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EXPERIMENTAL IMPLEMENTATION OF SWITCHING AND SWEEPING PIEZOELECTRIC PATCH VIBRATION ABSORBERS

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This paper presents experimental results on the implementation of switching and sweeping piezoelectric patch vibration absorbers to control the flexural response of a thin rectangular panel. The panel is equipped with five piezoelectric patches, which are connected to time-varying RLC-shunts. The inductive and resistive elements of the shunts are varied according to two laws. In the first one, they are iteratively commuted over a given set of values to cyclically control the resonant response of target flexural modes of the panel. In the second one, they are uniformly varied within specific ranges in such a way as to periodically control the resonant response of all flexural modes of the panel resonating in a given frequency band. The shunts include also a negative-capacitive active component, which is used to compensate the capacitive effect of the piezoelectric patches and thus to increase the control effectiveness of the shunts. The speed of the switching events or periodic sweeps are selected in such a way as the piezoelectric patch vibration absorbers can effectively control the response of the panel. The study shows that both switching and sweeping operation modes reduce the resonance peaks of either the targeted modes or the modes resonating in the target frequency band by values comprised between 3 and 15 dB.
Keywords: piezoelectric shunt, vibration absorber, smart panel, vibration control

1. Introduction

This paper presents initial laboratory measurement results of the flexural response of a thin rectangular panel equipped with five piezoelectric patches connected to either switching or sweeping time-varying shunts. In the first operation mode, the inductive and resistive elements of the shunts are iteratively commuted over a given set of values to cyclically control the resonant response of target flexural modes of the panel. Alternatively, in the second operation mode, the inductive and resistive elements of the shunts are uniformly varied to periodically control the resonant response of the panel flexural modes resonating in a given frequency band. To increase the vibration control effectiveness, the shunts incorporate also a negative-capacitive active component, which compensates the capacitive effect of the piezoelectric patches.

Forward [1], Hagood and von Flotow [2] and Wu [3] were among the first to propose the idea of connecting a piezoelectric transducer to a RL-shunt circuit in order to obtain a vibration absorber [4] that can be used either to control the response of mechanical systems to tonal excitations or to control the resonant response of distributed flexible structures subject to broad band excitations [5]. The shunt RL-elements are arranged either in series [2] or in parallel [3] in such a way as to form, together with the inherent capacitive effect of the piezoelectric element, a resonating electrical circuit, which is coupled to the hosting mechanical system or flexible structure via the piezoelectric transduction. The effectiveness of this electro-mechanical vibration absorber depends on the correct tuning of the

RL components [6-13]. As discussed in Ref. [6] for example, the inductive component should be tuned in such a way as the resonance frequency of the shunt is paired to the resonance frequency of the system to be controlled. Also, the resistive element should be chosen in such a way as to effectively dissipate the vibration energy absorbed from the controlled system into the electrical circuit. As with classical mechanical absorbers, the vibration absorption also depends on the scale of the absorber with reference to the scale of the hosting system. To maximise the effectiveness of the shunted piezoelectric absorber, the capacitive effect of the piezoelectric element should be as small as possible so that, to tune the shunt to a target frequency, a large shunt inductance should be implemented [6]. For this reason, several studies were carried out to investigate RLC-shunts encompassing a negative capacitance effect produced with active electrical components [14-21]. The possibility of implementing multi-resonant shunts was also investigated in many studies to generate a multiple vibration absorption effect that could be tuned to control the resonant response of several modes of the hosting structure [6,22-29]. The switching and sweeping piezoelectric patch vibration absorbers studied in this paper were also conceived to suppress the resonant response of multiple modes of the hosting flexible structure [30,31]. Indeed the switching operation mode iteratively commutes the parameters of a simple RL-shunt to control the resonant response of selected flexural modes of the panel structure. Alternatively, the sweeping operation mode periodically sweeps the parameters of the RL-shunt to control the response of those flexural modes that resonate in a given frequency band. Thus this second approach does not require precise tuning to the resonant response of given modes, i.e. it does not require a system identification initialisation. Moreover, it can work on structures whose dynamic response varies in time, for example because of temperature variations or tensioning effects due to operation conditions.

