SMART PANELS USING PIEZOELECTRIC ACTUATORS FOR ATTENUATION OF NOISE IN CLOSED ENVIRONMENTS

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Abstract. *In this work a numerical and experimental study for attenuation of mechanical vibration in smart panels is carried out aiming to attenuate noise in rooms. These structures, located in the noise propagation path, work as active walls reacting in opposition to the vibratory movement induced by the sound and reduce the transmission of sound waves to another environment. A finite element model was developed as a basis for the development of the experimental project. This allowed the inclusion of the dynamics of the piezoelectric element as an actuator and the control of vibration in open loop. The design of a system consisting of a single panel and of a double panel presented reductions of mechanical vibration and sound pressure. These reductions have demonstrated perspectives for use of the isolation systems based on panels in noise attenuation and of the use of the piezoelectric elements as actuators for this application.*

Keywords*: Smart Panel, Vibration control, Noise attenuation, Piezoelectric*

1. INTRODUCTION

High levels of vibration and noise associated to machines and equipment in operation are a problem because they cause bad performance of the machine and discomfort to the users. These high levels of vibration and noise can be related to misaligning or unbalancing of rotating parts, wearing of components, inadequate lubrication or incorrect assembly. Thus, the development of techniques of noise control and vibration is necessary, in particular using solutions involving active control (Souto, 2008). Together with the control system are the sensing elements and actuators capable to capture vibration/noise signals and to act by applying forces in order to reduce the level of mechanical vibrations. Among the elements used for such purpose there are the piezoelectric materials (PZT´s), which can be used as sensors and actuators for the control of vibration and noise when connected to structures in vibration. The piezoelectric materials have the capability of reciprocity in terms of conversion between electric field and mechanical deformation, beyond excellent capability of response in frequency in a large band (Qiu, 2006).

In a recent work, Silva (1998) presented a theoretical and experimental study of one technique of active control of vibration and noise for a structure of parallel circular plates with a diameter of 100mm, in which PZTs were connected as actuators. Attenuations of 9dB in transmitted noise for frequencies above 1,6KHz were obtained, using feedforward and feedback as control strategies. Petitjean et al. (2001) developed a theoretical and experimental work comparing some arrangements of sensors and actuators as well as strategies of feedback and feedforward control in a sandwich type fiber panel. In this panel eight PVDF's (Polyvinylidene Fluoride) sensors and eight PZT's sensors were glued in opposing sides of the panel.

Lee et al. (2002) studied a hybrid system of panels for reduction of the noise transmission. According to these authors, the conception of hybrid panels is an appropriate combination for noise control. The passive control acts on the high and mid frequencies and the active on the low frequencies. In their work they showed the possibility to attenuate the sound pressure level between 8dB and 13dB in the first and second mode by using active control, and 5dB with passive control by using a shunt circuit. Gardonio et al. (2004, 2004a) presented a theoretical and experimental study of intelligent panels for reduction of sound transmission, with sixteen decentralized control units. The panels were conceived with pairs of sensors of acceleration and piezoelectric actuators connected to them and a feedback strategy for the control system was adopted. Attenuations between 9 and 17dB for the kinetic energy of the plate and sound transmission were obtained, respectively. Carneal et al. (2004) conducted an analytical and experimental inquiry of the control of sound transmission in double panels, having used piezoelectric actuators. The application of their study was based on the transmission of noise from the outside to the inside of an airplane. Baudry et al. (2005), in turn, studied the active control of vibration using a combination of PZT actuators and PVDF sensors, decentralized and distributed on a panel. In their case, the performance and the stability of the system of active control was analyzed for several combinations of pairs of sensors and actuators, for the frequencies of 520Hz, 550Hz and 680Hz.

Kim et al. (2006) presented a work showing the performance in the reduction of noise with intelligent piezoelectric panels linked to a shunt circuit. The authors affirmed that reductions in sound pressure levels of the order of 9 to 15dB were obtained. Qui et al. (2006) developed a work in which an active control of vibration for plates was described, using a self-sensing actuator and adaptive control. According to these authors, in the self-sensing actuator, the piezoelectric element works either as a sensor or actuator, reducing the required number of piezoelectric elements in a structure. These authors observed that the vibration of the plate was suppressed successfully in multiple frequencies of the resonance below 1KHz.

