



COB-2021-0933

INVESTIGATION OF THE PASSIVE VIBRATION CONTROL USING LOW-COST PIEZOELECTRIC CERAMICS AND A PURELY RESISTIVE SHUNT CIRCUIT

Adailton Gomes Pereira

Maria Carolina Barcellos de Oliveira

Armando Ítalo Sette Antonialli

Sidney Bruce Shiki

UFSCar – Universidade Federal de São Carlos, Rodovia Washington Luís, km 235, São Carlos, SP, 13565-05, Brasil
adailton.goh@gmail.com, macarolbarcellos@gmail.com, antonialli@ufscar.br, bruce@ufscar.br

Abstract. *Vibrations are present in all mechanical structures and machines, usually being harmful to those systems. In this sense, passive vibration control techniques have been developed in order to minimize the occurrence of mechanical oscillations by adding damping to the system, usually without the need of a complex hardware. One of these techniques is characterized by the use of piezoelectric materials connected to an electrical circuit. In comparison to other techniques, it can be considered less robust but presents good results at the same time that it requires low investment. This work aims to analyze numerically and experimentally the efficiency of the aforementioned technique using a purely resistive electrical circuit in a cantilever aluminum beam. The value of the resistance was varied in both numerical simulations and experimental tests in order to understand its impact on the efficiency of the device under analysis. In the numerical and experimental analysis, the efficiency of the device in reducing the vibrations of the structure was proven. In the experimental tests, it was concluded that the piezoelectric shunt enabled to reduce mechanical vibrations up to 25% next to the resonance frequency.*

Keywords: *mechanical vibrations, passive vibration control, piezoelectric materials*

1. INTRODUCTION

The vibrations are present in our day-to-day from when we speak, that requires the oscillatory motion of larynges, to buildings and bridges that vibrate due to the wind (Rao, 2010). In general, vibrations are undesirable in most engineering systems and vibration control of structures is a fundamental issue in order to increase durability and performance. In engineering, most research is related to mitigating vibration ranging from the machining, aiming to minimize chatter (self-excited vibrations) to give a better finish to a mechanical part (Venter *et al.*, 2016), up to marine and offshore engineering to understand various vibration behaviors (Kandasamy *et al.*, 2016). These structures are often subjected to several types of environmental loads during their lifetime causing fatigue failure.

Vibration reduction can be achieved in several ways, the most common being to increase the damping of the system, allowing the structure to dissipate mechanical energy (Munoa *et al.*, 2016). The damping of the structure can happen passively or actively. Chung (2001) defines passive method as those that use some types of materials that have their own ability to absorb vibration energy and thus dissipate the energy in a passive way, and active methods make use of sensors and actuators to measure vibration and act on it in real time. Several devices were developed in order to minimize vibrations, such as the classic dynamic vibration absorber and viscoelastic absorbers, but lately a lot of research has been developed using smart materials.

Smart materials play an important role in mitigating vibration where ceramic piezoelectric is widely applied due to the fact that can be either used as sensor or actuator, because of its electromechanical coupling property (Park *et al.*, 2007). In energy harvesting, this property of ceramic piezoelectric is used to generate energy from structural vibrations. Furthermore, it has advantages compared to the conventional methods of thermal and solar harvesting, due to ambient vibrations that are quite persistent and make the conventional method difficult to operate (Safaei *et al.*, 2019). Some researches such as Erturk and Inman (2008) and Kim *et al.* (2010) have demonstrated how the energy generation occurs through the piezoelectric, as well as presented models of one degree of freedom that represent, in great detail and fidelity, an energy harvesting system in a cantilever beam.

In vibration control, piezoelectrics are used in several areas, but one of them gains greater visibility as it is a cheaper option and can still be used in several possible ways, that is the use of shunt circuits connected to the piezoelectric material. Where the piezoelectric converts the vibration into electrical energy which is then dissipated in the circuit. Silva

et al. (2015) used piezoelectric ceramics connected in series with a resonant shunt circuit for passive chatter control in the turning process, where the piezoelectric shunt acted similarly to the dynamic vibration absorber, reducing the vibrations generated during the process and improving the surface finish of the machined parts. Venter *et al.* (2016) used the same technique, however the piezoelectric shunt was analyzed, acting both passively and actively, mitigating vibrations during the process. Tairidis (2019) proposed a vibration control of a smart composite structure using shunted piezoelectric systems in order to overcome a deficiency in the shunt circuit, which is to act in the vibration modes in a pre-tuned way. It was developed and used a neuro-fuzzy control system to activate the appropriate shunt circuit, each time, providing the necessary adaptability to the entire system.