The paper is structured in four sections. Section two describes the smart panel with five piezoelectric patches experimental setup and the electronic system used to implement the switching and sweeping shunts. Section three shows the experimental results for the response of the panel when the five piezoelectric patches are connected to: a) fixed tuning shunts, b) switching shunts and c) sweeping shunts. Section four summarises the principal conclusions of the tests presented in this paper.

2. Experimental setup

Figure 1 shows the test rig used to carry out the experiments presented in this paper. Figure 1a, shows the smart panel with five shunted piezoelectric patch vibration absorbers whose dimensions and physical properties are summarised in Tables 1 and 2. As shown in Figure 2 the panel is clamped on a rigid frame, which is mounted on a solid Perspex box. The panel is excited by a point force produced by a shaker equipped with a load cell and the response of the panel is measured with a monitor accelerometer located close to the patch N. 4.

Table 1: Panel parameters

Parameter	Value
Dimension	$l_x \times l_y = 414 \times 314$ mm
Thickness	$h_p = 1$ mm
Density	$\rho_p = 2700$ Kg/m^3
Young's modulus	$Y_p = 7 \times 10^{10}$ N/m^2
Modal damping ratio	$\zeta_p = 0.02$
Shaker excitation force position	$x_f, y_f = 85{,}110$ mm
Monitor accelerometer position	$x_m, y_m = 147{,}97$ mm

Table 2: piezoelectric patch parameters

Parameter	Value
Dimension	$a_{pex} \times a_{pey} = 80 \times 80$ mm
Thickness	$h_{pe} = 1$ mm
Centre Positions j=2-5	$x_{c1}, y_{c1} = l_{xp}/2, l_{yp}/2$ $x_{cj}, y_{cj} = l_{xp}/2 \pm 60, l_{yp}/2 \pm 60$
Density	$\rho_{pe} = 7600$ Kg/m^3
Young's modulus	$Y_{pe}^E = 5 \times 10^{10}$ N/m^2
Piezo constants	$d_{31} = \mathrm{d}_{32} = -190 \times 10^{-12}$ m/V
Capacitance	$C_{pi} = 5.3 \times 10^{-8}$ F

The flexural vibration control effects produced by the five shunted piezoelectric patches were assessed by contrasting the 5 – 350 Hz Frequency Response Function (FRF) between the velocity measured at the monitor position and the force at the excitation position when the piezoelectric patches are short circuited and when they are connected to: a) fixed tuning shunts, b) switching shunts and c) sweeping shunts.

(a)

(b)

