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VIBRATION CONTROL IN A CANTILEVER BEAM USING NEGATIVE CAPACITANCE SHUNT CIRCUIT WITH RESISTOR IN SERIES COUPLED TO PIEZOELECTRIC TRANSDUCERS

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Abstract. *The mechanical vibrations related to structures, mechanisms and parts of machines are responsible for the loss of efficiency and failures in different systems, which due to the increased use of this equipment is associated with the advances of the electronics, has increased the need for a more efficient control of the vibrations generated. In recent years, the use of intelligent materials and structures for this purpose has grown significantly and can be applied in a wide range of operation. This work aims to reduce the vibration amplitudes of a crimped-free steel beam, using piezoelectric transducers bonded on its surface, associated to a negative capacitance shunt circuit with series electric resistance, in an experimental way, compared with the model numeric. The methodology used consisted of studying the behavior of the crimped beam when excited by an impact force, with an accelerometer bonded to its free end. The effects caused by the piezoelectric bonded on its surface when the circuit is activated and not activated, were analyzed to verify the reduction in the amplitudes of response of the system for the first two resonant frequencies. A reduction in the vibration amplitudes of approximately 18.72 dB for the first frequency and 18.56 dB for the second frequency, respectively, was obtained.*

Keywords: *Intelligent materials and structures. Piezoelectric transducers. Negative capacitance shunt circuit. Attenuation of vibration.*

1. INTRODUCTION

Most of the structures and equipment used today are exposed to the effects caused by excessive vibrations. They are due to earthquakes, actions of the winds, passage of vehicles on bridges, natural catastrophes, etc. Or inherent in mechanical systems, such as excessive vibration of internal combustion engines, washing machines, vibrating screens and so on. To minimize these effects, several different techniques have been studied and employed over the years, ranging from Dynamic Vibration Absorbers (ADV) to the use of "special" materials such as viscoelastics. More recently, so-called intelligent materials have been used for this purpose, which according to Leo (2007) can be defined as those exhibiting coupling between several physical domains (mechanical, electrical, thermal, etc.), which can generate force and movement.

The most used materials are Piezoelectric Materials, Shape Memory Alloys (SMA), Electroactive Polymers (EAP) and Electrolytic and Rheological Magneto Fluids. In the case of piezoelectric materials, which will be the materials used in this research, we have the most used types are piezoceramic and piezopolymers, among them, Lead Titanium Zirconate (PZT) and Vinylidene Polyfluoride (PVDF), respectively.

Thus, the main objective of this work is to obtain high reduction of vibration amplitudes in a steel beam using a piezoelectric transducer (QP10W) bonded to one of its faces, associated with a negative capacitance shunt circuit with series electrical resistance. The modal forms of the beam and their respective natural frequencies were studied, being constructed their Frequency Response Function (FRF) in numerical and experimental form.

2. THEORETICAL FOUNDATION

2.1 Cantilever Beam

In this section we will consider the vibration of the bar or beam, however, vibration of the beam in the direction perpendicular to its length is considered. Such vibrations are often called transverse vibrations, or flexural vibrations, because they move across the length of the beam. Consider too that the beam is of rectangular cross section *A(x)* with width h_y, thickness h_z, and length *l*. Also associated with the beam is a flexural (bending) stiffness *E.I(x)*, where E is the Young's elastic modulus for the beam and *I(x)* is the cross-sectional area of moment of inertial about the "*z* axis". From mechanics of materials, the beam sustains a bending moment *M(x,t)*, which is related to the beam deflection, or bending deformation *w(x,t)*, generating a shear deformation *V(x,t)*.