Knowing the relevance of this field of study and demonstrating the possibility of applying piezoelectric materials as vibration absorbers, this work proposes the study of the passive control of vibrations in a mechanical structure through a shunt circuit connected to low-cost piezoelectric ceramics commonly used in speakers and easy to purchase. To analyze the feasibility of this proposal, numerical and experimental studies are carried out for comparison purposes. Also, different resistance were analyzed in order to understand how the behavior of the structure was influenced by these values.

2. METHODOLOGY

2.1 Piezoelectric materials for vibration control

Smart materials are those that exhibit coupling between multiple physical domains (Leo, 2007). Piezoelectric materials are considered smart materials due to them electromechanical coupling, this means that the material exhibits mechanical strain when voltage is applied. This is called inverse piezoelectric effect and this phenomenon is possible due to crystalline nature of piezoelectric materials, which have dipoles in each unit cell. Dipoles are pairs of positive and negative charges separated by a constant distance and distributed randomly in the material, as shown in Fig. 1. When an electric field is applied the dipoles tend and orient themselves according to this field. With their rotation and since they are fixed in the material, this alignment generates mechanical deformation.

This kind of material can also exhibit the direct effect, that occurs when there is application of mechanical stress on the material, generating an electric field between the electrodes due to the rotation of dipoles, which results in an electrical output and, according to Leo (2007), this phenomenon was first studied by the Curie brothers in the 19th century. A widely used example of a piezoelectric material is lead zirconate titanate, also known as PZT.

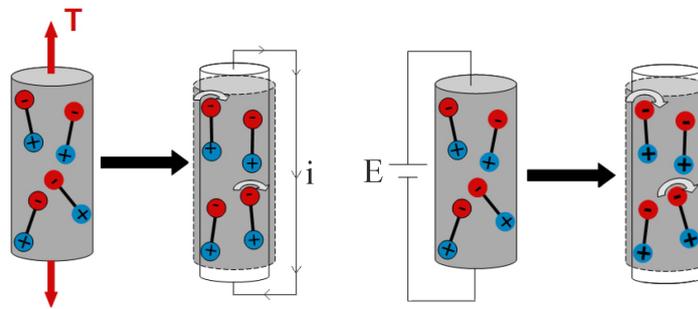


Figure 1: Direct and converse effect.

The direct effect can be described in Eq. (1) that relates mechanical stress T [N/m^2] and strain S [m/m] when the piezoelectric material is under this effect (Leo, 2007):

$$S = \frac{1}{Y} T = sT \quad (1)$$

where, S is called the mechanical compliance and Y is young's modulus in tension and deformation direction. And the relationship of mechanical stress and electrical displacement D [C/m^2] it is given by Eq. (2):

$$D = dT \quad (2)$$

where, d [C/N] is the piezoelectric strain coefficient.

Describing the converse effect, Eq. (3) shows the relationship between electrical displacement and electric field (E). In which, this relationship is given by the dielectric permittivity (ϵ) of the piezoelectric material.

$$D = \epsilon E \quad (3)$$

The Equation (4) demonstrates the relationship between mechanical strain and electric field in a piezoelectric material. Where, this is given by piezoelectric strain coefficient (d).

$$S = dE \quad (4)$$

Due to electromechanical coupling the material is subject to mechanical and electrical boundary conditions. For this, two cases are analyzed where the electrodes of piezoelectric material are connected to a switch. First case is where there is a closed circuit (short circuit), the charges are free to flow through the conductor, but the electric field is null ($E = 0$). In the second case there is an open circuit, in which case the loads cannot flow in the circuit ($D = 0$).

