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Neural Network and Shunt Control for Beam Structure: Multimodal Approach

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Abstract. *Piezoelectric materials have been extensively studied in recent years for the development of electromechanical harvesting and damping devices. Usually linked to a structure, these kinds of materials convert kinetic energy into electric energy, and your electronic parameters interact directly to the vibrations of the system they are coupled on. Therefore, this work aims at the usage of artificial neural network techniques in the implementation of a multimodal shunt control in a structural set of a cantilever beam coupled to a piezoelectric layer in the piezo-beam configuration. For the architecture of the neural network was used software with finite element model implemented, and efficiency analysis was done by comparing the algorithm's response and the peaks of the beam for the first two natural vibration modes to piezoelectrics of 10mm, 25mm and 50mm of length. The results show that the neural network provides an average gain superior to 23dB for both modes, in an average time of 50 seconds, defining a range of damping for the piezo layer of 5 to 45mm from the crimp, and respectively showing the 10mm piezoelectric as the best in damping per area.*

Keywords: *Vibrations Control, Neural Network, Smart Structures, Shunt Control, Cantilever Beam*

1. INTRODUCTION

The field of smart structures, or structures with integrated sensors and actuators, has arisen to offer improved vibration control in applications where passive techniques are either insufficient or impractical. The introduction of these materials with small volume, low weight, and ease of structural integration, made piezoelectric sensors and actuators has been the overwhelming transducer of choice for smart structures. (Aphale *et al.*, 2007). It is well known that there are several difficulties associated with the control of flexible structures, the foremost of which are: variable resonance frequencies; high system order; and highly resonant dynamics. Traditional control system design techniques such as LQG, H2, and H∞ commonly appear in research works and have been well documented. Unfortunately, the direct application of such techniques tends to produce control systems of a high order and possibly poor stability margins. (Santos and Trindade, 2009) The design of controllers for smart structures is a challenging problem due to the presence of non-linearities in the structural system and actuators, the limited availability of control force, and the non-availability of accurate mathematical models. (Rao *et al.*, 1994). In this scenario, the usage of neural network techniques for vibration control has been receiving attention for its constant self-learning features that make this model capable of changing its parameters to adapt to different structural conditions or variable external excitation.

Works in this area have become common. Can be cited some few example, as the proposition of a fuzzy-logic algorithm to the vibration suppression of a clamp-free beam with piezoelectric sensor/actuator (Zeinoun and Khorrami, 1994), or the developed of a nonlinear feedforward controller for smart structures, that showed that the neural network is essentially a transversal filter with a nonlinear hidden layer between the input and output. (Snyder *et al.*, 1995). Therefore, this work aims the usage of an Artificial Neural Network to define Resistance and Inductance parameters for a Resonant circuit, through autonomous attenuation, which associated with a piezoelectric layer are set off to provide multi-modal shunt control in a cantilever beam.

2. Equation of Motion for Beam Structure

For the study of the structure was adopted the classic beam model (piezoceramic-host). (Santos, 2008). In this case was considered only the presence of deflection, disregarding the shear, thus Bernoulli Euler theory can be developed the equation of motion for the structure. With the applied theory of the Bernoulli can be developed the equation of motion for the structure, this form the structure-patches-circuits coupled equations of motion can be written as

$$\begin{bmatrix} M & 0 \\ 0 & M_q \end{bmatrix} \begin{Bmatrix} \ddot{u} \\ \ddot{D}_p \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & C_q \end{bmatrix} \begin{Bmatrix} \dot{u} \\ \dot{D}_p \end{Bmatrix} + \begin{bmatrix} K_m & -\bar{K}_{me} \\ -\bar{K}_{me}^t & \bar{K}_e \end{bmatrix} \begin{Bmatrix} u \\ D_p \end{Bmatrix} = \begin{Bmatrix} F \\ F_q \end{Bmatrix}, \tag{1}$$

where M_q is the inertial vector due to the presence of resistance and inductance, u and D_p are the vectors global mechanical displacement and electric displacement dofs. M, K_m, $\bar{K}_{me}$, $\bar{K}$ are the mass and mechanical, piezoelectric and dielectric stiffness matrices and F is the mechanical excitation force vector. C_q and F_q are the matrix of the damping and the vector of force dues the presence of resistance and inductance, but how in this work is studded only the output mechanical the value of the vector of electric voltage is equal zero.

