are a significant contributor to interior cabin noise. In addition, high variability in the sound pressure levels exists near aircraft windows usually being the highest at most frequencies and these noise levels are considered highly annoying to a large percentage of passengers, as confirmed by careful psychoacoustic tests [4].

Conventional solid aircraft windows are manufactured from solid plexiglas material. To improve their acoustic performances, damped plexiglas window panels are fabricated using two or three layers of plexiglas, separated by air gap, with transparent viscoelastic damping material sandwiched between the layers, [5-6]. Tests at NASA Langley Research Centre have examined their acoustic benefits by evaluating the transmission loss for diffuse acoustic excitation and the radiated sound power for point force excitation, [7].

Since weight constraints are a substantial challenge in applying noise control treatments on advanced damped windows, active noise reduction concepts applied to multi-pane window configurations may lead to a weight-efficient solution for the interior noise control without excessive penalties. Unlike passive treatments, typically located behind the sidewall trim panels, active control systems can contribute to enhance acoustic properties of the interior cabin in the low-medium frequency range, improving comfort perception for passengers.

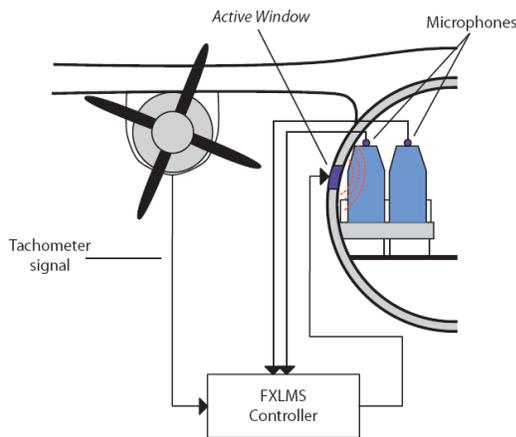
The work presented in this paper extends the numerical and the experimental activities described in [8-9], by assessing the feasibility of an active control system suitable for advanced aircraft windows. A feed-forward control strategy is implemented in a DSP control board in order to evaluate the controller performances through real-time interior noise experiments. The acoustic response measurements of the window are compared to the numerical results of the hardware-in-the-loop simulations in order to evaluate the effectiveness of the proposed control methodology as well as the reliability of the experimental system identification approach used to compute the unknown plant responses of the disturbing noise source and the active window prototype. The active window demonstrator is mounted on a side of a reverberant steel box and its control authority, which corresponds to the cancelling sound waves generating capability to destructively interfere with the interior acoustic field emitted by a loudspeaker, is tested. Structural piezoelectric actuators are used to generate in-plane and eccentric forces controlling the inner glass window pane.

## **2. OVERVIEW OF THE ACTIVE WINDOW PROTOTYPE**

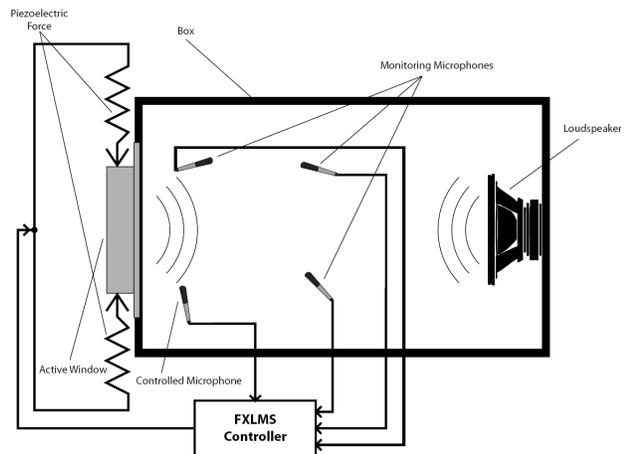
The main noise sources and the transmission paths through the aircraft fuselage have a great influence on interior cabin noise. In this study, the active window prototype is tested in a practical

acoustic environment exhibiting predominance of tonal spectral components. A four and six-bladed propeller aircraft having fundamental frequency at about 124 Hz and 150 Hz respectively, such as the ATR regional aircraft, built by the French-Italian aircraft manufacturer, is chosen as potential candidate for the application of such a technology to civilian aircraft. The narrow-band case, simulating interior noise during an aircraft maneuver, is analyzed as well by driving the disturbing source with a chirp signal varying between 120-130 Hz. In this case, the adaptivity and the robustness of the self-tuning noise controller are assessed by monitoring the control effectiveness with respect to the time-varying noise disturbance.

