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DESIGN AND DEVELOPMENT OF AN ACTIVE CONTROLLED WINDOW WITH HIGH SOUND TRANSMISSION LOSS

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ABSTRACT

Improving the sound transmission loss (STL) of glazed facades is needed, as required by the 89/106/CEE European Directive, which imposes high STL values for building facades, whose weak part is generally constituted by the presence of windows, sometimes making them not adequate to observe the recently enacted requirements. As passive means (e.g. double windows and laminated glazing) were shown to be effective for increasing STL levels only in the medium-high frequency range of sound waves, in this paper an active control system for the coverage of a lower set of frequencies is experimented, where traffic and railway noise produces high levels of disturbance. This paper investigates the ASAC control system as applied on an experimental active control window prototype, focusing mainly on a dedicated technology that is able to improve its STL in the low frequency range, whose effectiveness has been shown by both Finite Element analyses and experiments.

KEY WORDS

ASAC System, Sound Transmission Loss, PZT Actuators, Finite Element Analysis.

1. INTRODUCTION

The 89/106/CEE European Directive, has made protection against noise a compulsory requirement for buildings. In fact, glazed facades often represent the main problem, as they can respect the strict limits imposed by national regulations only when using expensive solutions. The two main types of passive means for improving STL presently known are laminated glass technology and double glazing, but those methods do not work in the low frequency range: double glazing improve STL in the middle frequency range, while laminated glass panels are useful just to shift the coincidence effect towards higher frequencies [1]. As it can be deduced from the standard UNI 12354:2000, the overall sound reduction index for a generic wall depends on the sound reduction indices of the elements it is made up of and from flanking transmission paths. The first components for a generic façade is given by the insulation of windows and the insulation of opaque elements. It is possible to show [1] that the presence of windows make the opaque part ineffective in improving the overall sound reduction index above a certain point. In other words, windows are too weak in comparison with the opaque part and act as a preferred path for sound transmission. Therefore, the overall sound reduction index should be improved by enhancing the acoustic performances of windows, that are extremely weak in the range of frequencies close to resonances. Hence it is necessary to adopt active technologies that can enhance acoustic performances of windows in the low frequency range, where their resonance frequencies fall. Ref. [2] presents a full description of all the active approaches presently available, whose basic subdivision states between: Active Noise Control (ANC) and Active Structural Acoustic Control (ASAC). The authors have already explained in other contributions [1,3] that the first is not suitable for the purpose of improving windows' STL because it is based on the production of a cancelling wave that interferes destructively with the disturbing one: it means that some loudspeakers and microphones need to be installed in the receiving environment, and that their functioning should change according to the room shape and to the presence of people, that is clearly not feasible. For that reason the ASAC one was adopted for controlling glazed facades, which is performed by changing the vibration field of structures radiating noise. In this paper it will be shown that ASAC is really effective for sound reduction as both Finite Element simulations and experiments validated such a technology for glazed panels.

2. THE TESTED TECHNOLOGY FOR ASAC CONTROL

2.1 Overview of the Whole Control System

As anticipated in the introduction, the ASAC is suitable because both sensors and actuators are placed on the vibrating glass panels and decrease the noise source's intensity. In Ref. [4] piezoelectric patch actuators were shown to produce control actions not strong enough for glass panels (which has rather high stiffness). Instead piezoelectric stack actuators (PZT) are the best approach for this purpose [5], because they can provide high forces with very low displacements. In Ref. [3] it was shown also that 1 or 2 actuators are enough to properly control acoustic vibrations of glass: preliminary simulations showed that, according to the theoretical behavior of windows subject to acoustic excitations and controlled by one or two point forces, it is possible to reduce noise re-irradiation up to 15 dB. However in that case the real behavior of controlling actuators was approximated with point forces, neglecting further disturbances to glass panels, due to the stiffening structure they need work. When an electric field is sent to actuators like the ones depicted in Fig. 1, they undergo an elongation which transfers an impulse to the glass only in case they are stiffened on the other side. Such a stiffening structure interferes with the dynamic behavior of glass, which must be taken into account when forecasting the expected acoustic improvements provided by the ASAC system.