Assuming that the coefficients are all constant and that no external force is applied, it is possible to obtain the equations for free vibration of uniform beams, which can be presented as (Inman, 2001):

$$\rho.A(x).\frac{\partial^2 w(x,t)}{\partial t^2}+\frac{\partial^2}{\partial x^2}\left[E.I(x).\frac{\partial^2 w(x,t)}{\partial x^2}\right]=f(x,t) \tag{1}$$

$$E.I.\frac{\partial^4 w(x,t)}{\partial x^4}+\rho.A.\frac{\partial^2 w(x,t)}{\partial t^2}-\rho.I.\left(1+\frac{E}{\kappa^2.G}\right)\frac{\partial^4 w(x,t)}{\partial x^2.\partial t^2}+\frac{\rho^2.I}{\kappa^2.G}.\frac{\partial^4 w(x,t)}{\partial t^4}=0 \tag{2}$$

Where G is the shear modulus, and κ^2 is a dimensionless factor that depends on the shape of the cross-sectional area. The constant κ^2 is called a shear coefficient and has been tabulated by Cowper (1966). The Eq. (1) is called the Euler-Bernoulli beam model or classical beam model and Eq. (2) is called the Timoshenko beam model.

2.2 Piezoelectric Transducers

Piezeletricity was discovered by the Currie brothers in France in 1880 during laboratory experiments with quartz crystals. These crystals, also known as piezoelectric transducers, which are most often ceramic, natural or synthetic, have the characteristic that when applied an electric voltage on its surface, this material is capable of generating a stress or deformation (contraction or expansion). This behavior is called the inverse effect. The opposite behavior is also observed, i.e. when applied a stress or deformation on the surface of the material, it generates an electric voltage. This effect is known as direct effect.

According to Hagood and von Flotow (1991), a general expression describing the behavior of piezoelectric materials linearly can be written as:

$$\begin{bmatrix} D \\ S \end{bmatrix}=\begin{bmatrix} e^T & d \\ d^t & s^E \end{bmatrix}.\begin{bmatrix} E \\ T \end{bmatrix} \tag{3}$$

Where, *D* is the vector of electrical displacement (*C/m²*); *E* is the vector of electric field (*V/m*); *S* is the vector of material engineering strains (non-dimensional); *T* is the vector of material stresses (*N/m²*); *ε* is the matrix of dielectric constants for the material (*C²/(N.m²)*); *s* is the matrix of compliance for the material (*m²/N*); *d* is the piezoelectric material constant relating strain to voltage (*m/V*).

2.3 Negative Capacitor Shunt Impedances

According to Moheimani and Fleming (2006), negative capacitor shunt circuits constitute an active technique for structural vibration control. Although negative capacitors cannot be constructed from passive components and do not guarantee unconditional closed-loop stability, they are simple in conception and are known to provide good performance with little dependence on structural resonance frequencies. Its major disadvantage is the sensitivity to the variations of capacitance of the transducer, restricting its use in applications that do not involve variation of temperature.

The circuit acts as an element that opposes the impedance of the piezoelectric by generating an impedance of the same magnitude, but with opposite phase, creating a negative capacitance. Where resistance *R* is used as the energy dissipating element by Joule effect, due to the electric current generated in the transducer when the structure to which it is coupled moves. The proposed circuit is shown in Figure 1.

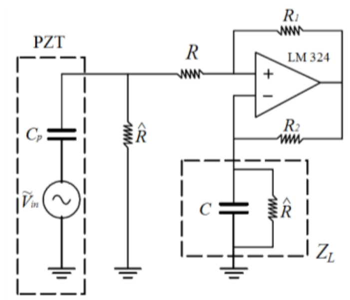

Figure 1. Electrical circuit used.

The circuit shown in Figure 1 is composed of an operational amplifier (LM324) with two adjustment resistors R_1 and R_2, by the impedance Z_L, which is the impedance which will be canceled with the input impedance, formed by a capacitor C in parallel with a resistance $\hat{R}$, and by the piezoelectric at the input of the circuit, represented by an electric voltage source in series with the impedance C_P.

Moheimani and Fleming (2006) said that practical difficulties such as bias-current and offset-voltage induced errors are usually solved by placing a large parallel resistance ($\hat{R}$) across Z_L. A resistor in series with the input has also been used to overcome problems due to stray negative resistance and for use as tuning parameter. Therefore, for the system to become stable it is necessary that $C > C_P$ e $\hat{R} >> R > 0$. Thus, for $Z_{in}(s)$ to be equal to $Z_L(s)$, a resistor must be added in parallel with the piezoelectric, so that both impedances have the same magnitude. The electrical components used in the circuit and their respective values are shown in Table 1.