Fig. 1 shows a sketch of the window prototype installed onboard a turboprop aircraft. The feedforward control algorithm is used to calculate the input signals driving the structural actuators, forcing the active window, to cancel acoustic noise in a specific area within the enclosure. The reference signal is derived from the Blade Passage Frequency (BPF) of the propeller, sensed by a tachometer, to modify the interior acoustic field through feedback of acoustic sensors distributed throughout the cavity. The controlled noise (error signal) is measured by a microphone mounted on the headrest of the seat place inside the cabin. As described in section 4.2, the experimental set-up is an idealized arrangement of such a scenario. The test facility is a reverberant steel box, having acoustic hard wall boundary conditions, and the disturbing source is placed inside the cavity, as sketched in Fig. 2. The reference signal of the controller is taken directly from the signal generator.

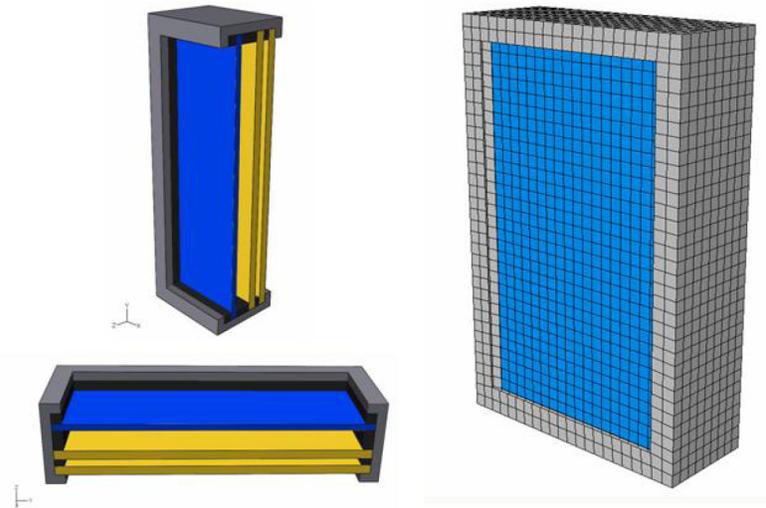


**Figure 1. Active window for interior noise control**

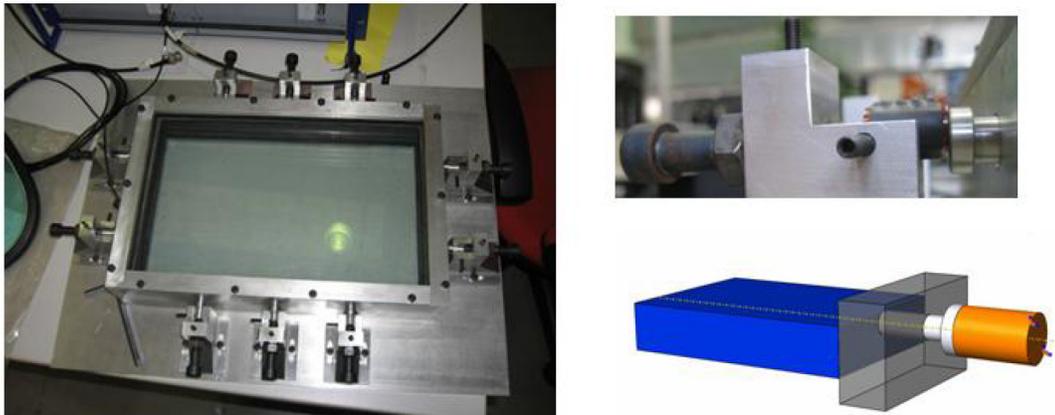


**Figure 2. Experimental layout of the interior noise tests**

The smart window prototype is designed with three panes and two acoustic cavities between them. The FE model of the triple-pane window is shown in Fig. 3. The actuation mechanism is based on no. 10 piezoelectric stacks integrated into the frame in order to generate in-plane and eccentric forces controlling the window pane vibrations. The vibrations induced by piezo stack actuators exciting the flexural modes of the window panes are driven to radiate the anti-noise acoustic waves producing destructive interferences. The assembled prototype and the actuation mechanism are detailed in Fig. 4.