Thus, in Eq. (5), one can write a matrix notation of direct and converse effect with mechanical compliance (s^E) in constant electric field and a dielectric permittivity (ϵ^T) mechanical strain free.

$$\begin{bmatrix} S \\ D \end{bmatrix} = \begin{bmatrix} s^E & d \\ d & \epsilon^T \end{bmatrix} \begin{bmatrix} T \\ E \end{bmatrix} \quad (5)$$

Solving Eq. (5), it is possible to determine the piezoelectric coupling coefficient (k). Which quantifies the percentage of energy conversion between the physical and mechanical domains for each material.

$$k = \frac{d}{\sqrt{s\epsilon}} \quad , \text{ where, } \quad 0 \leq k \leq 1 \quad (6)$$

In vibration control, piezoelectric materials show some advantages in comparison to other techniques or materials. In addition to being able to be used both as a sensor and an actuator, they are light materials and their use does not add much weight to the structure, they allow the achievement of wide control bandwidths and significant forces and low power consumption (Berardengo *et al.*, 2021). Therefore, it can be used in passive and active vibration controls.

The active control, generally, makes use of the inverse effect, in which it measures a parameter related to vibration and then applies a signal proportional to that measurement on the piezoelectric material. And in passive control it has the purpose of increasing the damping of the structure without any external power supply for vibration energy dissipation (Munoa *et al.*, 2016). In which, the piezoelectric material is used to convert mechanical energy into electrical energy for then another device to dissipate it.

2.2 Resistive shunted piezoelectric

Piezoelectric materials can be used in several ways to control vibrations, making use of direct and inverse effects a portion of the mechanical energy associated with the vibration can be transformed into electric energy and dissipated. One of these applications is passive vibration control, in which the material is connected to a shunt circuit that has the function of dissipating the electrical energy which has been converted from mechanical energy by the piezoelectric (Hagood and von Flotow, 1990).

As shown by Viana and Steffen (2006), the most common shunt circuits are resistive, resonant, capacitive and switched. Where each one acts in a different way to increase the dampening. Resistive circuit behaves similar to viscoelastically-damped systems. The resonant behaves similarly to the classical dynamic vibration absorber. Capacitive circuit changes the stiffness of the piezoelectric element. And switched can adjust the behavior of the circuit in response to any change in the system. In this work it was only studied the resistive shunt.

Figure 2 shows how the piezoelectric material is connected to the shunt circuit ($Z_i^{SHUNT}(s)$), which in this case is composed only of an electrical resistance.

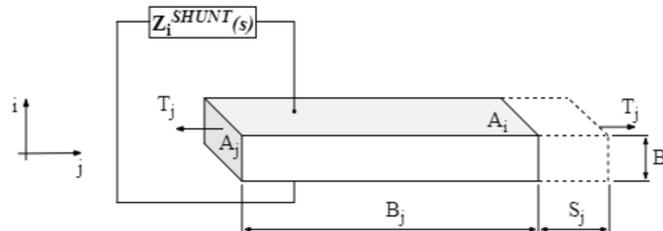


Figure 2: Piezoelectric patch bounded to a shunt circuit.

From this it is possible to determine some terms that correlate the properties of the piezoelectric material with those of the shunt circuit, as described in Viana and Steffen (2006) and Hagood and von Flotow (1990). The first is the electromechanical coupling coefficient (k_{ij}) where i and j are the directions it is acting, which now becomes the generalized electromechanical coupling coefficient, Eq. (7), defined as:

$$K_{ij}^2 = \bar{K} \frac{k_{ij}^2}{1 - k_{ij}^2} \quad (7)$$

where, \bar{K} is the ratio between the piezoelectric short circuit modal stiffness and the total system modal stiffness. The Equation (8) indicates how to determine the resonance frequency of the mechanical system corresponding to the open circuit case.

$$w_n^E = \sqrt{\frac{(K + K_{jj}^E)}{M}} \quad (8)$$

Where, K is the mechanical stiffness, K_{jj}^E is the stiffness of the piezoelectric in open circuit case and M is the mass of the system. Where, in Eq. (9) and (10), γ represents the non-dimensional frequency and ξ is the damping factor.

$$\gamma = \frac{s}{w_n^E} \quad (9)$$

$$\xi = RC_{PZT}^S w_n^E \quad (10)$$

Starting from the basic equation of motion, Eq. (11), it is possible to express the dynamic behavior of a structure with piezoelectric shunt coupled to it. One of the ways is to model the system with one degree of freedom as shown in Fig. 3, where it has parameters of mass (M), stiffness (K) and system damping (c) it is performed only due to the shunted piezoelectric ($Z(s)$).