A less explored aspect in the literature is the reduction of noise at frequencies below 200Hz. In this case, the passive control needs thick elements that occupy great space. It also requires active control controllers and actuators that respond at low frequencies. In this work, the control of vibration of the panels at resonance (around 50 Hz) was investigated, focusing the investigation in the low frequency range. The strategy of feedforward control is applied in a system of single and double panels, having a piezoelectric actuator glued in the center of the panel, aiming at reducing the vibration level of the panel and consequently the noise in closed environments which made use of such systems. Results of attenuation of vibration and sound pressure are presented.

2. SIMULATION

To begin, the system investigated consisted of a single panel of aluminum with clamped edges, with a piezoelectric element glued in its center. A uniform pressure field was created on one side of the panel and an electrical voltage applied to the PZT, which was placed on the other side. In this case, when the panel is deformed by the effect of pressure, the PZT is deformed so as to oppose the deformation of the panel.

2.1. Simulation of the piezoelectric plate glued to the aluminum plate (smart panel)

In the model, the piezoelectric plate was glued at the center of an aluminum panel with dimensions 488 x 408 x 1mm, as shown in Fig. 1. A finite element mesh was created in such a way that the nodes of the aluminum panel and of the PZT plate should coincide for a perfect link between the plate and panel. The edges of the aluminum panel were clamped.

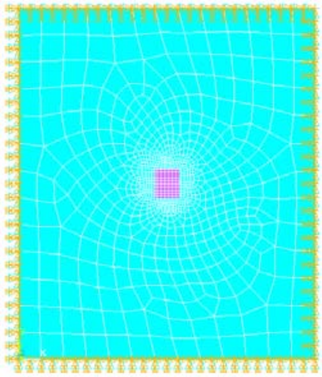


Figure 1. Smart panel with piezoelectric actuator

Modal and transient analysis analysis for the smart panel were developed. The results of the modal analysis were the modes of vibration of the panel and the natural frequencies associates to these modes. In this work, the focus was the first mode of vibration, which presented a natural frequency of 48,75Hz. As for the transient analysis, a sinusoidal pressure field with a frequency coincident to that of the fundamental mode of the panel was applied. At the same time, a sinusoidal and opposing electric field was applied in the piezoelectric plate, in order to produce an opposing force to the panel vibration, applied at the center of the smart panel. This simulation showed that with this PZT it was possible to obtain a reduction of approximately 37% in the level of vibration.

2.2. Characteristics of the piezoelectric actuator

In general, the piezoelectric effect can be defined as the conversion of mechanical energy into electric energy (direct mode) or the conversion of electric energy in mechanical energy (inverse mode). Thus, a piezoelectric system consists of two coupled physical systems, mechanic and electric (Moheimani et al. 2006).The mechanical deformation can be calculated by the constitutive equation of a piezoelectric ceramic (Eq.(1)):

$$S = s\sigma + dE \tag{1}$$

where S is the deformation, s the elastic coefficient, σ the mechanical tension, d is the piezoelectric coefficient and E the applied electric field.

In the simulations, the finite element program ANSYS was used. This program presents an element to model the PZT, enabling mechanical and electrical energy to be converted into each other (Furukawa et al. 1997, Hernandes, 1999, Johnson, 2005). A matrix of dielectric constants (permittivity), piezoelectric matrix (piezoelectricity) and matrix of elastic coefficients (compliance) is required (Forster et al. 2000, Chen et al. 2003). The values of the piezoelectric properties employed in the simulation are presented in Tab. 1. For the simulation, a piezoelectric plate with dimensions of 38 x 32 x 0,2 mm was used, in which a sinusoidal electric field of 100Vpp in the frequency of 50Hz was applied.

Table 1. Values of the piezoelectric properties.