**Figure 3. Sketch and FE model of the Active Window Prototype**



**Figure 4. Manufactured prototype and the actuation mechanism**

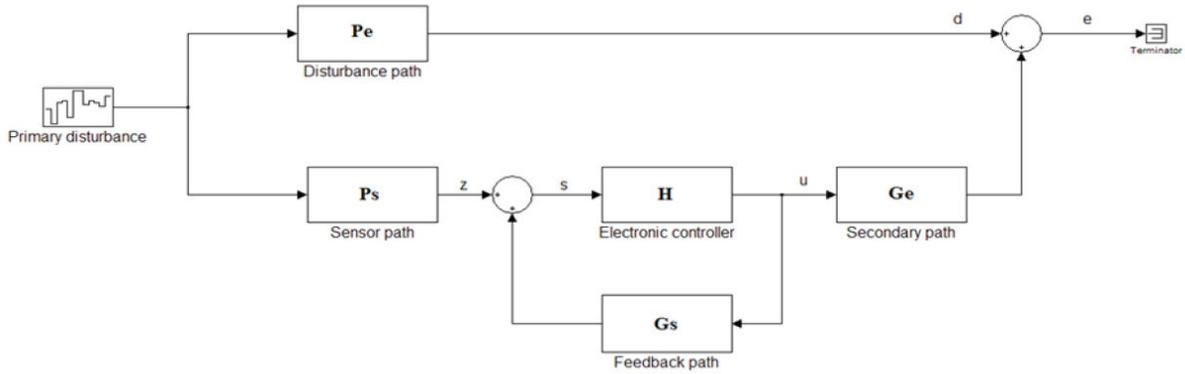
In this paper, a single channel filtered-x LMS algorithm is implemented in a DSP control board to cancel out the primary noise at the error sensor which estimates the disturbing noise produced by a loudspeaker. Unlike standard feedforward architectures, which requires prior knowledge of disturbance through the use of an upstream reference microphone, the reference signal is assumed to be taken directly by the primary source. This approach is particularly useful for periodic signals, like the propeller-induced noise of a four/six-bladed propeller aircraft, because such noise signals can be perfectly synchronised to the BPF of the propeller. In addition, the installation of a reference microphone on the exterior of windows seems to be not feasible due to functional issues.

The performances of the active control system applied to the window prototype are experimentally investigated. The primary noise field is emitted by a loudspeaker placed inside the cavity. The control signals are computed by the filtered-x LMS controller on the base of the error signal measured by the sensor (controlled microphone) placed inside the cavity. This allows controller computing the optimum voltage and phase to be supplied to the actuators in order to control the radiated noise in the attempt to reduce the global noise inside the enclosure.

### 3. BLOCK DIAGRAM FOR FEEDFORWARD CONTROL

The block diagram of a single-channel feedforward active control system is shown in Fig. 5. The primary disturbance is captured by the error sensor by the Disturbance path  $Pe$  to give  $d$ , and it is measured by the reference sensor by the Sensor path  $Ps$  to give  $z$ . The output of the secondary actuator impinges the error sensor via the Secondary path  $Ge$ , and also affects the reference signal via the Feedback path  $Gs$ .

In an adaptive feedforward control system, the signal driving the secondary source is obtained by properly filtering the reference signal via a digital controller so that to generate the correct control signals minimizing the instantaneous squared error  $Z(n) = e^2(n)$ . The adaptive filtering is realised by identifying the internal model of the plant response prior to the control system being switched on (off-line system identification) in order to estimate how changes in the error signal are affected by changes in the controller coefficients.



