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SHUNTED PIEZOELECTRIC PATCH VIBRATION DAMPER TUNED ONLINE TO MAXIMISE ELECTRIC POWER ABSORPTION

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ABSTRACT

This paper presents an electromechanical vibration damper unit, composed by a thin piezoelectric patch connected to self-tuning shunt. The shunt encompasses either single or multiple branches, each with a resistor-inductor-capacitor in series. In this way, each branch band-filters the electric response of the shunt around its resonance frequency generating individual electro-mechanical vibration absorption effects. Thus, the branches can be tuned to control the resonant response of low-order flexural modes of the hosting structure. The paper proposes a two-paths tuning strategy where the inductance and resistance in each branch are tuned sequentially along constant-resistance and constant-inductance directions seeking the maximisation of the time-averaged electric power absorbed by each branch, which is shown to be equivalent to the minimisation of the time-averaged total flexural kinetic energy. The proposed two-paths tuning method guarantees convergence to the optimal resistance and inductance even with the variation on the mechanical response of the hosting structure. Experimental measurements taken on a thin steel plate equipped with five shunted piezoelectric patches have shown that the proposed self-tuning electromechanical vibration absorber units generate reductions of the resonant responses of the first second and fourth flexural modes of the order of 14 dB, 4 dB, 8 dB.

Keywords: *multimodal vibration control, adaptive vibration control, self-tuning shunt, tunable vibration absorber, piezoelectric vibration absorber.*

1. INTRODUCTION

This paper presents a study on the extremum-seeking online tuning of a piezoelectric vibration absorber for broadband vibration control of a mechanical system subject to stochastic stationary excitation, which is based on the maximisation of the time-averaged electric power absorbed by the shunt. A piezoelectric patch connected to a Resistive-Inductive (RL) shunt can be set to work as a classical mass-spring-damper mechanical vibration absorber [1], which can be suitably used to control the resonant response of the hosting mechanical system due to a stationary stochastic excitation. As discussed in Refs. [2-5], the combined resistive-inductive effects of the shunt combine with the capacitive effect of the piezoelectric transducer to form a resonating frequency. Hence, to maximise the energy absorption, the RL components should be tuned in such a way the shunted piezoelectric patch resonates at about the resonance frequency of the target mode of the hosting structure and is critically dampened. This paper proposes a local tuning strategy, where the resistive and inductive components of the shunt are tuned to maximise the time-averaged vibration energy absorption from the resonant response of a target flexural mode of the hosting structure, which can actually be suitably measured with respect to the time-averaged electric power absorbed by the shunt. The idea can be implemented either on simple RL shunts or on more complex shunts formed by multiple-branches in parallel, each encompassing a resistor, inductor and capacitor in series, which generate a band-filtered resonant response. In this second case, the single shunted patch can thus be employed to control the resonant responses of multiple flexural modes of the hosting structure. For brevity, the paper will show results on the single branch solution only.

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2. EXPERIMENTAL SETUP: PLATE STRUCTURE WITH THE FIVE CONTROL UNITS

Figure 1 shows the thin flat rectangular panel hosting structure considered in this study, which is made of steel. Five thin square MFC piezoelectric patches are bonded on the panel with the terminals connected via ad hoc interface circuits to a multi-channel dSPACE digital board used for the online implementation of the five self-tuning series RL-shunts [6].

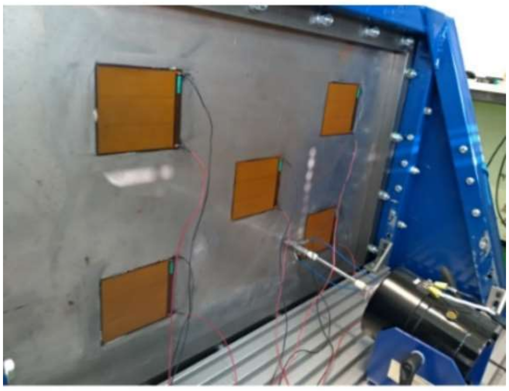

Figure 1. Plate with piezoelectric patches connected to the proposed RL shunt in series.