PROPERTIES OF THE PZT	
Piezoelectrictricity	$10^{-12}\times\begin{bmatrix}0 & 0 & 281{,}25\\ 0 & 0 & 281{,}25\\ 0 & 0 & -390\\ 0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}(m/V)$
Permittivity	$\begin{bmatrix}1.2 & 0 & 0\\ & 1.2 & 0\\ \text{sym} & & 1.2\end{bmatrix}$
Compliance	$10^{-11}\times\begin{bmatrix}1{,}515 & -0{,}530 & -0{,}530 & 0 & 0 & 0\\ & 1{,}515 & -0{,}530 & 0 & 0 & 0\\ & & 1{,}515 & 0 & 0 & 0\\ & & & 1{,}923 & 0 & 0\\ & \text{sym} & & & 1{,}923 & 0\\ & & & & & 1{,}923\end{bmatrix}(\mathrm{N/m^2})$

3. EXPERIMENTAL SETUP

The experimental setup is primarily based on the separation of two environments through a system of smart panels. In the first environment, a source of sound pressure is placed (the source of excitation) that generates vibrations at the panel. As the panel vibrates, the sound produced in one environment reaches the other. In the side of the latter environment, an opposite force is applied through the piezoelectric actuator. In this case, the signal of sound pressure from one side of the panel is captured and passes through the control system, which generates an electric signal for the piezoelectric actuator to move in the opposing direction of the movement of the panel.

3.1. Control system

In this work, a control system consisting of a filter of eighth order, two amplifiers and retardation phase block was used to control the level of vibration of the smart panel and the feedforward control strategy was adopted. The vibration signal of the smart panel, collected through a sensor, was processed by the control system, which in turn generated an output in proportion to the mechanical vibration imposed to the smart panel. The block diagram with the transfer functions of each stage of the control system is shown in Fig. 2. Two amplifiers were used, one to adjust the input signal being transferred to the controller (Ke) and the other to provide a gain at the output of the control (Ks). A low-pass filter of eighth order, shown in four stages of filters of second order (Filter 1 - 4), was used to cut off frequencies above 50Hz. A retardation phase block aimed at providing an opposing signal to the displacement of the smart panel, for reduction of its deformation.

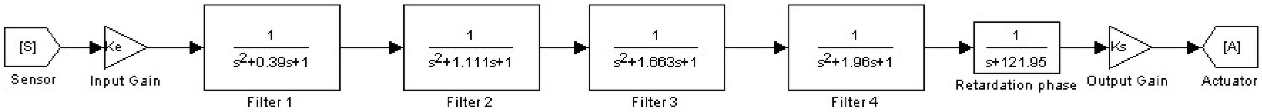


Figure 2. Block diagram of the controller

3.2. Experimental test

The test system is shown in Fig. 3, which consisted of an aluminum plate and one piezoelectric element glued at its center, being called as smart panel. The size of the plate is 520 x 440 mm and its thickness is 1 mm. The plate is clamped at the four edges by a strip with a width of 16 mm, so that the vibratory area is 488 x 408 mm (as adopted in the simulation previously described). The size of the PZT element is 38 x 32 mm and its thickness is 0.2 mm. The material properties of the aluminum are shown in Table 2, which are in agreement to values of the literature.

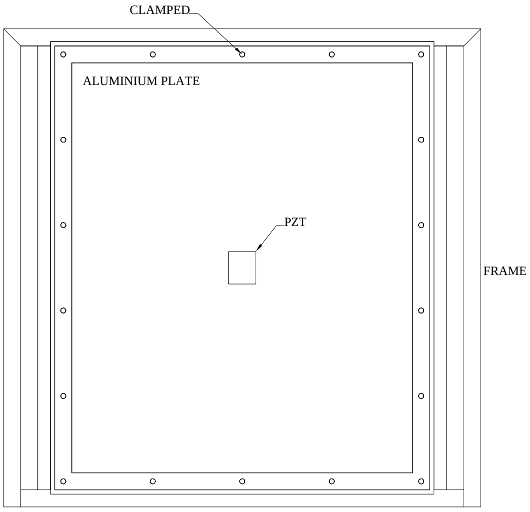


Figure 3. Smart panel with PZT in its center

Table 2. Values of the properties of aluminum.

PROPERTIES OF THE ALUMINUM	
Elastic modulus (N/m^2)	7,0 x 10^{10}
Poisson ratio	0,35
Density (kg/m^3)	2432,8

In Figs. 4 and 5 two experimental configurations that were employed are shown, including the control system. In the two cases the vibration of the plate was originated from a source of sound pressure. In the first experiment, Fig. 4, the signal of sound pressure picked by a microphone (sound level meter) passes through the control system, which in turn applies an opposing electric tension in PZT actuator, in order to reduce the level of vibration of the smart panel. In the second experiment, Fig. 5, the input signal sent to the control system is picked by the piezoelectric plate connected to the plate which receives the sound pressure directly (plate 2 in Fig. 5); therefore, the signal sent to the control system comes from the vibration of this plate.