In the general case, ASAC control systems are characterized by the positioning of actuators and control sensors directly on the controlled vibrating source: they are fixed on glass panels to reduce glass vibrations and the radiated noise as a consequence.

Figure 1 Some Marketed PZT Stack Actuators

There are two types of ASAC control. The first is of feed-forward type, which requires for prior knowledge of disturbance through the use of a reference microphone: in the case of buildings this seems impractical, because it would require the installation of a microphone on the exterior of windows, which is not feasible for functional and esthetic issues. The second is the feedback type (Fig. 2): sensors are positioned on the vibrating surface to detect disturbance coming from the exterior thanks to the use of electronic filters, which analyze those signals and check the vibration induced by the noise; then actuators are switched and the controller separates the vibration induced by the disturbance from the action of PZT stack actuators: at this phase sensors acquire error signals, allowing the controller to compute the optimum voltage to be supplied to actuators in order to reduce the re-irradiated noise towards the interior. Control signals are sent by one amplifier, which converts the inputs from the controller into corresponding voltages for actuators.

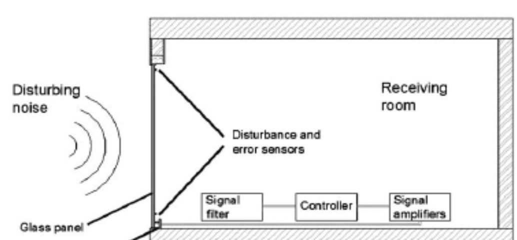

Figure 2 Feedback ASAC Control System

2.2 Design of the Control Strategy

It is shared that when many inputs and outputs are used in the control algorithm, the state space mathematical formulation is advisable [6]. It is used to simplify the equations of vibrational behavior for a glass layer [5]:

$$\ddot{\xi}_{mn} + 2\omega_n \dot{\xi}_{mn} + \omega_n^2 \xi_{mn} = \sum_{i=1}^{L} q_{mn}^{i} \quad (1)$$

into a set of first order differential equations, where both vibrations and re-irradiated sound is computed:

$$\begin{aligned} \dot{k} &= A_G \cdot k + B_G \cdot \dot{\xi} \\ y &= C_G \cdot \dot{k} + D_G \cdot \dot{\xi} \end{aligned} \quad (2)$$

where eq. (2-a) is devoted to the description of the plate vibration field (k), which is dependent to the system's input (ξ); eq. (2) gives back radiated sound (y), which is the final output of the whole system's functioning. The use of first order linear equation simplifies all the mathematical formulation, without renouncing to a thoughtful description of the system behavior. However we should consider that the radiating behavior of windows cannot be completely described by the use of radiation filters, as the state space approach would require. Hence we would suggest in our paper to use an integrated system where state space and finite Element simulations are used at the same time. We would like to make an integrated approach, where two mathematic features are used: at every iteration, state space computations are used to minimize the chosen cost-function, whose inputs are provided by the outcomes of the dynamic and acoustic analysis carried on by the Finite Element software program LMS VirtuaLab Acoustics™.

The main advantage of the integration of these two instruments is given by the ability of the second kind of calculation to produce reliable results, even when complex configurations of actuators fixed on glass panels are experimented. These reliable and accurate results are then exploited for the computation of the optimum control, required to minimize acoustic efficiency of the noise source structure, whose procedures are analytically rigorous and, as can be read in Refs. [5, 7], are generally based on the minimization of a cost function.

2.3 Proposal of One Technology for Controlling Buildings' Windows

The PZT stack actuators in Fig. 1 undergo a strain proportional to the voltage difference provided at their extremes. In order to transfer a certain amount of force to the surface on which they are applied, they need a stiffening structure on the other extreme point, whose role can be explained as depicted in Fig. 3: a stiffening contrast on the actuator.