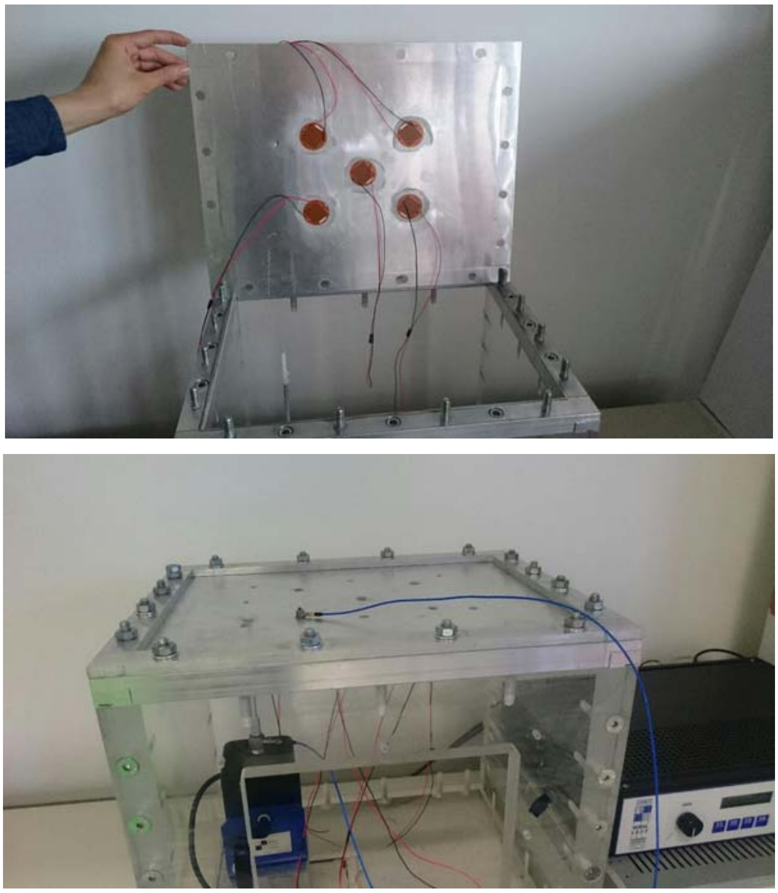

Figure 1: Laboratory setup.

The flexural response of a panel with a shunted piezoelectric patch as that shown in Figure 2a is normally modelled in terms of modal responses due to the flexural modes of the panel and piezoelectric patch, which are characterised by modal mass m_r, modal stiffness k_r and modal damping c_r. As shown in Figure 2b, the response of each mode can thus be modelled in terms of a modal mass-spring-damper parallel system, which is coupled via a modal transduction coefficient ψ_r, to a resonating electric mesh, formed by a capacitor C_p, which accounts for the capacitive effect of the piezoelectric transducer, and, in parallel a RLC shunt network. As thoroughly described in Ref. [32] and schematically described in Figure 2c, the shunted piezoelectric patch generates on the modal mass-spring-damper systems an equivalent mechanical vibration absorber system. Thus, the inductive and resistive components of the shunt can be selected such that the equivalent mechanical absorber is tuned to minimise the response of a specific mode of the structure [7-13]. More specifically the inductive component is normally set such that the electric network resonates at a frequency close to the resonance frequency of the controlled flexural mode. Also, the resistive component is selected in such a way as the electrical network effectively dissipate the vibration energy absorbed from the controlled mode. In this study, the shunt includes a negative capacitance effect, which as anticipated in the introduction, is used to lessen the effect of the piezoelectric capacitance. As a result, to match the resonance frequency of the shunt with that of the controlled mode, the shunt inductance is scaled up and this increases the effectiveness of the electro-mechanical absorber [6,22-29]. The literature offers a

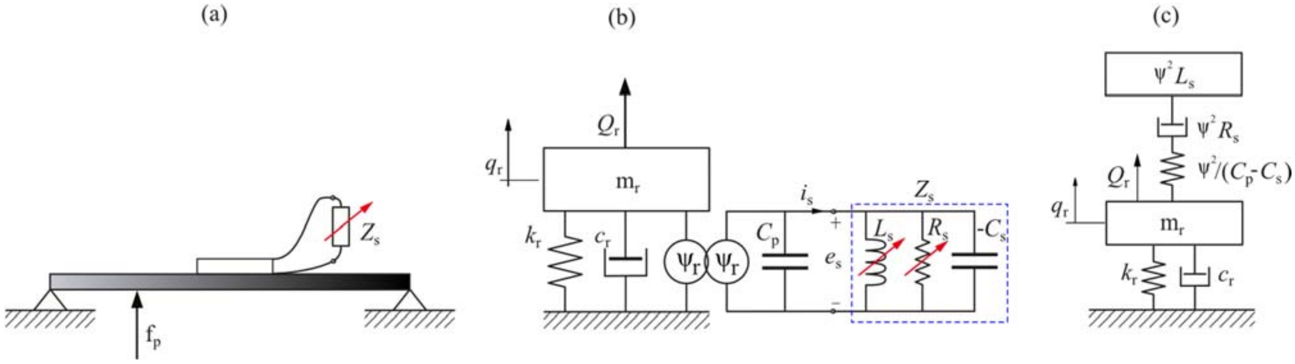

Figure 2: RLC shunts implemented in the five piezoelectric patches.