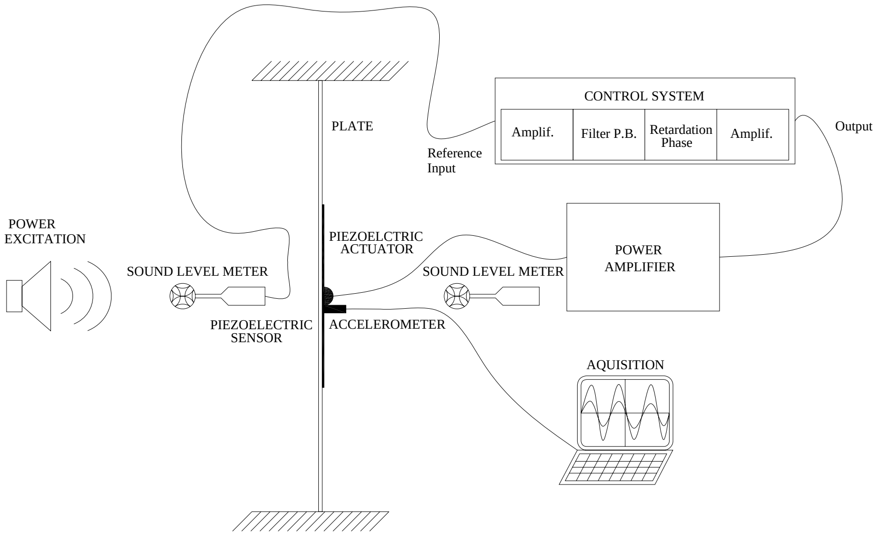


Figure 4. Experimental setup with one panel

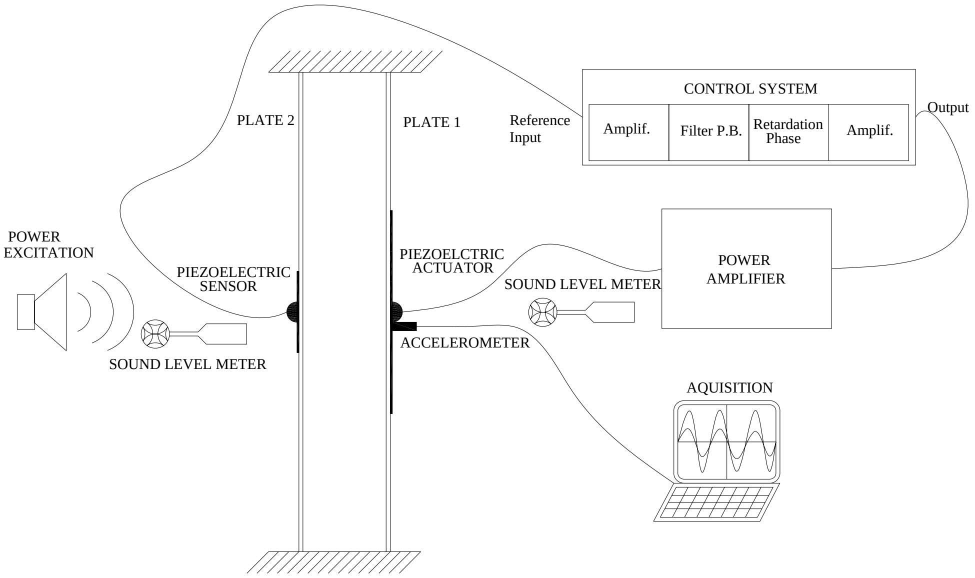
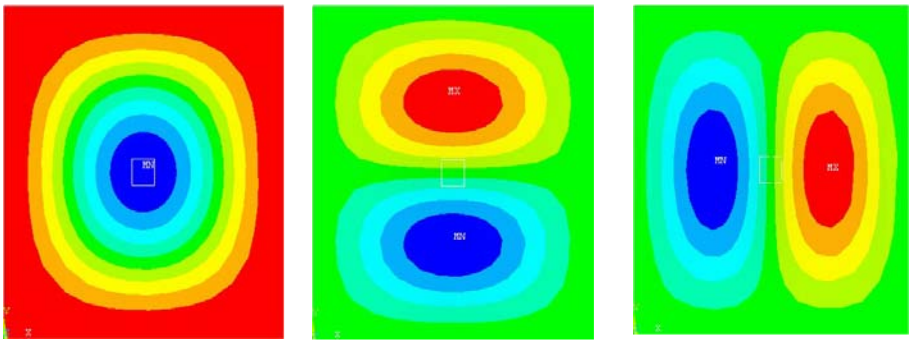