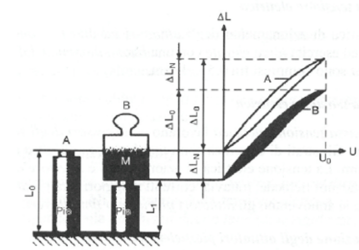

Figure 3 Force Transducer by PZT actuators to Plane Surfaces

In actual use, this system could be realized in a number of different ways: for instance actuators could be inserted between a stiffening structure bonded on the glass plate or on the fixed frame of the controlled window [1]. All the experiments described in the following chapters have been performed by stiffening the actuators through the use of one mass like in Fig. 4, because it is thought to be representative of the general solution for the final actuator, where it is required to produce control point forces.

3. DYNAMIC BEHAVIOR OF ACTIVE CONTROLLED WINDOWS

Both experiments and Finite Element Analyses have been performed on an actively controlled window prototype, where one stack actuator has been installed according to the configuration depicted in Fig. 3. The main aim of the experiments was to validate the model that will be used in the following paragraph to estimate the acoustic improvements which can be provided by such a system.

Figure 4 Experimental Set Up

The experimental set up (Figure 4) used for experiments was made up of one acquisition and control system, and the prototype of window: a rectangular window prototype (1.4x1.0) m wide and 0.006 m thick was built. Arranging a uniform tightening of the glass panel all along the border lines allowed to simulate a simply supporting constraint, by fixing the glass between four cylindrical Teflon made bars with a diameter of 0.01 m on the glass and other four bars under the glass. Two bars were 1.4 m long and other two where 1.0 m long to assure the presence of the constraint all along the perimeter of the prototype. An aluminum metal frame with a rectangular (0.13x0.05) m cross section (ALUSIC type produced by Sicomat s.a.s) was used to provide a uniform contact between glass and Teflon. Four equally spaced cap screws on the shorter side were screwed for the stability of the whole system, and subject to a uniform torque of 0.1 N·m. On the glass one actuator was installed, stiffened through the use of a 96.36 g mass (Fig. 5).

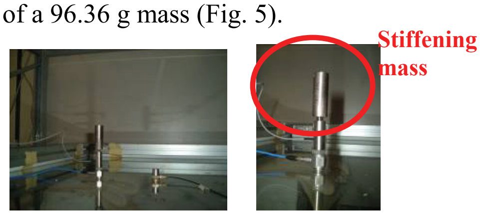

Figure 5 Installation of the Stack Actuator

The first step required the execution of a modal analysis (while the PZT stack actuator was switched off). The experimental set up was made of an instrumented hammer for exciting the structure, one accelerometer connected to a signal amplifier, one PXI™ (distributed by National Instrument) acquisition system, equipped with Labview™ software program for data elaboration.

A grid of points has been drawn on the glass, where measures would have been acquired through the accelerometer. At each measure the PXI acquisition system has recorded data relative to both force generation by the instrumented hammer and vibration generation on each of the points on the grid. At every excitation the accelerometer has been moved from on point of the grid to another. From the acquired data about vibration analyses it is then possible to compute the Response Frequency Function of the glass, and then the modes of the glass have been determined. Table 1 shows the very low shifts between experimental and numerical results.