number of analytical expressions for the tuning of the shunt RL components, which refer to the simplified model shown in Figure 2b [7-13]. However, as discussed in Ref. [6], with two dimensional structures, the cross contribution of multiple modes of the structure should be taken into consideration for a correct tuning of the shunt parameters. As a result it is not possible to derive explicit expressions for the optimal tuning of the shunt RL components. Thus, in this study the RL components of the shunt for the fixed tuning and for the switching operation modes were selected with a trial and error exercise. More precisely, the shunt inductance was initially selected such that the resonance frequency of the shunt circuit coincides with the resonance frequency of the target flexural mode to be controlled. Also, the shunt resistance was initially fixed such that the electrical resonating circuit is critically damped. For the sweeping shunt, the RL components were uniformly swept in given ranges whose limiting values were calculated by tuning the shunt to the lower and upper bounds of the sweep frequency range, i.e. 47 to 317 Hz. Table 3 summarises the tuning frequencies for the fixed tuning, switching and sweeping operation modes implemented in this study.

Table 3: Operational frequency control for each absorber and for each operational control method

Type	Absorber 1 [Hz]	Absorber 2 [Hz]	Absorber 3 [Hz]	Absorber 4 [Hz]	Absorber 5 [Hz]
Fixed	49	87	127	221	315
Switching	49,87,127,221,315	87,127,221,315,49	127,221,315,49, 87	221,315,49, 87,127	315,49, 87,127,221
Sweeping	47-317	47-317	47-317	47-317	47-317

For the switching operation mode, the shunts were synthesised with a control algorithm that switched sequentially the shunt RL elements between the tuning values listed in second row of Table 3. As suggested in Refs. [5,31], the duration of each switching iteration was set to be equal to the time constant of the shunt circuit τ_s to allow the time necessary to absorb and dissipate vibration energy of each target mode at each iteration. For the sweeping operation mode, the natural frequency of the shunt electrical circuits were swept between the lower and upper limits of the frequency control range according to the following law $\omega_{sw}(t) = \omega_1 + (\omega_2 - \omega_1)[\sin(2\pi f_s t)]^2$, where ω_1 and ω_2 are the lower and upper values of the control frequency range shown in the third raw of table 3 and f_s is the sweeping frequency, which was set to 6 Hz. As claimed in ref. [31], the inductances were thus sweept following the law $L_s(t) = 1/(\omega_{sw}^2(t)(C_p - C_s))$. Also, the resistances were swept in such a way as to keep the quality factor in the shunt circuits equal to $Q_s = 3.3$, in which case $R_s(t) = Q_s\sqrt{(C_p - C_s)/L_s(t)}$ [31]. The five absorbers acted on the whole control frequency band $(\omega_2 - \omega_1)$ asynchronously with the phase shift of $\pi/5$ between each other.

To facilitate the experimental work, the shunts were synthesised digitally in a multi-channel dSPACE control system, which was connected to the piezoelectric patches. Considering a single patch, as shown in Figure 3a, an instrumentation amplifier, with relatively high input impedance, was connected to the piezoelectric patch terminals to provide the shunt voltage to the dSPACE input channel, without affecting the current flow through the terminals of the patch. The dSPACE was then set to synthetize a specific voltage drop at the output terminal such that, combined with the resistor voltage drop, it generates the desired shunt voltage drop per unit current flow, i.e. the desired shunt impedance as shown in Figure 3b.