Table 1. Parameters of negative capacitance shunt circuit.

Circuit Component	***Value***
$R_1 = R_2$ ($k\Omega$)	*10*
$\hat{R}$ ($M\Omega$)	*3.3*
R (Ω)	*100*
C_P (nF)	*85*
C (nF)	*90*

3. METODOLOGY

The computational tool used to perform the simulations was the ANSYS® Workbench in partnership with the toolbox called PiezoAndMEMS® (Piezoelectrics and Micro-Electromechanical-Systems). The mesh used was a mesh structured with rectangular elements of 5 *mm* for the beam and 0.5 *mm* for the piezo, with a total of 8354 elements and 59679 nodes, respectively, as shown in Figure 2. The element used for the piezoelectric was SOLID226, which has 20 knots with 5 degrees of freedom per node. For the beam, the element SOLID186 was selected, which is also defined by 20 nodes, but with 3 degrees of freedom per node. In order to emulate the piezoelectric load, the element CIRCU94 was used, which is a circuit-like element used in piezoelectric analysis.

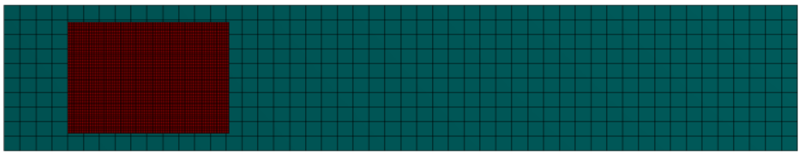

Figure 2. Schematic representation of the mesh generated in the structure.

This coupling is possible due to the type of contact that was used, where the number of elements / nodes of the two bodies do not necessarily have to be equal, since penetration detection does not allow one body to be intercepted by the other. The type of contact of the system was defined as bonded and the contact formulation was performed using the Multi-Point Constraint Method (MPC), always with the Nodal-Normal to Target type detection method. The average global damping factor used was $\xi = 0.04$, with an electric load or resistance of 20 $M\Omega$ between the surfaces of the piezoelectric. The excitation of the beam was performed by applying a harmonic force with amplitude of 1 N at its free end. The properties of the beam and the piezoelectric (Quickpack Piezo Products, 2019) are shown in Table 2.

Table 2. Properties of the beam and piezoelectric used in the numerical analyzes.

Beam (Stainless Steel)			
Description	***Unit***	***Symbol***	***Value***
Young's Modulus	*Pa*	E	210×10^9
Tensile Strength Limit	*Pa*	σ_R	250×10^6
Poisson's Ratio	-	ν_B	0.3
Density	kg/m^3	ρ_B	7850
Piezoelectric (QP10W)			
Description	***Unit***	***Symbol***	***Value***
Capacitance	*F*	C_P	85×10^{-9}
Strain Constant	*m/V*	d_{31}	-190×10^{-12}
Electromechanical Coupling Factor	-	k_{31}	0.36
Stress Constant	*V.m/N*	g_{31}	-11.3×10^{-3}

In order to perform the experimental tests, the beam was considered crimped-free with the transducer bonded on its surface, positioned in the region of maximum deformation to make piezo more efficient, where the piezoelectric used is type QP10W produced by the company Midé®. The tests were carried out on an inertial table, with the beam subjected to an impact type excitation, performed by an impact hammer at 150 *mm* from the crimping, model 086C03 ICP® from the manufacturer PCB® Piezotronics and acquired by an accelerometer type sensor ICP® 352B10 from the same manufacturer, positioned at its free end, at approximately 250 *mm* from the crimping. The representation of dimensions of the beam and piezoelectric (Quickpack Piezo Products, 2019) used are shown in Figure 3.