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F(t) \quad (11)$$

By doing so, one can write the Eq. (12) which is the transfer function that represent the displacement of the system with a shunted piezoelectric and a force being applied to the mass. For the purely resistive piezoelectric shunt Hagood and von Flotow (1990) presented the Eq. (13) that determines the optimal resistance (R) of the electrical circuit for a given frequency (ω).

$$\frac{x}{F} = \left(\frac{1}{K + K_{jj}^E} \right) \left(\frac{\xi\gamma + 1}{\xi\gamma^3 + \gamma^2 + \xi(1 + K_{ij})\gamma + 1} \right) \quad (12)$$

$$R = \frac{\sqrt{1 - k_{ij}^2}}{\omega C_{PZT}^S} \quad (13)$$

Having the transfer function it is possible to make a theoretical prediction of the behavior of the system, in the purely resistive case, and also, analyze the influence of the resistance variation on vibration mitigation.

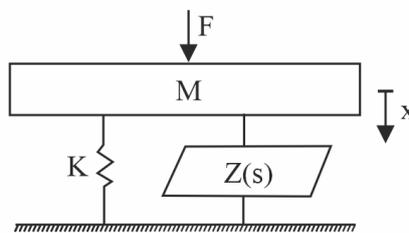


Figure 3: 1-DOF model of the system.

2.3 Description of simulations and experiments

This work aims to analyze numerically and experimentally the efficiency of the passive control of vibration using a purely resistive electrical circuit. The value of the resistance was varied in both numerical simulations and experimental tests in order to understand its impact on the efficiency of the device under analysis. The experiments were performed on a cantilever aluminum beam with dimensions of 200x25,4x2 mm. Where, based on that, their equivalent parameters were determined and used in the simulations.

Two low-cost piezoelectric ceramics 7BB-20-6C from muRata with capacitance 500 pF each were attached next to the clamped end of the beam. These materials were connected to a variable resistance, in practical experiments, with 5 k Ω , 10 k Ω and 1 M Ω in order to dissipate the energy. Only in the simulations was used the optimal resistance, which was determined at 62 k Ω . The beam was excited by a Pasco SF-9324 electrodynamic shaker with a stepped sine input. The frequency range of the signal was set to sweep from 16 to 64 Hz with steps of 1 Hz. Each frequency was excited during

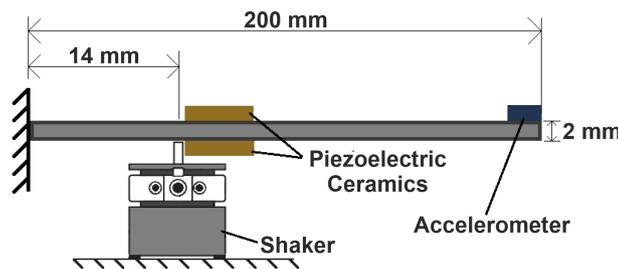


Figure 4: Arrangement of the practical experiment.

nearly two seconds while an ADXL335 low-cost accelerometer was used to measure the vibration in the free end of the structure as showed in Fig. 4. An Arduino Uno was used to process signal measured by the accelerometer.

The practical experiments sought to understand the dynamic behavior of the passive dissipation device when the shunt circuit is open, short-circuited and when the electrical resistance is varied. Five tests were performed for each configuration of the experiments in order to verify the repeatability of the data, with circuit cases and varying resistance

In the numerical analysis, simulations were performed in the Octave software using all the above-mentioned information, dimension and beam material, characteristics of piezoelectric material, resistance values and circuits conditions, with the equations presented in section 2.2. The resistances used were the same as in the practical experiment to have a previous notion of what would be seen in the experiments, except for the optimal resistance, which was not possible to carry out the practical experiments. The signals measured in practical experiment were treated and processed in Octave.