Table 1 Experimental and Numerical Modal Analysis

MODI m,n	lastra + attuatore	lastra	ERRORE ASS	ERRORE %
1.1	25.5	25.50	0.00	0
2.1	47	47.50	0.50	1.05
1.2	66.5	67.00	0.50	0.75
3.1	85	85.50	0.50	0.58
2.2	89	89.00	0.00	0.00
3.2	116.5	129.50	13.00	10.04
4.1	133.5	134.50	1.00	0.74
1.3	141	141.00	0.00	0.00
Non definito	164.5	166.5	2.00	1.20
4.2	181	181.50	0.50	0.28
Non definito	187.5			
4.1	200	201	1.00	0.50
3.3	204	203.5	0.50	0.25
4.2	245.5	245.5	0.00	0.00

Numerical data have been generated using ANSYS™ software tool. It is able to overcome other available analytical methods [8], because it can take into account the presence of the actuator with its stiffening mass. The glass plate has been modeled as a shell type plate 0.006 m thick, (1.4x1.0) m wide, with a Young modulus of 6.9x10 MPa, density of 2450 kg/m^3, Poisson coefficient of 0.33. The optimum mesh size was chosen as a squared type element with a 0.02 m side, after an iterative refinement starting from elements with a side size of 0.05 m. Before performing the modal analysis an element simulating the actual actuator has been added on the glass: one steel parallelepiped shaped volume with a 0.02 m long side, Young modulus of 2.5x10^5 MPa, Poisson coefficient of 0.33 and density equals to 22158 kg/m^3. The small shifts between experimental and numerical results (on the average 1.5%) show the validity of this model.

As second validation it was decided to compare the window prototype's dynamic behavior, when excited by point forces comparable with the one which can be provided by the actuator at low frequencies. The same experimental set up for signal acquisition as before has been used during the experiments, but with a different apparatus for signal generation: in Fig, 6 the actuator with its signal amplifier is photographed in case *a* (purchased by PHISIK INSTRUMENTE), such as the load cell for force monitoring in case *b* (by PCB). All the data have been recorded by a 14 bit National Instruments acquisition board of case *c*. In Fig. 7 we can see the glass plate vibration when excited by the actuator's 0.17 N force at 80.8 and 141.6 Hz respectively. First of all the necessary voltages to produce a 0.17 N point force have been analyzed; then the vibration behavior generated by such a force on the glass has been monitored.

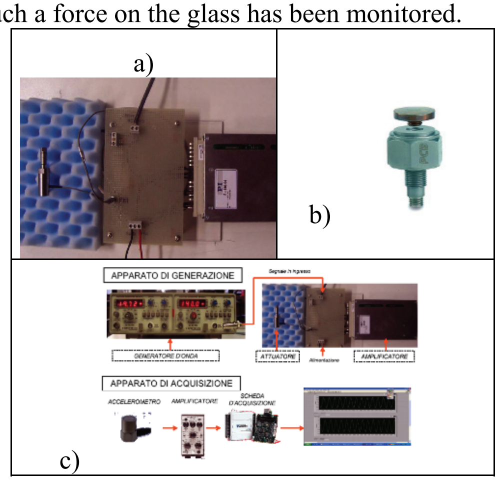

Figure 6 Set Up for Generation of Control Forces

In Figure 7 we can appreciate the practical agreement between numerical and experimental measures.

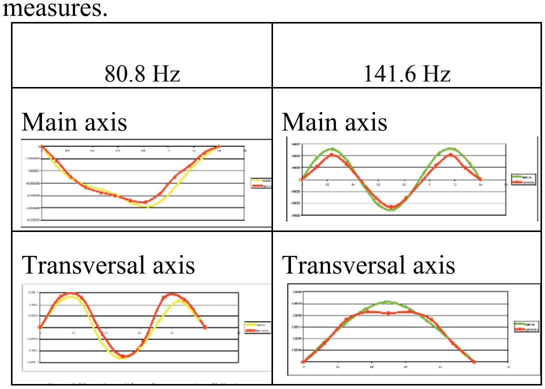

Figure 7 Numerical & Experimental Vibration Analysis

4. ACOUSTIC IMPROVEMENT DUE TO PZT CONTROL SYSTEM

Once that a numerical model for simulating the acoustic behavior of actively controlled windows has been validated, it can be used to infer acoustic improvements that can be brought by such a technologic solution. This estimation has been pursued by comparing noise levels monitored for two different conditions:

1. Free field irradiation,
2. Irradiation into a reverberating room,

When windows are: a) Standard (no control);

b) Actively controlled through ASAC.