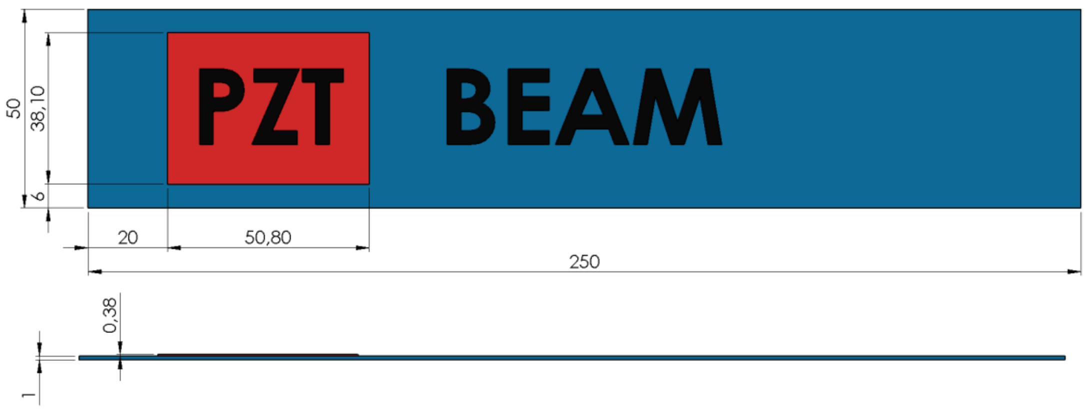

Figure 3. Dimensions of beam and piezoelectric transducer used.

4. RESULTS AND DISCUSSIONS

Through the constitutive equations, it was possible to observe the behavior of the system impedances, verifying that Z_P, Z_L and Z are equal in magnitude, but Z_P and Z are 180º out of phase, generating the desired effect, in which the electrical impedance created has the same magnitude of Z_P, but lagged, so that they oppose and cancel out in the frequency band for which they were configured.

The numerical results of ANSYS® modal analysis, with their respective resonance frequency and vibration modes, can be seen in Figure 4, for the first and second transverse frequencies of oscillation of the system, respectively.

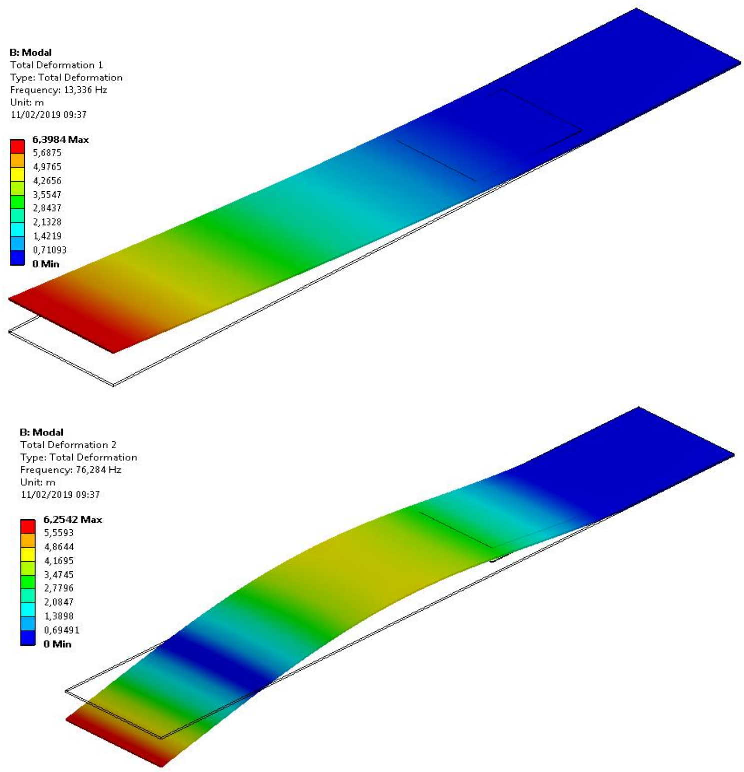

Figure 4. System resonance frequencies and their respective modes of vibration.

For the first natural frequency of vibration the value was 13.34 *Hz* and for the second it was 76.28 *Hz*. These frequencies were also represented by the Bode diagram shown in Figure 5.