3. COST FUNCTIONS

Two cost functions are addressed in this/ work. The first is based on the time-averaged of the overall kinetic energy of the plate $\overline{K} = E[K(t)]$ (here $E[\quad]$ is the expectation operator), where, taking into account the total mass of the plate *m*, the istantaneous kinetic energy was derived derived from a grid of *N* velocities $\dot{w}_i$ measured with a laser vibrometer

$$K = \frac{1}{2N} m \sum_{i=1}^{N} \dot{w}_i^2 \tag{1}$$

Alternatively, following the works presented in Refs. [7,8] for shunted electromagnetic seismic vibration absorbers, this paper suggests employing as cost function the vibration energy absorbed by the shunted piezoelectric patch, which, as shown in Ref. [9,10], is related to the time-averaged electric power absorbed by the shunt $\overline{P} = E[P(t)]$, where the instantaneous power was derived from the measured voltage across the resistor R_s as follows

$$P(t) = \frac{v_R^2(t)}{R_s} \tag{2}$$

4. EXPERIMENTAL RESULTS

4.1 Parameter mapping

To start with, this section presents a tuning analysis for the case where all piezoelectric patches are connected to individual RL-shunts set to control the resonant response of the first mode of the panel. To this end, RL-maps have been built from a vast measurement campaign for the reference and tuning cost functions, that is the time-averaged total flexural kinetic energy $\overline{K}_r(R_{sj}, L_{sj})$ and the the time-averaged electric power absorbed by the shunt $\overline{P}_r(R_{sj}, L_{sj})$, band filtered at the resonance frequency of the first mode. Here the objective is to verify if the minimum of $\overline{K}_r(R_{sj}, L_{sj})$ and the maximum of $\overline{P}_r(R_{sj}, L_{sj})$ occur for the same values of the shunt resistance R_{sj} and inductance L_{sj}.

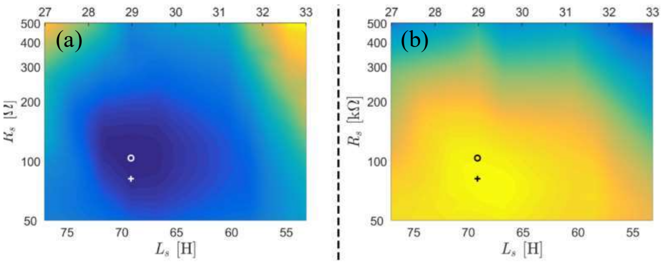

Figure 2. Maps of the time-averaged (a) kinetic energy and (b) absorbed electric power for the resonant response of the first flexural mode. The "o" and "+" markers denote the $\min(\overline{K}_r)$ and $\max(\overline{P}_r)$, respectively.

Figure 2 shows the measured maps of the reference cost function, $\overline{K}_r(R_{sj}, L_{sj})$ (left hand side plots), and tuning cost function, $\overline{P}_r(R_{sj}, L_{sj})$ (right hand side plots), when the shunts are set to control the resonant response of the first mode (*r*=1). The map of $\overline{K}_r$ is characterised by a non-convex inverse bell-shape with a single minimum whereas the map of $\overline{P}_r$ has a mirror non-convex bell-shape with a single maximum. The maximum of $\overline{P}_r$ occurs for about the same RL values than those that guarantee the minimisation of $\overline{K}_r$. Therefore, the maximization of the time-averaged electric power absorbed by the shunt can be suitably used to tune the shunts in such a way as to minimise the resonant response of the target flexural mode. The bell shape of the power cost function suggests that, as proposed in Refs. [9,10], the inductor and resistor components in each branch can be tuned sequentially along constant-resistance and constant-inductance paths respectively, which also display bell shapes. The maxima of these non-convex paths can be conveniently searched with the Extremum Seeking algorithm [11].