3. RESULTS

3.1 Numerical analysis

Initially simulations were performed to visualize the efficiency of the piezoelectric shunt in mitigating vibrations in the structure and to be able to predict how the device behaves when the resistance is varied. Figure 5 shows the results obtained by giving a step function input into the system. It can be observed that among the resistances used in the simulation the optimal ($62 \text{ k}\Omega$) presented the best vibration absorption, soon after comes $10 \text{ k}\Omega$, $5 \text{ k}\Omega$ and $1 \text{ M}\Omega$ showed the same performance and under short and open circuit conditions the vibration was practically not dampened. This behavior is observed because in short circuit condition it presents zero resistance, not dissipating the energy, and when in open circuit the energy is prevented from passing through the circuit and dissipation does not occur. On the right side there is a cutout of each signal to demonstrate it in more detail in the time interval from 0.8 to 1 second.

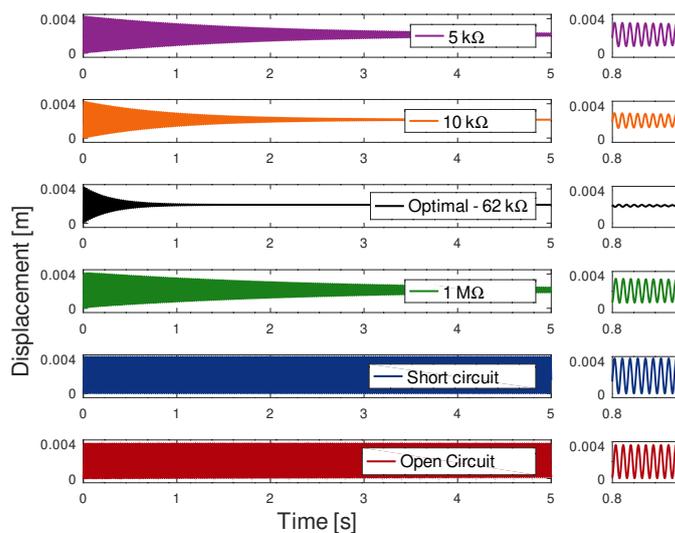


Figure 5: Step function input response.

Figure 6 shows the frequency response function (FRF) plotted from the Eq. (12). Here the same behavior shown in the step function response can be evidenced. The FRF for optimal resistance has smaller vibration amplitudes what was expected, then $10 \text{ k}\Omega$, $5 \text{ k}\Omega$ and $1 \text{ M}\Omega$ practically the same amplitude and short and open circuit practically the same amplitudes as well. It can be notice that the three curves, $5 \text{ k}\Omega$, $10 \text{ k}\Omega$ and short circuit, have peaks close to $42,7 \text{ Hz}$ and

43.8 Hz for 1 MΩ and open circuit. It means these are the natural frequencies of the system when a circuit is connected under the described conditions. Further, the simulations show that very high and very low resistances have approximate performance, and the optimal value (62 kΩ) demonstrates the best performance.

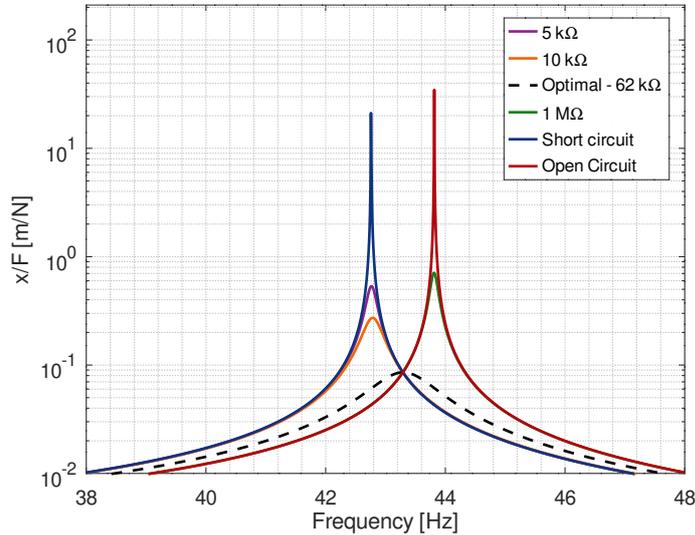


Figure 6: Frequency response function.

3.2 Practical experiment

As data were collected five times for each condition under analysis, Fig. 7 shows only one of the acquisitions made. This graph shows the vibration behavior of the structure under the different frequencies imposed by the stepped sine input simulated by the shaker. It is possible to notice that there are several small acceleration peaks, which represent the transient regime of the response between two frequencies, and it is also possible to observe a larger peak around 50 seconds which represents that it was at that moment that the structure was being excited in its resonance frequency.