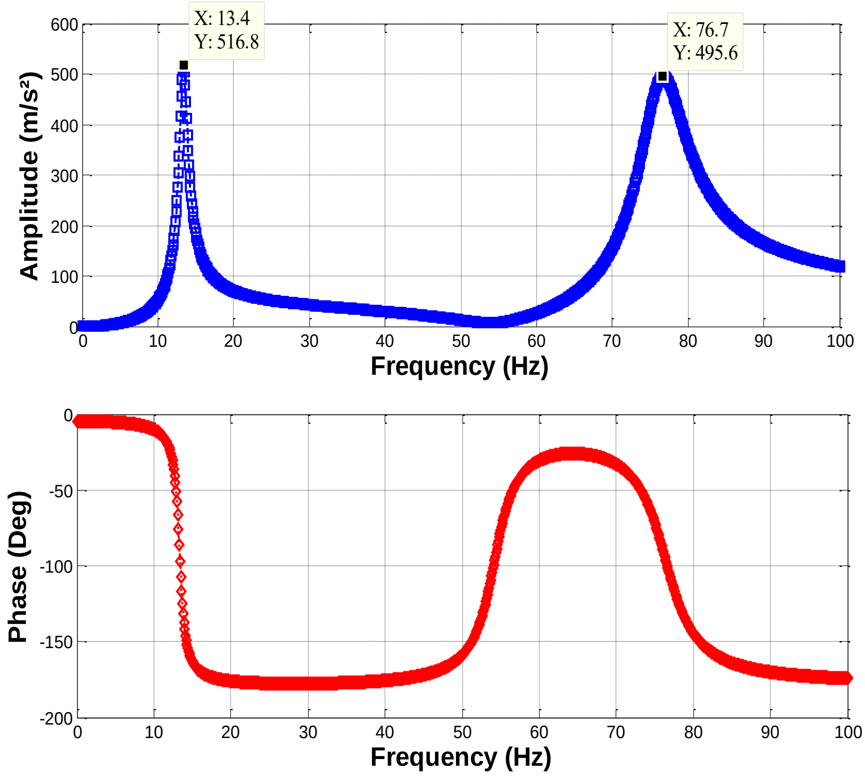

Figure 5. Amplitude and phase of the beam.

The system response as a phase variation was also obtained for a harmonic force type input in *N* and for an output represented as a displacement in *m*. The response of this phase variation can be seen in Figures 6, for the first and second resonant frequency of the system.