Figure 5. Experimental setup with double panel

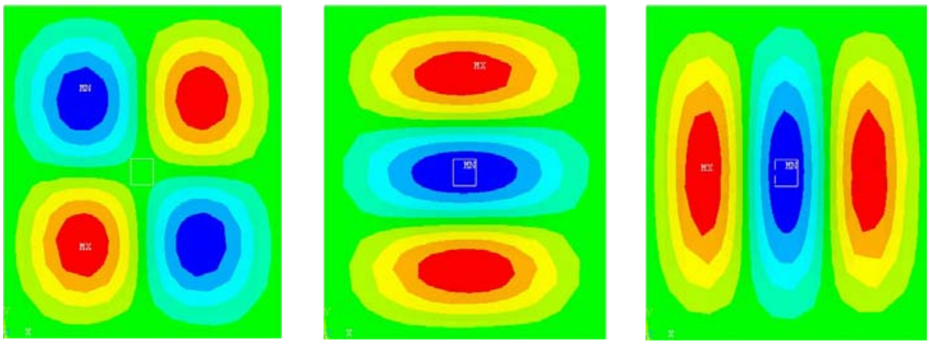
4. RESULTS AND DISCUSSION

4.1. Results of numerical modal analysis

The modal analysis of the smart panel, for a single panel, shown in Fig. 6 was performed using the commercial finite element software ANSYS. The material properties of the piezoelectric element (PZT) and of the aluminum shown in Tab. 1 and Tab. 2 were used in the analysis. The size of the vibrating area is 488 x 408 mm. In the finite element model, it was assumed that the four edges of the aluminum plate were clamped. The ANSYS element used to model the aluminum plate was Shell 93, with 8 nodes and 6 degrees of freedom per node. The element used to model the PZT was 3D Solid226, with 20 nodes and 4 degrees of freedom per node. The first six modes of vibration of the smart panel are shown in Fig. 6. In Tab. 3 the respective natural frequencies of such modes are shown.



first mode (*a*) second mode (*b*) third mode (*c*)



fourth mode (*d*) fifth mode (*e*) sixth mode (*f*)

Figure 6. Results of the simulation with finite elements

Table 3. Values of the natural frequencies.

MODE	FREQUENCY (Hz)
first	48,75
second	88,43
third	109,62
fourth	146,40
fifth	152,38
sixth	200,00

The focus was on the attenuation of mechanical vibrations in the frequency of the first mode. It should be noted that in this mode the level of displacement of the panel is more intense providing a better signal to be captured by the sensors.

4.2. Results of numerical trasient analysis

In the transient analysis a comparison was made between the response of the system with and without the active control. In the case the active control was on, an electric field was applied to the PZT opposite to the sound pressure applied to panel. The result is shown in Fig. 7 for a single panel, in which a reduction of approximately 37% in the amplitude of the vibration signal of the smart panel was obtained. The simulation with the piezoelectric element glued to the aluminum plate and with the system of control acting shows a possibility for the future development of an ideal size of the piezoelectric actuator that will be able to provide greater level of attenuation in panel systems.