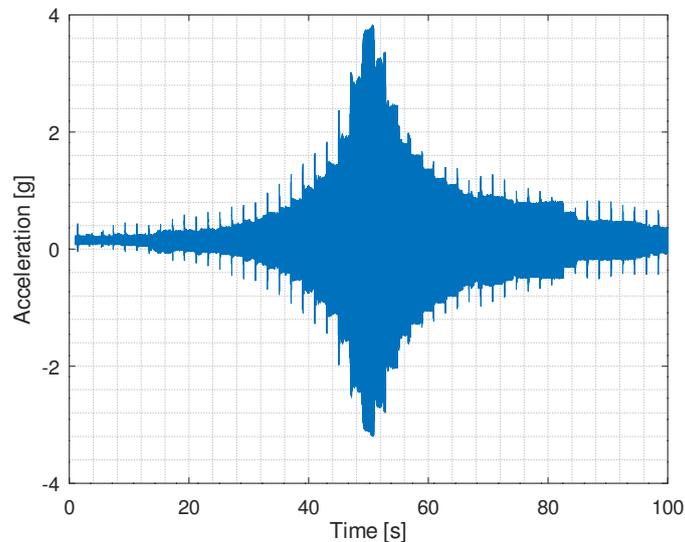


Figure 7: Vibration signal.

In the processing of the obtained data in the practical experiments, the peak signal acceleration for each frequency excited by the shaker was measured, as presented in section 2.3 From this, the steady state response amplitude of each experiment were developed, which represents the amplitude of vibration for each frequency excited by the shaker. Figure 8 and 9, present the five curves corresponding to the five experiments carried out in each circuit configuration and a highlighted curve representing the average of the values found are also present. So we can quickly see that the circuit with 10 kΩ resistance has smaller amplitudes.

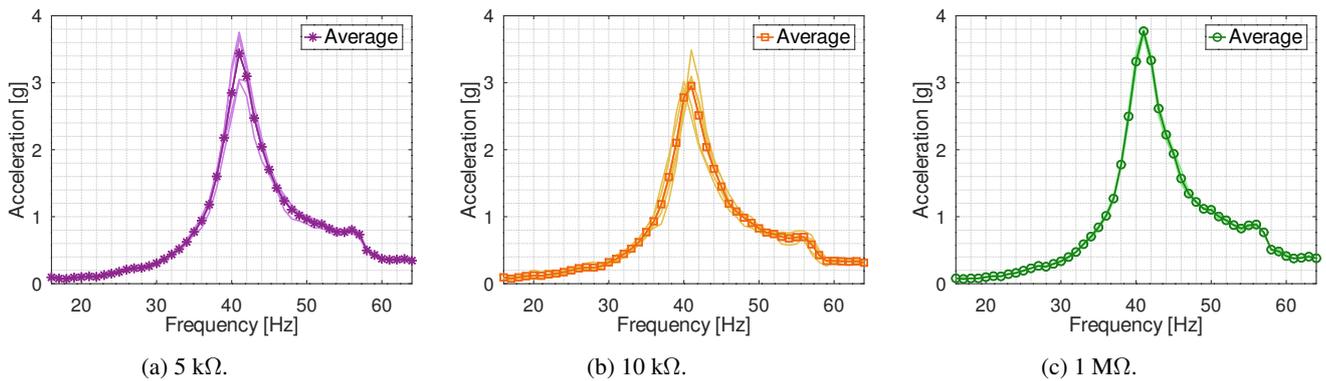


Figure 8: Steady state response amplitude for different resistance.

Having the experimental data presented in this way, it is possible to observe that with values below 30 Hz the acceleration values are low, but soon after it the acceleration magnitude increases exponentially until reaching a maximum value around 41 Hz. After this frequency peak, the values of the acceleration go down as the frequency increases. Thus, it is possible to state that the value of the structure resonance frequency is approximately 41 Hz, as it is in this frequency value that the highest acceleration value is found, characterizing the resonance phenomenon. And in all cases, regardless of the resistance value or whether the piezoelectric material was connected to the circuit or not, the resonance frequency is the same. However, in Fig. 8b it is possible to notice small variation in the resonance frequency as shown in the simulations. In the other figures this behavior may not be seen due to the frequency spacing being 1 Hz.