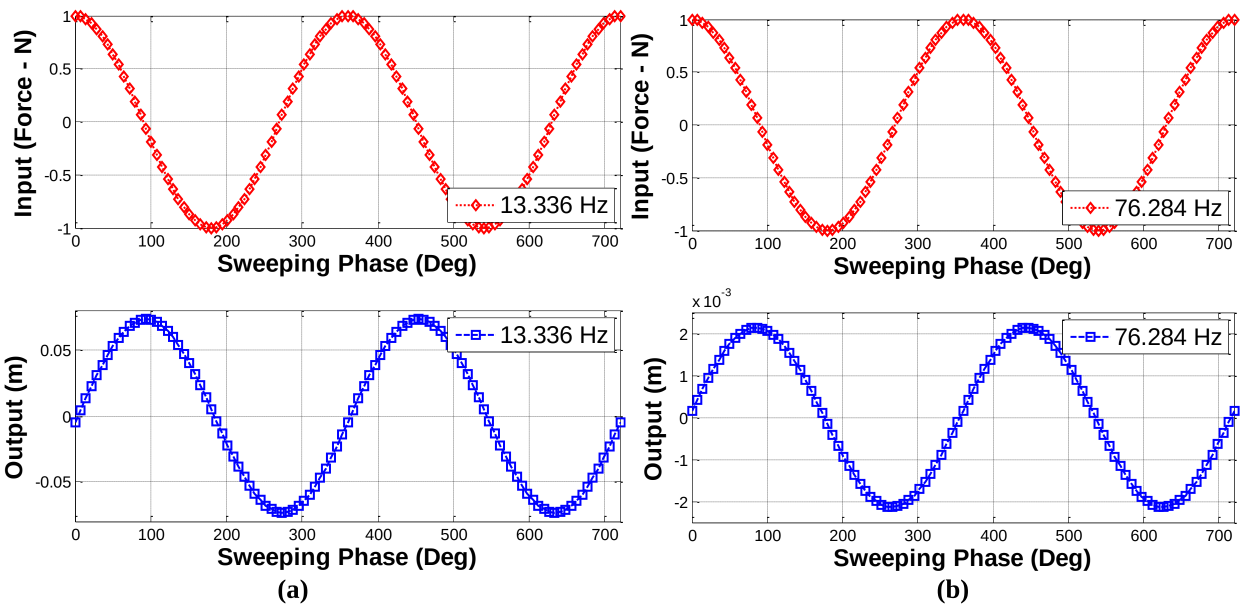

Figure 6. System displacement for the frequencies of 13,34 *Hz* (a), and for 76,28 *Hz* (b).

For the results obtained experimentally, the behavior of the structure in the domain of time and frequency was determined. The reduction of the displacement amplitudes in time can be observed in Figure 7.

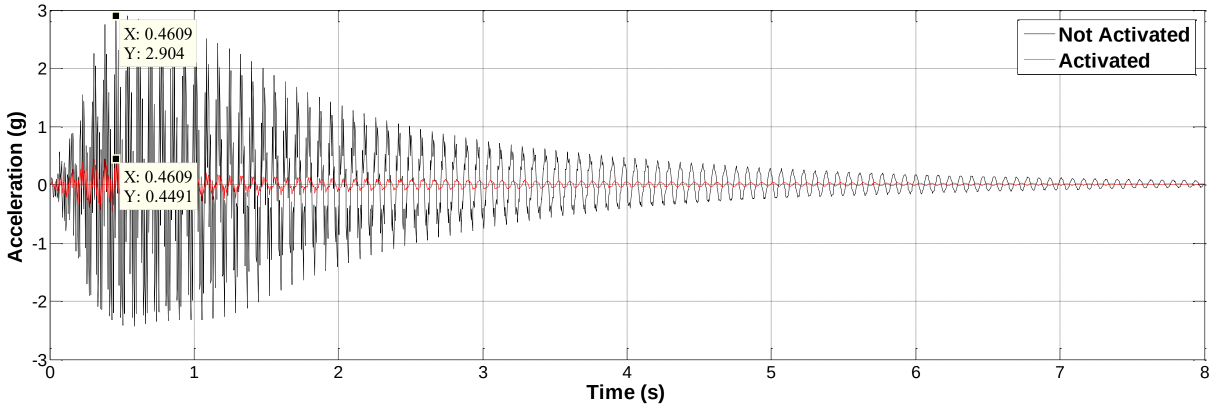

Figure 7. System response in the time, with the circuit activated and not activated.

While in Figure 8, the experimental FRF graphs of the structure with the coupled transducer are presented, and the results are compared with the open loop and closed loop.