**Figure 5. Block diagram of a single-channel feedforward active control system**

Among the feedforward control algorithm, the Filtered-x LMS is the most widely used adaptive controller capable to track time-varying disturbances by updating the coefficients of the FIR filter so that to minimize a quadratic cost function given by the mean square of the error signal, [10]. The coefficients of such a filter adaptive are sequentially adjusted so that they evolve in a direction which minimizes the mean-square error, according to the following adaptation algorithm :

$$w(new) = w(old) - \mu \frac{\partial \hat{Z}}{\partial w}(old) \quad (1)$$

This is called the steepest-descent algorithm, where  $\mu$  is a convergence factor and  $\hat{Z}(n)$  is the quadratic cost function to minimize, defined as:

$$\hat{Z}(n) = E[e^2(n)] \quad (2)$$

where  $E$  denotes the expectation error.

Instead of updating the filter coefficients with an averaged estimate of the gradient, the coefficients can be updated at every sample time using an instantaneous estimate of the gradient, which is sometimes called the stochastic gradient. This update quantity is equal to the derivative of the instantaneous error with respect to the filter coefficients:

$$\frac{\partial e^2}{\partial w} = 2e(n)r(n) \quad (3)$$

where  $r(n) = [r(n) \cdots r(n-I+1)]^T$  is the vector of past values of the filtered reference signal.

The adaptation algorithm thus becomes:

$$w(n+1) = w(n) - \alpha r(n)e(n) \quad (4)$$

where  $\alpha = 2\mu$  is the convergence coefficient.

In practice, the filtered reference signal is derived by an estimated version of the true plant response represented by the plant model which prefilters the reference signal so that the measured error signal and the filtered reference signal are aligned in time to give a valid cross-correlation estimate. This can be implemented as a separate real-time filter,  $\hat{G}(z)$ , which is used to generate the filtered reference signal,  $\hat{r}(n)$ , as illustrated in Fig. 6.

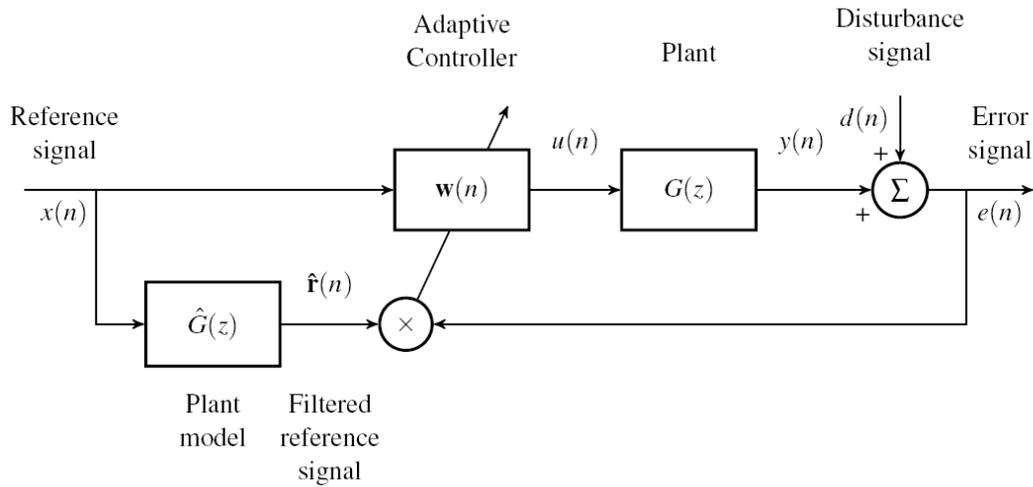


Figure 6. Block diagram of the filtered reference LMS algorithm

### 3. THE REAL-TIME CONTROLLER

Numerical simulations on local noise control using the Active Window model coupled with the filtered-x LMS controller are detailed in [8-9]. The active control system, whose capabilities in reducing noise in an enclosure were simulated, has been modified and discretized for its practical use in real-time. The models of the primary and secondary disturbances as well as the resulting error signal, have been replaced by inputs and outputs channels on the DSP control board connected to the concerned physical systems, i.e. the loudspeaker, the Active Window prototype and the control microphone, respectively. Moreover, the sound pressure inside the reference enclosure has been monitored by further three microphones connected to the DSP.