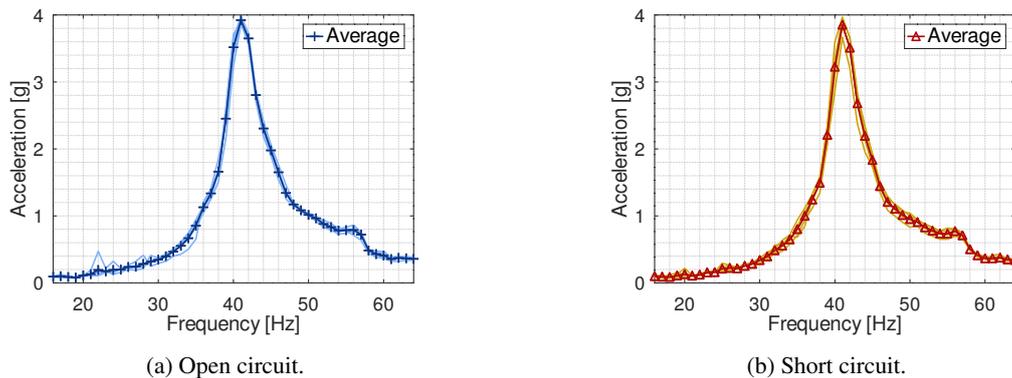


Figure 9: Steady state response amplitude for circuits cases.

In Figure 10 one can notice the configuration that presents the highest level of vibration is the open circuit, which simulates the structure without the beneficial effect of piezoelectric shunt, followed by the short circuit and 1 MΩ configuration. In those conditions, the resistance value is so high that prevents the passage of current through the circuit, making the device not to act. The other resistances, 5 kΩ and 10 kΩ, showed a significant reduction in vibrations with values of 3,44 g and 2,96 g, respectively. Thus, the piezoelectric shunt device with 10 kΩ resistance showed the best efficiency in mitigating vibrations in the structure.

4. CONCLUSIONS

After analyzing the results presented, it can be concluded that the piezoelectric material connected to the shunt circuit in fact mitigated the vibrations in the structure. And it was possible to observe this in both analyzes, simulations and experimental practices. In the simulations where the system response were analyzed to an step function input and the frequency response function of systems with resistance 5 kΩ, 10 kΩ, 62 kΩ (optimal), 1 MΩ, short and open circuit, the resistance of 10 kΩ and optimal had the best performance in mitigating vibrations. With resistance values of 5 kΩ and 1 MΩ the performance was practically the same, and under short and open circuit conditions almost the same vibration damping were observed.

In the practical experiments, the piezoelectric shunt device behaviors that were observed in the numerical simulations were confirmed. Among the conditions analyzed, the 10 kΩ resistance showed the best result, being approximately 25% lower than in open circuit. And in short circuit, open circuit and 1 MΩ cases presented the highest vibration levels when compared to 5 kΩ and 10 kΩ. Thus demonstrating the efficiency of shunt piezoelectric in mitigating vibrations.

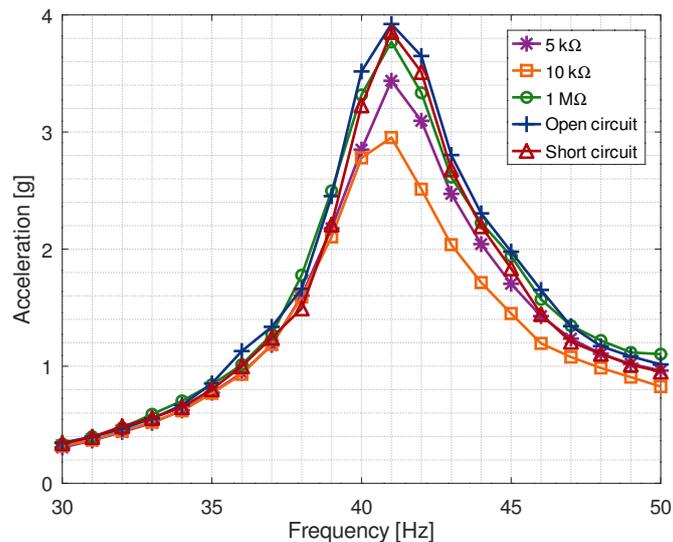


Figure 10: All average response.