4.2 Extremum seeking algorithm

The two-paths tuning search was implemented in each shunt with the extremum seeking algorithm [11]. The tuning of the shunt inductance (L-tuning) and resistance (R-tuning) were implemented sequentially with the same procedure. With this algorithm, the electric power absorbed by the shunt, $P_{sj,\mathrm{i}}$, is first derived from the voltage drop across the shunt resistor, that is the shunt voltage $v_{sj,\mathrm{i}}$. Then power signal is then forwarded to the extremum seeking feedback loop to generate the inductance tuning parameter. For experimental purposes, the shunt has been implemented digitally on a computer board, although in practice it should be implemented in a self-contained, low-power consumption, electronic circuit.

4.3 Self-tuning results

Fig. 3 shows the instantaneous changes of the shunt inductance and resistance when the proposed two paths self-tuning of the RL-shunt is implemented in sequence. Upon convergence of the shunt components to the optimal values, a time window is contrasted against a response of an open circuit under the same stochastic disturbance in Figs 4 and 5. The results shows an increase of the voltage on the resistor as well as a decrease on the spatial average of the velocity response of the plate. This indicates a clear reduction on the flexural response of the hosting plate by the maximisation of the dissipated electric power. As indicated on Fig. 6, the reduction of the resonant response of the first flexural mode is in the order of 14 dB. Reference [12] reports more general results when multiple branches are implemented to control the resonant responses of multiple target flexural modes of the hosting structure.

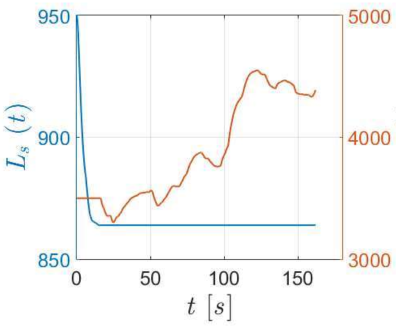

Figure 3. Tuning values for inductance (blue) and resistance (red).

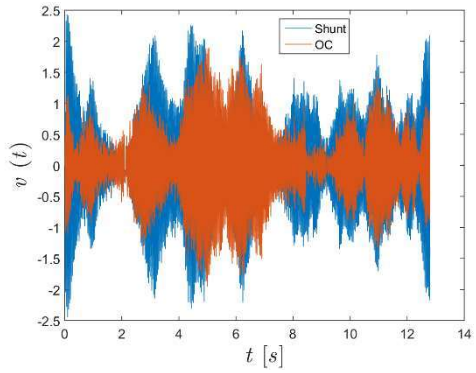

Figure 4. Voltage output with the shunt in open circuit (red) and after the self-tuning (blue)

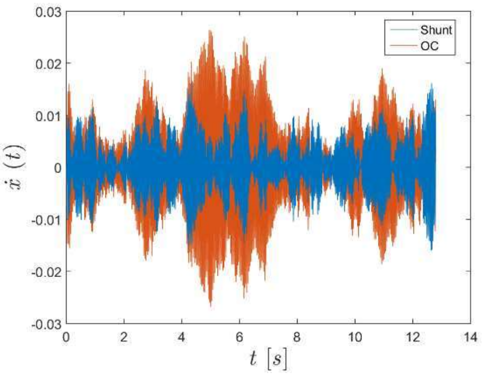

Figure 5. Averaged plate velocity with the shunt in open circuit (red) and after the self-tuning (blue)

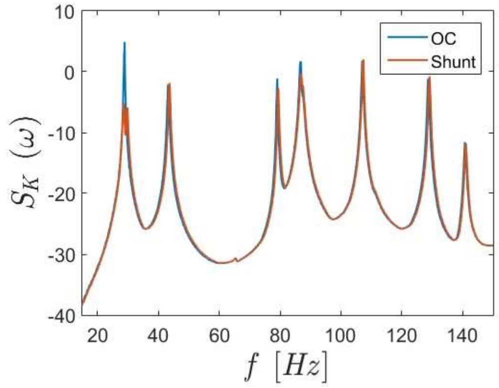

Figure 6. Power spectral density of the averaged kinetic energy between the open circuit (blue) and the shunt after the self-tuning (red)