The SISO FXLMS controller has been developed in Simulink© block diagram environment. The C code has been generated in Real-Time Workshop© and implemented in a dSPACE DSP board. A DS1103 PPC Controller Board with real-time processor and comprehensive I/O has been used.

As it can be seen on Fig. 9 and Fig. 10, the graphical interface developed in dSPACE ControlDesk to manage the real-time signals is composed of two panels. The first one allows the user to command the state of the program running on the DSP with a red pushbutton and a LED indicating the state. This state can be *stop*, *pause* (meaning that the program is stopped but already initialized), or *start*.

Independently of the fact that the program is running, the acquisitions can be performed and the user can set a number of parameters, such as the duration of the acquisition, the sample time, the triggering, the path of the file to save, the name of that file, etc. A radiobutton allows to choose the type of the reference signal, which can be either a sine or a predefined chirp. A blue pushbutton can switch on or off the controller. Some of the controller parameters can be modified, such as the convergence coefficient alpha and the leakage factor beta. The main signals can be monitored on the right part of the panel. The reference signal is plotted in magenta, the input signal to the piezo actuators in red and the signal measured by the control microphone in green.

The second panel allows the user to monitor all the microphones (ie. the control microphone and the three monitoring ones) in order to estimate the resulting area of noise attenuation. The red pushbutton allows commanding the state of the program running on the DSP.

## 4. EXPERIMENTAL ACTIVITIES

### 4-1. Hardware description

A test apparatus consisting of a reverberant steel box having acoustic hard wall boundary conditions, has been designed, built and calibrated for these experiments. This experimental interior noise facility has a volume of 1 cubic meter with interior dimensions of 1.2 meters in height, 1.06 meters in width and 0.79 meters in length. The thickness of each steel panel is 30 mm.

Being transmission loss proportional to the structural mass, the box has been designed to reduce as much as possible the sound transmission through its faces with respect to that expected through the window prototype mounted on one face of the box.

The active window prototype consists of an aluminium frame, measuring 22.2 x 34.2 x 8.72 cm, containing three window panes with a transparent area of 32 x 20 cm. For this study, the window has been manufactured flat for ease of fabrication and testing. The physical and geometric characteristics of the prototype has been chosen to be similar to those of the windows of a civil aircraft. Two of the three panes are made of 0.94 cm thick glass and separated by an airspace of 0.80 cm. The third pane, which is made of acrylic, is 0.64 cm thick and is separated from one of the glass pane by a 2.30 cm airspace. The panes are supported by strips of elastomer. A silicon rubber is used to secure the windows in the aluminium frame. A sketch of the window frame and layers is shown in Fig. 4. Fig. 7 shows the active window prototype installed in the interior noise facility.