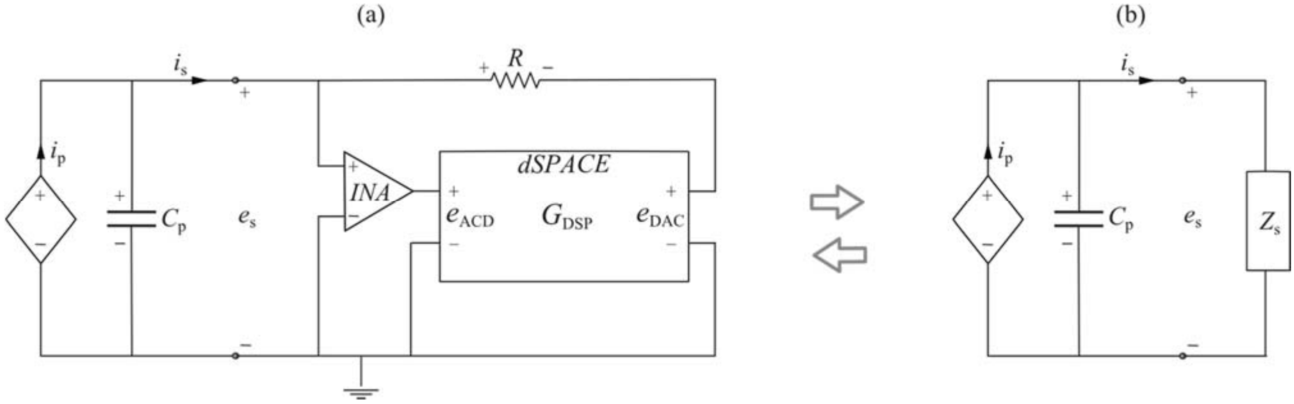

Figure 3: Electrical implementation of the shunts with dSPACE.

Considering the electrical scheme (a), the following equations can written:

$$e_{ADC} = e_s\ , \quad e_{DAC} = G_{DSP} e_{ADC}\ , \quad e_s - e_{DAC} = R i_s \tag{1-3}$$

Also, according to the electrical scheme (b)

$$e_s = Z_s i_s\ . \tag{4}$$

Thus combining Eqs (1-4) leads to the following equations:

$$Z_s = \frac{e_s}{i_s} = \frac{R}{1-G_{DSP}}\ , \quad G_{DSP} = \frac{e_{DAC}}{e_{ADC}} = 1 - \frac{R}{Z_s} \tag{5,6}$$

Here Z_s is the desired shunt impedance while G_{DSP} is the transfer function implemented in the dSPACE system, which, considering Figure 1b, result given by

$$\frac{1}{Z_s} = \frac{1}{R_s} - C_s s + \frac{1}{L_s s}\ , \quad G_{DSP} = 1 - \frac{R}{R_s} + R C_s s - \frac{R}{L_s s} = \frac{R R_s C_s L_s s^2 + (R_s - R) L_s s - R R_s}{R_s L_s s}\ . \tag{7,8}$$

The G_{DSP} transfer function is improper, thus to implement it in dSPACE it has been pre multiplied by a low pass filter with corner frequency above the 350 Hz considered in this study. Also, a high pass filter with very low corner frequency has been implemented to avoid DC coupling.

3. Experimental measurements

3.1 Fixed tuning shunts

Figure 4 shows the spectrum of the velocity measured with the accelerometer per unit force exerted by the shaker when the panel is equipped with the five piezoelectric patches either in short circuit (solid red line) or connected with fixed tuning shunts (solid black line). The graphs shows that the shunted piezoelectric patch absorbers produce between 3 and 15 dB reductions of the resonance peaks of the targeted modes.

3.2 Switching shunts

Figure 5 shows the spectrum of the velocity measured with the accelerometer per unit force exerted by the shaker when the panel is equipped with the five piezoelectric patches either in short circuit (solid red line) or connected with the switching shunts (solid black line). The switching shunts produce very similar control effects than the fixed shunts, with reductions of the resonance peaks of the targeted flexural modes comprised between 3 and 14 dB.

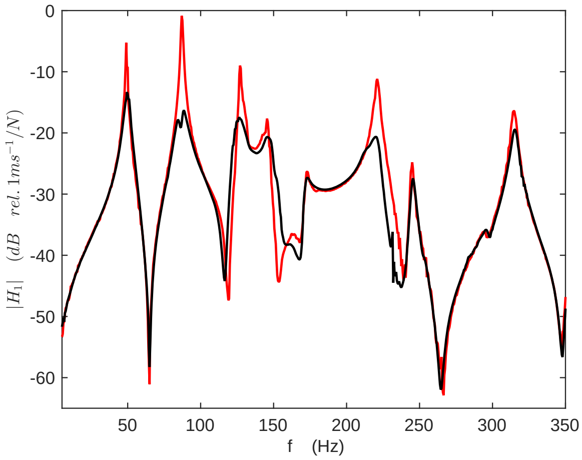

Figure 4: spectrum of the velocity measured with the accelerometer per unit force exerted by the shaker when the panel is equipped with five piezoelectric patches in short circuit (solid red line) and connected with fixed tuning shunts (solid black line).