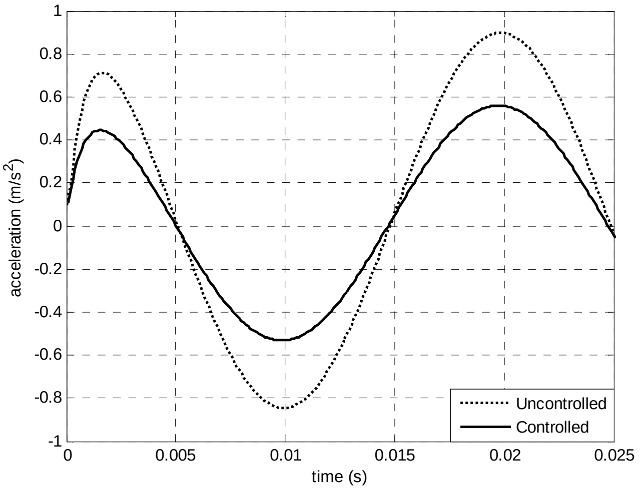


Figure 7. Simulation of smart panel with application of control

4.3. Results of experimental modal analysis

For the experimental modal analysis, the smart panel (single panel) was divided into rectangular elements the dimensions of which were 20 x 24,5 mm and it is shown in Fig. 8. Measurements were taken in each corner of these elements. A reference accelerometer was fixed at the central point of the panel and another (traveler) accelerometer was moved around the 441 points of measurement. In each measurement, a ratio was made between the respective spectral amplitudes (corresponding to the frequency of resonance of the first mode) from the measurement at the central point to each of the respective points in which the traveler accelerometer was placed at a time. This procedure was adopted for the system with and without the active control. In both cases the vibrating shape of the panel in the first mode was the same.The result of the modal test of the smart panel is shown in Fig. 9. In both situations the largest vibration displacement was at the center of the panel, as expected.

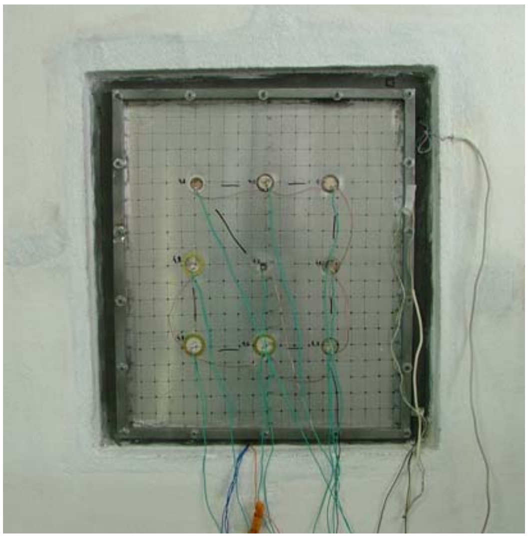


Figure 8. Experimental smart panel

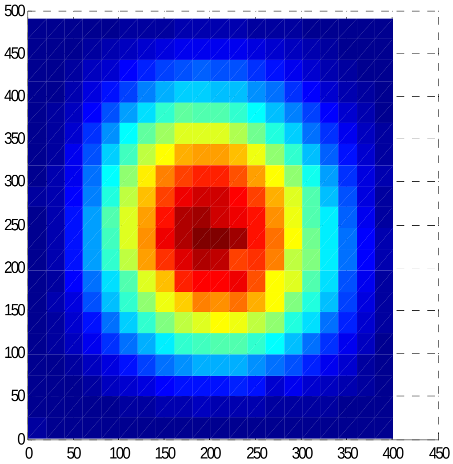


Figure 9. Experimental smart panel

4.4. Results of experimental transient analysis

For each experiment the mean value from five samples was taken as the obtained reference attenuation. The following attenuations were calculated: on the sound pressure, from the reading of the sound level meters; on the vibration signals, in the time and frequency domain. For the experiment of Fig. 4 (single plate) a mean attenuation of sound pressure of approximately 10,9dB in the frequency of interest was found. In Fig. 10, it is shown the result of one of the vibration measurements of the smart panel in the time and frequency domain, picked from the accelerometer. In this experiment, a second mode of vibration of the panel was also excited. It can be observed that it was also possible to attenuate this mode in 3,3 dB, approximately. The values of the attenuations of the levels of vibration and sound pressure for five sets of measurements conducted in this experimental setup are shown in Tab. 4.

Table 4. Values of the attenuation of mechanical vibration and sound pressure of the experimental setup of Fig. 4.