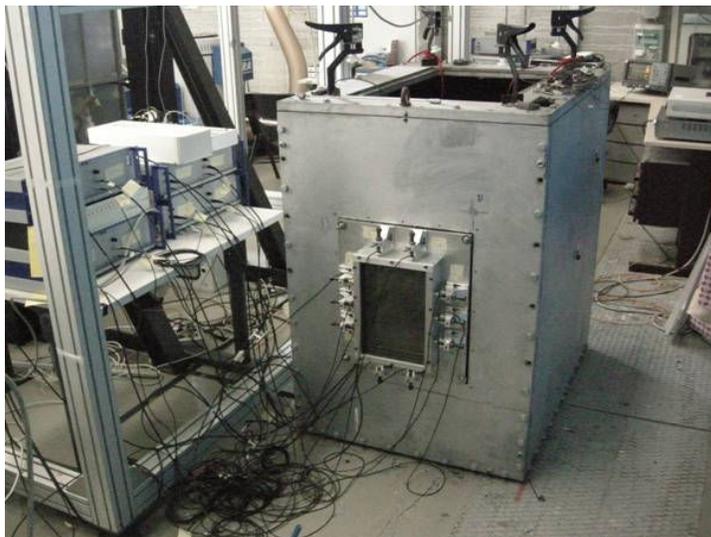


Figure 7. Active window installed in the interior noise facility

## 4-2. Test Set-up

The experimental campaign has been performed at the Smart Structures and Vibro-Acoustic laboratory of CIRA (the Italian Aerospace Research Centre). The loudspeaker and microphones arrangement is shown in Fig. 8. In this set-up, no. 1 error sensor, no. 3 monitoring sensors, no. 8 actuators and one reference signal are used. The control and the three monitoring microphones are respectively located at a distance of 20 cm, 25 cm, 40 cm, 42 cm from the window. No. 8 power amplifiers have been selected to drive the piezoelectric stack actuators. The primary noise source inside the enclosure has been driven by combining the DSP-based digital signal generator with an audio amplifier. The SISO (Single-Input Single-Output) architecture has been investigated. This means that only one error microphone has been used as input to the control algorithm while no. 8 actuators have been grouped and driven together by one channel of the controller. A series of high pass filters has been used to block unwanted low frequency noise from the microphone measurements. The power of the control signals has been increased by the respective amplifiers, which converted the inputs from the controller into corresponding voltage for actuators. Although actuators and sensors position has not been optimized, the experimental set-up has been designed to allow an exhaustive assessment of the system effectiveness. Such a set-up is suitable also for MIMO (Multi-Input Multi-Output) experiments. In that case, proper signals for each piezo actuator have to be computed taking into account the coupling factors existing between the error microphones and the secondary sources.

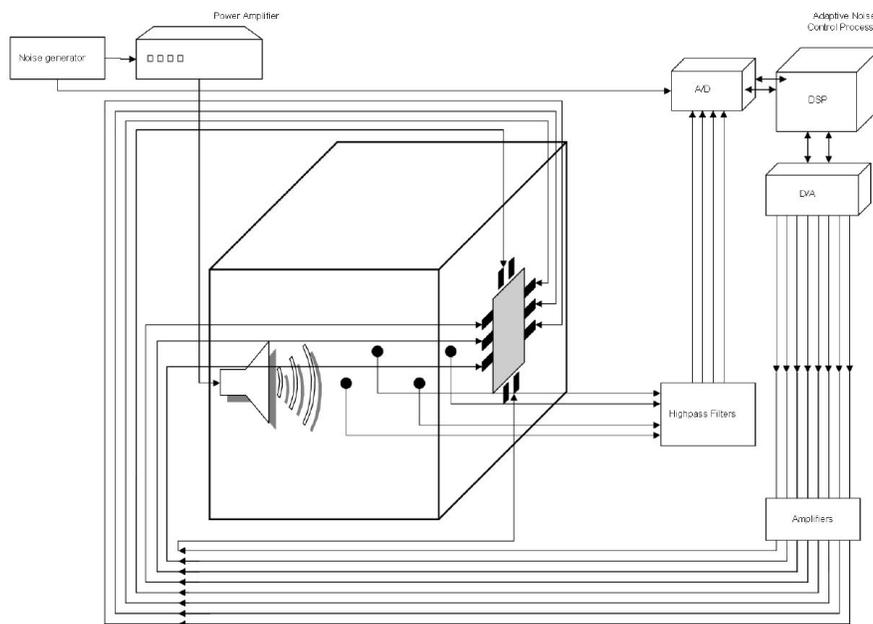
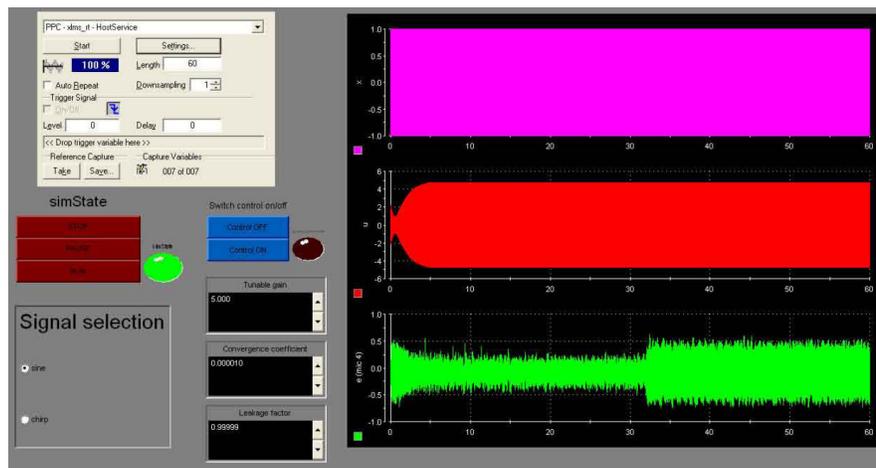