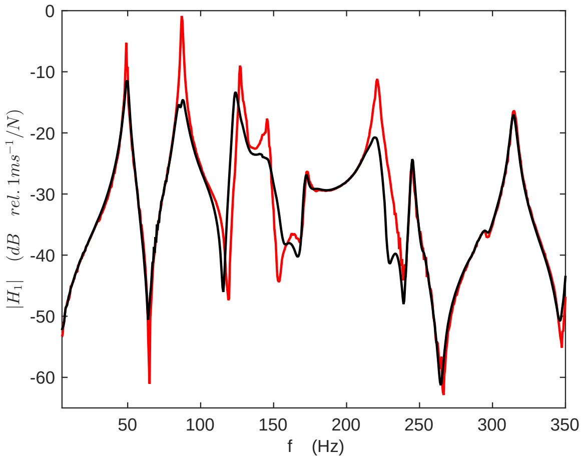

Figure 5: spectrum of the velocity measured with the accelerometer per unit force exerted by the shaker when the panel is equipped with five piezoelectric patches in short circuit (solid red line) and connected with switching shunts (solid black line).

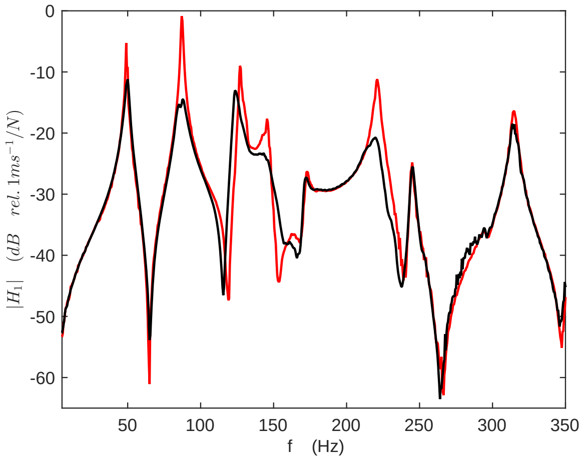

Figure 6: spectrum of the velocity measured with the accelerometer per unit force exerted by the shaker when the panel is equipped with five piezoelectric patches in short circuit (solid red line) and connected with sweeping shunts (solid black line).

3.3 Sweeping shunts

Figure 6 shows the spectrum of the velocity measured with the accelerometer per unit force exerted by the shaker when the panel is equipped with five piezoelectric patches either in short circuit (solid red line) or connected with the sweeping shunts (solid black line). Also the sweeping shunts produce very similar control effects than the fixed shunts and switching shunts, with reductions of the resonance peaks of the flexural modes that resonates in the target frequency band in the range of 3 to 14 dB.

4. Conclusions

This study has presented experimental results on the flexural vibration control effects produced between 5 and 350 Hz by an array of five time-varying shunted piezoelectric patch absorbers bounded on a thin aluminium panel. In particular, the study has considered two operation modes where the shunted piezoelectric patch absorbers are either iteratively switched or periodically swept to control respectively target resonant flexural modes and all flexural modes resonating in a target frequency band. The vibration control effects of the switching and sweeping operation modes have been contrasted with the control effect produced by a classical fixed tuning operation mode. The experimental tests have shown that the proposed time-varying operation modes produce about the same reductions of the flexural response at the principal resonance frequencies comprised in the 5 to 350 Hz frequency band. This is a rather interesting result, particularly for the sweeping operation mode, which operates blindly and does not require precise tuning. Thus it can be operated without the need of an initial system identification installation phase that would be necessary to tune the shunts for the classical, fixed tuning, and for the switching operation modes. Moreover, it can be effectively operated on time varying structures that undergo substantial variations of the response, due to changes of temperature or to mechanical tensioning effects that may occur during operation.

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