TIME DOMAIN (dB)	FREQUENCY DOMAIN (dB)	SOUND PRESSURE (dB)
8,5	15,5	11,3
6,5	14,7	11,3
7,4	14,7	10,6
6,8	14,3	10,8
6,7	14,1	10,7

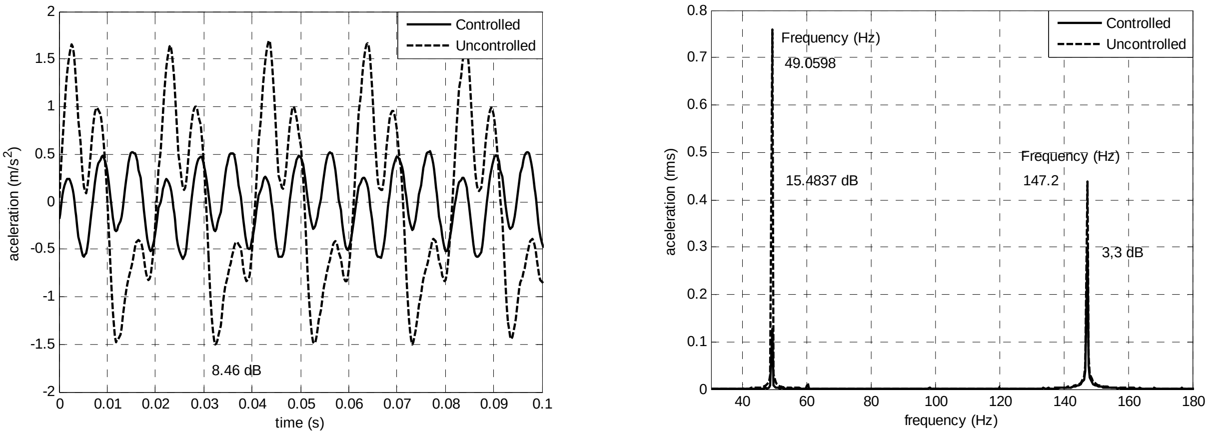


Figure 10. Vibration signatures and respective spectra for the experimental setup of Fig. 4.

For the experiment of Fig. 5, mean attenuation of sound pressure of approximately 6,4dB in the frequency of interest was found. The result of one of the vibration measurements in the time and frequency domain are shown in Fig. 11, picked by the accelerometer. In Tab. 5 it is shown to the values of the attenuations of the levels of vibration and sound pressure for five sets of measurements collected in this experimental setup.

Table 5. Values of the mechanical vibration and sound pressure of the setup experimental of Fig. 5.

TIME DOMAIN (dB)	FREQUENCY DOMAIN (dB)	SOUND PRESSURE (dB)
6,6	6,7	6,9
6,6	6,7	6,9
5,5	5,5	5,6
6,1	6,0	6,2
5,9	6,0	6,3

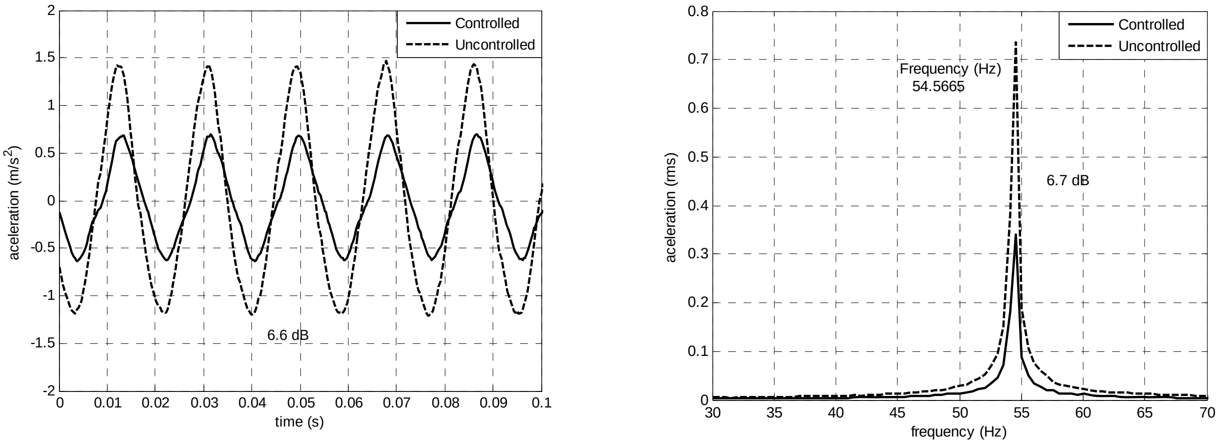


Figure 11. Vibration signatures and respective spectra for the experimental setup of Fig 5.