All the simulations have been carried out in the case of disturbing noise emitted at the resonance frequency of 140 Hz, because a parametric study has shown it to be the most efficient mode in the low frequency range. Its intensity has been chosen according to the one which can be emitted by a lorry in the nearby (about 2 m far) passing at an average speed (70 km/h) [9]. Conditions 1-a and 1-b have been simulated by assuming that noise is re-irradiated into an anechoic room (enclosed by totally absorbing walls) (1x1x1.4) m large. The model has been implemented in the VirtuaLab™ software, through two steps: first it has been verified that the dynamic behavior of the plate subject to every load condition was the same as the ones computed by the validated ANSYS™ model. Then the vibration tool of the software has been used together with the acoustic tool, in order to infer its performances. In Fig. 8-a we can appreciate free-field noise re-irradiation in the non controlled case, while Fig. 8-b is referred to the controlled case: the highest noise level drops from 62.4 to 49.4 dB (with a 13 dB decrease). A bit, but not too much, different is the situation for the reverberating room in Fig. 9. It is supposed that noise is re-irradiated inside a (2.4 x 2.5 x 2.8) m large room, with the following characteristics: ceiling acoustic impedance was assumed equals to 650-6000i kg/(m^2·s), the wall surrounding the window acoustic impedance equals to 10000-1000i kg/(m^2·s), for the other walls 7700000-100i kg/(m^2·s), and the floor perfectly reflecting. In this case we have a reduction of 9.3 dB, and in the right framed part of each figure it is shown that at a 1m distance from the irradiating window, the maximum noise level is reduced of 10.1 dB.

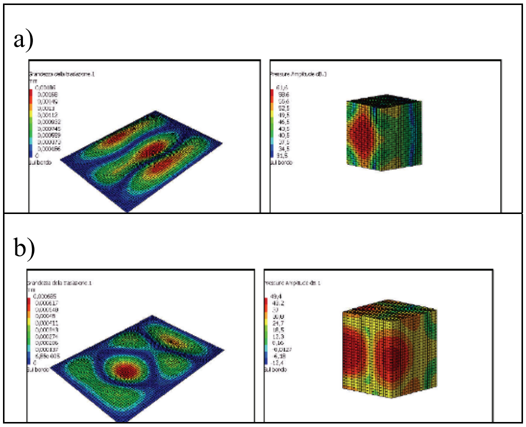

Figure 8 Free-Field Noise Reduction Due to the Use of ASAC Control

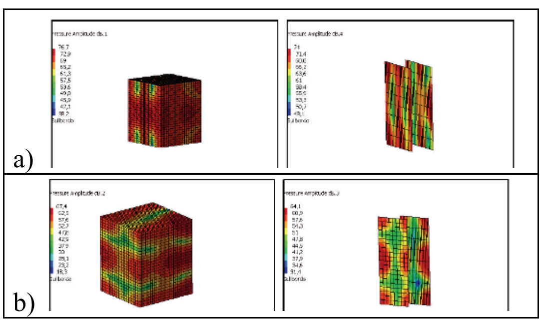

Figure 9 Noise Reduction Due to the Use of ASAC Control Inside a Reverberating Room

5. CONCLUSIONS AND FUTURE RESEARCH

It is straightforward to conclude the big step forward that can be represented by ASAC. Moreover, this research step has been made more reliable, because simulation were conducted taking into account the real properties of the technology used for vibration control (PZT actuator plus its stiffening structure), which modifies the theoretical behavior that would be attributable to glass panes subject to merely point forces (as assumed by analytic models). So far we can conclude that the presence of the stiffness on the PZT stack actuator does not compromise its effectiveness. Other surveys about different technologies will be made, analyzing how they perform throughout the whole noise spectrum.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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