5. ACKNOWLEDGEMENTS

This research is supported by CAPES 88887.602218/2021-00. The authors would like to thank the CNPq 432002/2018-9 and FAPESP 2015/25146-3, 2018/25135-0 for promoting the purchase of the computational tools used in this work.

6. REFERENCES

- Berardengo, M., Manzoni, S., Høgsberg, J. and Vanali, M., 2021. “Vibration control with piezoelectric elements: The indirect measurement of the modal capacitance and coupling factor”. *Mechanical Systems and Signal Processing*, Vol. 151, p. 107350.
- Chung, D., 2001. “Materials for vibration damping”. *Journal of materials science*, Vol. 36, No. 24, pp. 5733–5737.
- Erturk, A. and Inman, D.J., 2008. “On mechanical modeling of cantilevered piezoelectric vibration energy harvesters”. *Journal of intelligent material systems and structures*, Vol. 19, No. 11, pp. 1311–1325.
- Hagood, N.W. and von Flotow, A., 1990. “Damping of structural vibrations with piezoelectric materials and passive electrical networks”. *Journal of Sound and Vibration*, Vol. 146, No. 2, pp. 243–268. ISSN 10958568. doi:10.1016/0022-460X(91)90762-9.
- Kandasamy, R., Cui, F., Townsend, N., Foo, C.C., Guo, J., Sheno, A. and Xiong, Y., 2016. “A review of vibration control methods for marine offshore structures”. *Ocean Engineering*, Vol. 127, pp. 279–297.
- Kim, M., Hoegen, M., Dugundji, J. and Wardle, B.L., 2010. “Modeling and experimental verification of proof mass effects on vibration energy harvester performance”. *Smart Materials and Structures*, Vol. 19, No. 4, p. 045023.
- Leo, D.J., 2007. *Engineering analysis of smart material systems*. John Wiley & Sons.
- Munoa, J., Beudaert, X., Dombovari, Z., Altintas, Y., Budak, E., Brecher, C. and Stepan, G., 2016. “Chatter suppression techniques in metal cutting”. *CIRP Annals - Manufacturing Technology*, Vol. 65, No. 2, pp. 785–808. ISSN 17260604. doi:10.1016/j.cirp.2016.06.004.
- Park, G., Bement, M.T., Hartman, D.A., Smith, R.E. and Farrar, C.R., 2007. “The use of active materials for machining processes: A review”. *International Journal of Machine Tools and Manufacture*, Vol. 47, No. 15, pp. 2189–2206. ISSN 08906955. doi:10.1016/j.ijmachtools.2007.06.002.
- Rao, S.S., 2010. *Mechanical Vibrations*. Prentice Hall, 5th edition. ISBN 978-0-13-212819-3.
- Safaei, M., Sodano, H.A. and Anton, S.R., 2019. “A review of energy harvesting using piezoelectric materials: state-of-the-art a decade later (2008–2018)”. *Smart Materials and Structures*, Vol. 28, No. 11, p. 113001.
- Silva, M.M., Venter, G.S., Varoto, P.S. and Coelho, R.T., 2015. “Experimental results on chatter reduction in turning through embedded piezoelectric material and passive shunt circuits”. *Mechatronics*, Vol. 29, pp. 78–85. ISSN 09574158. doi:10.1016/j.mechatronics.2015.06.002.
- Tairidis, G.K., 2019. “Vibration control of smart composite structures using shunted piezoelectric systems and neuro-fuzzy techniques”. *Journal of Vibration and Control*, Vol. 25, No. 18, pp. 2397–2408.
- Venter, G.S., Silva, L.M.d.P., Carneiro, M.B. and da Silva, M.M., 2016. “Passive and active strategies using embedded piezoelectric layers to improve the stability limit in turning/boring operations”. *International Journal of Advanced Manufacturing Technology*, Vol. 89, No. 9-12, pp. 2789–2801. ISSN 14333015. doi:10.1007/s00170-016-9620-2.

Viana, F.A.C. and Steffen, V., 2006. "Multimodal Vibration Damping through Piezoelectric Patches and Optimal Resonant Shunt Circuits". Vol. XXVIII, No. 3.

7. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.