The control system used with the piezoelectric actuator was capable to attenuate vibration and sound pressure in the two types of adopted experimental configurations (single and double panels). The experimental setup of Fig. 4 (single panel) showed greater attenuation level than the experimental setup of Fig. 5 (double panel). However, in the first experiment a microphone was used to pick the input signal sent to the control system, whereas in the second experiment the signal was picked through a piezoelectric sensor connected to the outside panel. Therefore, it is not possible to affirm that a system attenuates more than the other, but is possible to confirm that both systems reduced the mechanical vibration and the transmitted noise for low frequencies, when the active control was on.

5. CONCLUSIONS

According to results obtained in experimental tests and simulations it is possible conclude that the structure of simple panel and double panels with an piezoelectric actuator glued in the center, showed reductions in mechanical vibration when a control system was in operation . It was observed that the strategy of the control feedforward control showed efficiency for the system of simple and double panels. As a result, reductions of sound pressure level in the environment were observed, in one case reaching 11 dB. With the simulation of the control system acting on the panel, it will be possible to determine the size of the piezoelectric actuator that would provide greater attenuation of vibration for the same power applied.

6. REFERENCES

Baudry, M., Micheau, P., Berry, A., 2005, “Decentralized harmonic active vibration control of a flexible plate using piezoelectric actuator-sensor pairs”, Journal of the Acoustical Society of America, v. 119, pp. 262-277.

Carneal, J. P., Fuller, C. R., 2004, “An analytical and experimental investigation of active structural acoustic control of noise transmission through double panel systems”, Journal of Sound and Vibration, v. 273, pp. 749–771.

Furukawa, C. M., Buiochi, F., Matuda, M. Y., Adamowski, J. C., 1997, “Modeling power piezoelectric transducers”, Congresso Brasileiro em Engenharia Mecânica.

Gardonio, P., Bianchi, E., Elliott, S. J., 2004, “Smart panels with velocity feedback control systems using triangularly shaped strain actuators”, Journal of the Acoustical Society of America, v. 117, pp. 2046 – 2064, Dec..

Gardonio, P., Elliott, S. J., 2004a, “Smart panels for active structural acoustic control”, Smart Materials and Structures, v. 13, pp. 1314–1336, Jul..

Hernandes, J. A., Almeida, S. F. M., Nabarrete, A., 1999, "Stiffening effects on the free vibration behavior of composite plates with pzt actuators", Congresso Nacional de Engenharia Mecânica.

Johnson, R. L., 2005, "Characterization of piezoelectric ZnO thin films and the fabrication of piezoelectric micro-cantilevers", Thesis D.Sc., Iowa State University, Iowa, U.S.A.

Kim, J., Jung, Y. C., 2006, "Piezoelectric Smart Panels for Broadband Noise Reduction", Journal of Intelligent Material Systems and Structures, v. 0, pp. 1 – 6.

Lee, J. K., Kim, J., Rhee, C. J., Jo, C. H., Choi, S. B., 2002, "Noise reduction of passive and active hybrid panels", Smart Materials and Structures, v. 11, pp. 940–946.

Moheimani, S. O. R., Fleming, A. J., 2006, Piezoelectric transducers for vibration control and damping, Germany, Springer Science.

Petitjean, B., Legrain, I., Simon, F., Pauzin, S., 2001, "Active Control Experiments for Acoustic Radiation Reduction of a Sandwich Panel: Feedback and Feedforward Investigations", Journal of Sound and Vibration, v. 252, pp. 19 – 36, Aug..

Qui, J., Haraguchi, M., 2006, "Vibration control of a plate using a self-sensing piezoelectric actuator and an adaptive control approach", Journal of Intelligent Material Systems and Structures, v. 0, pp. 1-9.

Silva, S. A., 1998, "Controle ativo de vibração e ruído em estruturas flexíveis utilizando atuadores piezoelétricos", Tese de D.Sc., UFPB, Brasil.

Souto, R. S., 2008, "Active control of vibration in plates using piezoelectric actuators - application the attenuation of noises in closed environments", Tese de D.Sc., UFPB, Brasil.

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