Figure 8. Sketch of the experimental set-up

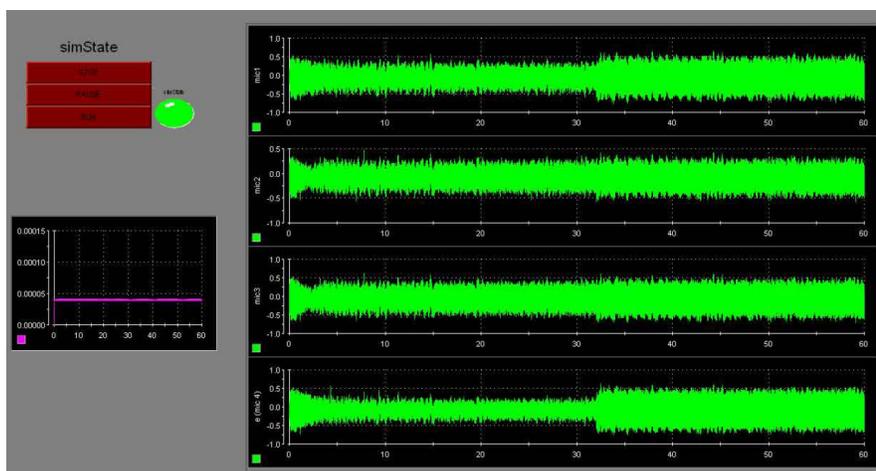
## 4-3. Experimental results

The control system capabilities in adaptively attenuating the acoustic field in the reference enclosure have been experimentally evaluated. Assuming that the modeled plant response of the window prototype, obtained in the earlier work, was accurate enough to represent the behaviour of the secondary path, the real-time levels of noise have been measured with and without control. Since the main impact in the interior noise of a turboprop aircraft is the acoustic impingement of the propeller, the disturbing noise has been imposed at 124 Hz and 150 Hz corresponding to the fundamental frequencies of a four/six bladed propeller. Although the real mechanism of sound excitation,

transmission, and acoustic radiation of aircraft windows is totally neglected in this set-up, it is felt to contain the most important features of the problem and therefore should provide a good understanding of the phenomena occurring when significant tonal noise has to be eliminated with ANC. Throughout the experiments, a sample time of  $5 \cdot 10^{-5}$  seconds has been used as well as a FIR filter length of 512 coefficients. Fig. 9 and Fig. 10 show the graphical interfaces developed in ControlDesk showing the acoustic measurements taken during the real-time experiments. The green signal on Fig. 9 is the time history of the pressure signal, i.e the error signal, measured by the control microphone when the disturbance is set to 124 Hz. Its left part shows the resulting sound pressure when the control is turned ON, while its right part shows the resulting sound pressure when the control is turned OFF. The magenta signal and the red signal are respectively the reference signal and the anti-noise. Fig. 10 shows the sound pressure measured by the monitoring microphones inside the reverberant enclosure. Further experiments have been performed by increasing the frequency of the disturbing noise up to 150 Hz.



**Figure 9. Real-time results of noise attenuation on the controlled microphone for the tonal disturbance (124 Hz)**



**Figure 10. Real-time results of noise attenuation on the monitoring microphones for the tonal disturbance (124 Hz)**

Tab. 1 summarizes the experimental results obtained in both cases of acoustic excitation, taking the difference between the root mean square pressure of the signal with control ON and OFF, then scaled in percentages and in decibel Sound Pressure Level.