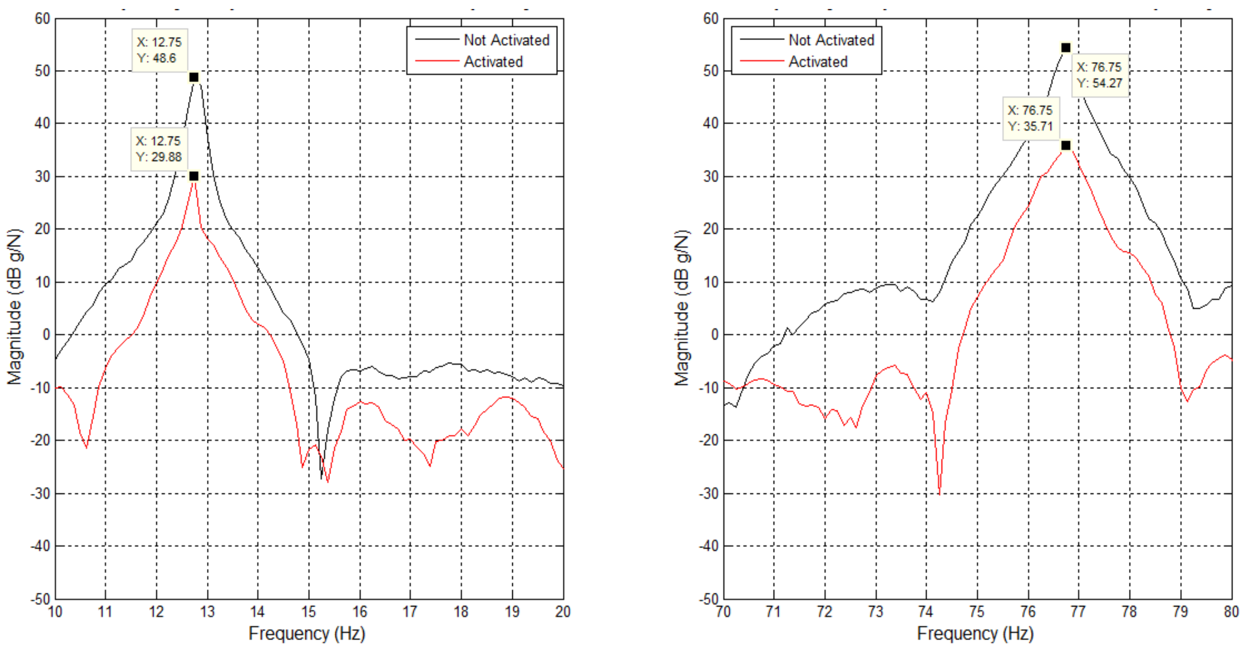

Figure 8. FRF of the beam for the natural frequencies of the system.

As shown previously, it was found that there was a reduction of the amplitudes of response of the system, when the circuit is activated. This reduction was 18.72 *dB* and 18.56 *dB*, which in percentage represents 38.52% and 34.19%, for the first two natural frequencies of the structure, respectively. What in time is equivalent about 85% reduction in response amplitudes of the system with reference to the high values of peak-to-peak amplitude, which is shown in Figure 7, with activated and not activated system.

The frequency values obtained in numerical form for the first and second resonance frequencies were, respectively, 13.34 *Hz* and 76.28 *Hz*. For the natural frequencies obtained experimentally, the values of 12.75 *Hz* for the first and 76.75 *Hz* were found for the second. These values represent a variation of 4.63% for the first natural frequency and 1.01% for the second natural frequency. Another characteristic of this type of control is that the natural frequencies are not altered by the activation of the circuit - that is, the rigidity does not change, proving that the amplitude reduction is only due to the increase in damping.

5. CONCLUSIONS

In this way, the efficiency and robustness of the proposed system is proven, being able to attenuate more than one natural frequency in an autonomous and independent way. By having simple construction and presenting a wide range of actuation, this system can be applied in several different systems, since well dimensioned.

The results obtained were satisfactory and in agreement with the values presented in the consulted literature. Therefore, the control strategy, the circuit utilized and the implementation of the Negative Impedance Circuit (NIC) were executed to the satisfaction and were able to reach the desired goal.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Cowper, G. R., 1966. "The Shear Coefficient in Timoshenko's Beam Theory". Transactions of the ASME, *Journal of Applied MechanicsI*, Vol. 33(2), pp. 335-340. doi:10.1115/1.3625046.

Hagood, N.W., Von Flotow, A., 1991. "Damping of Structural Vibrations with Piezoelectric Materials and Passive Electrical Networks". *Journal of Sound and Vibration*, Vol. 146, pp. 243-268. https://doi.org/10.1016/0022-460X(91)90762-9.

Inman, D. J., 2001. *Engineering Vibration*. Prentice Hall International, New Jersey, 2nd edition. ISBN: 013-0174783.

Leo, D. J., 2007. *Engineering Analysis of Smart Material Systems*. John Wiley & Sons, Virginia, 1st edition. ISBN: 978-0-471-68477-0.

Moheimani, S. O. R., Fleming, A. J., 2006. *Piezoelectric Transducers for Vibration Control and Damping*. Springer, Newcastle, Australia, 1st edition. ISBN-13: 9781846283314.

Quickpack Piezo Products, 2019. *Material Properties & Spec Sheets*. Mide Technology Corporation.

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