5. CONCLUSION

This paper has briefly discussed the implementation of self-contained vibration control units formed by a piezoelectric patch connected to either a single RL branch or a multiple RLC branch self-tuning shunt, which can be bonded on thin structures to control the resonant response of target flexural modes exposed to broadband excitations. The study has considered a model problem encompassing a rectangular thin plate with five piezoelectric patches excited by a stochastic broadband force. For brevity the paper has reported results for the single RL branch shunt arrangement. The study has shown that the minimization of the time-averaged flexural kinetic energy cost function and the maximization of the time-averaged electric power absorbed by the shunt are characterised by mirror bell surfaces with respect to the resistance and inductance parameters of the shunt. Moreover, the minimum of the kinetic energy cost function occurs for the same optimal resistance and inductance values that give the maximum of the electric power absorption. Therefore, the shunts can be suitably tuned by maximizing the time-average electric power absorbed by the shunt. The paper has considered a two-patch tuning strategy where the inductance and resistance components are tuned sequentially along constant resistance and constant inductance paths respectively using the extremum seeking control algorithm. On-line experiments have shown that the proposed on-line local tuning of the five piezoelectric patches generates reduction of the resonant responses of the first mode of the order of 14 dB.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] J. Hogsberg, and S. Krenk: "Balanced calibration of resonant shunt circuits for piezoelectric vibration control," *J. Intel. Mater. Syst. Struct.*, vol 23, pp. 1937-1948, 2012.

[2] O. Thomas, J. Ducarne, and J.-F. Deü: "Performance of piezoelectric shunts for vibration reduction," *Smart Mater. Struct.*, vol 21, 2012.

[3] M. Berardengo, A. Cigada, S. Manzoni, and M. Vanali: "Vibration control by means of piezoelectric actuators shunted with LR impedances: Performance and robustness analysis," *Shock and Vib.*, vol 2015, pp. 1-30, 2015.

[4] P. Gardonio, and D. Casagrande: "Shunted piezoelectric patch vibration absorber on two-dimensional thin structures: Tuning considerations," *J. Sound Vib.*, vol 395, pp. 26-47, 2017.

[5] J. P Den Hartog: *Mechanical Vibrations*., McGraw-Hill, New York, 4th Ed, pp. 87-121, 1956.

[6] L. Dal Bo, P. Gardonio, D. Casagrande, and S. Saggini: "Smart panel with sweeping and switching piezoelectric patch vibration absorbers: Experimental results," *Mech. Syst. Signal Proc.*, vol. 120, pp. 308-325, 2019.

[7] P. Gardonio, E. Turco, A. Kras, L. Dal Bo, and D. Casagrande: "Semi-active vibration control unit tuned to maximise electric power dissipation," *J. Sound Vib.*, vol 499, 116000, 2021.

[8] E. Turco, P. Gardonio, and L. Dal Bo: "Tuning of a shunted electromagnetic vibration absorber based on the maximisation of the electrical power dissipated," *Proc. Inst. of Mech. Eng., Part C: J. Mech. Eng. Sci.*, vol 235, no 14, pp. 2570-2586, 2021.

[9] P. Gardonio, G. Konda Rodrigues, L. Dal Bo, and E. Turco: "Extremum seeking online tuning of a piezoelectric vibration absorber based on the maximisation of the shunt electric power absorption," *Mech. Syst. Signal Process.*, vol 176, 2022.

[10] G. Konda Rodrigues, P. Gardonio, L. Dal Bo, and E. Turco: "Piezoelectric patch vibration control unit connected to a self-tuning RL-shunt set to maximise electric power absorption," *J. Sound Vib.*, vol. 536, p. 117154, 2022.

[11] K. B. Ariyur and M. Krstić: *Real-Time Optimization by Extremum-Seeking Control*, John Wiley & Souns, Inc., 2003.

[12] G. Konda Rodrigues, P. Gardonio, L. Dal Bo, and E. Turco: "Multimodal vibration control with piezoelectric patches connected to self-tuning RLC shunts, *Mech. Adv. Mater. Struct.*, vol 30, no 5, pp. 1050-1063, 2022.