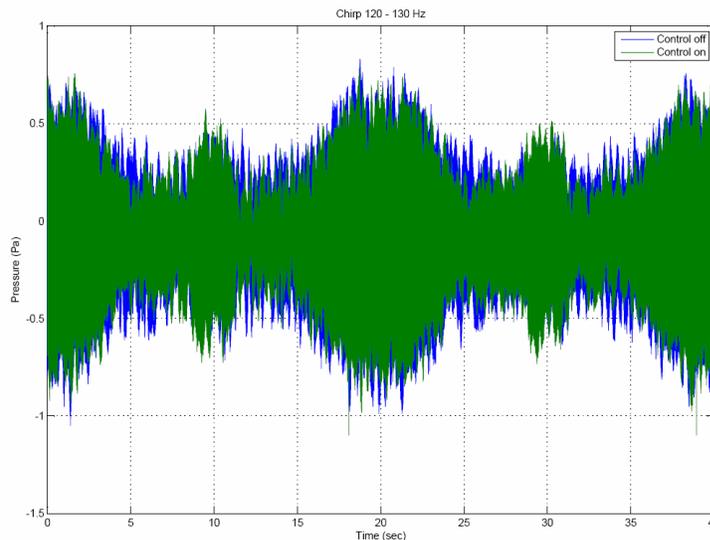
	Tonal disturbance at 124 Hz		Tonal disturbance at 150 Hz	
	Signal reduction (%)	Noise reduction (dB SPL)	Signal reduction (%)	Noise reduction (dB SPL)
control microphone	45,7	5,3	51,8	6,3
monitoring microphones				
mic. 1	42,3	4,8	36,1	3,9
mic. 2	20,5	1,9	10,6	0,9
mic. 3	13,6	1,3	16,8	1,6

**Tab 1. Summary of the results for the real-time noise control**

	Tonal disturbance at 124 Hz		Tonal disturbance at 150 Hz	
	Signal reduction (%)	Noise reduction (dB SPL)	Signal reduction (%)	Noise reduction (dB SPL)
numerical results	80,8	14,3	87,9	18,4
experimental results	45,7	5,3	51,8	6,3

**Tab 2. Comparison between the numerical results and the real-time experiments**

The adaptivity of the noise controller has been investigated as well by imposing a narrow-band disturbance modelled by a bidirectional linear chirp in the range of 120-130 Hz and with a duration of 10 sec. The real-time controller rapidly changed the filter coefficients to adapt itself to a disturbance varying both in amplitude and frequency starting from an initial state depending on the initial conditions. Although the control system exhibited promising levels of attenuation, Fig. 11, the controller performances have been limited by the high level of random noise captured by the microphones.



**Figure 11. Real-time results for a narrow-band disturbance (120-130 Hz)**

## 5. CONCLUSIONS

An active noise reduction concept applied to a aircraft passenger window prototype has been presented. The potential of the control system applied to the laboratory prototype has been experimentally demonstrated by comparing noise levels measured in a specific area inside an enclosed space in uncontrolled and controlled conditions. Results for the single-tone acoustic excitation showed the greatest reduction was obtained at the fundamental frequency of 150 Hz. Since this excitation frequency was approximatively equal to the structural-acoustic coupled resonance of the box cavity, as described in the earlier work, the higher signal-to-noise ratio of the acoustic response increased the degree of coherence between the reference signal and the disturbance, leading to meaningful reductions in noise level at the error sensor position. This result has been consistent with the numerical simulations detailed in [8-9]. Furthermore, it is noticeable that the controller performance measured in practice has been clearly degraded with respect to the predicted one, Tab. 2. These discrepancies, observed by comparing the measured and the predicted levels of noise suppression, can be attributed to two main factors. First, the ability of the practical feedforward controller to implement the frequency response required for perfect control, and second, the assumption that the signal measured at the error sensor is linear and time invariant as well as the physical system under control.

If these conditions are not fulfilled, it is generally necessary to remeasure the response of the plant over the timescale of the possible changes for control to be maintained. This process is called on-line system identification.

Finally, the experimental activity has been performed in a very noisy environment (laboratory conditions). This is confirmed by the high level of random noise measured in the listening room, whose effects have not been considered in the numerical simulations. Nevertheless, better results are expected by performing further experiments inside an anechoic chamber.

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