3. FINITE ELEMENTO MODEL OF PIEZOELECTRIC BEAMS

The structure is a fixed beam of the aluminum of dimension 220 mm in length, width of 25mm and thickness of 3 mm, the piezoelectric has a variable length, width of 25mm and thickness of 0.5 mm, as we can see in the Figure 1. The extension piezoceramics are made of PZT-5H material whose properties are: $\bar{C}_{11}^D = 97.767$ GPa, $\rho = 7500Kg.m^{-3}$, piezoelectric coupling constants $\bar{h}_{31} = 1.3520x10^9$ N.C^1, and dielectric constants $\bar{\beta}_{33}^{\epsilon} = 57.830x10^6 m.F^1$. For the beam has: $\rho = 2700Kg.m^{-3}$ and $E = 70x10^9 MPa$. (Santos, 2008).

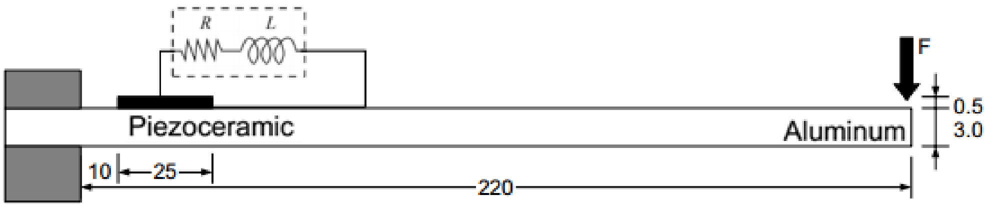

Figure 1. Representation of cantilever beam with bonded extension piezoceramic patch.

The optimization had the focus in resistance and inductance values of the circuit, wherever the resistance (R) is responsible in damping by means of Joule effect and the inductance (L) is responsible to control resonant frequency of the structure, this form had use a shunt circuit, the representation for this system can be seen in Figure 2.

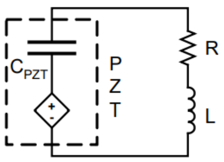

Figure 2. Configuration of the RLC circuit together with the piezoelectric.

Analysis of the equations for harmonic vibrations

For analysis of harmonic vibration, the proposed model (Santos, 2008) is used to evaluate the mobility (velocity/force) frequency response function of the base structure. The resistive (R) or resonant (RL) shunt circuit affects both the passive control performance. In this way, it became necessary to use the circuit that will dissipate the energy or to storage for later use. How this work analyze a purely mechanical excitation, such as F_q = 0 and F = $bfe^{j\omega t}$, the amplitude of a displacement output y = c_pu can be written as $y = G(\omega) f$, where the FRF $G(\omega)$ is

$$G(\omega) = c_p\{(-\omega^2 M + K_m - \bar{K}_{me}(\omega^2 M_q + i\omega C_q + \bar{K}_e)^{-1}\bar{K}_{me}^t)\}^{-1} b \tag{2}$$

Analyzing the equation 2 it can be noted that the resistance and the inductance have the capacity to change the rigidity properties of the piezoelectric material, in this way it will be applied to the case types i) open-circuit when R_c tending to infinity and ii) short-circuit when $Lc = Rc = 0$. For the open circuit it has

$$G^{oc}(\omega) = c_p\{-\omega^2 M + K_m\}^{-1} b \tag{3}$$

To the closed circuit

$$G^{sc}(\omega) = c_p\{-\omega^2 M + [K_m - \bar{K}_{me}\bar{K}_e^{-1}\bar{K}_{me}^t]\}^{-1} b \tag{4}$$

You may note that no structural modification is observed in the open circuit box, whereas in the case of a short circuit, the rigidity of the piezoelectric patches is reduced.

3.1 Vibration Control using piezoelectric actuators and state feedback

This way is necessary to rewrite the motion equations in the form of state space, containing the displacements and modal velocities of the piezoelectric patches and their derivatives of time.

$$\dot{z} = \hat{A}z + \hat{B}V_c + \hat{B}_f f \;,\; y = \hat{C}_y z, \tag{5}$$

where

$$z = \begin{bmatrix} \alpha \\ q_p \\ \dot{\alpha} \\ \dot{q}_p \end{bmatrix},\; \hat{A} = \begin{bmatrix} 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \\ -\Omega^2 & K_p & -\Lambda & 0 \\ L_c^{-1}K_p^t & -\Omega_e^2 & 0 & -\Lambda_e \end{bmatrix},\quad \hat{B} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ L_c^{-1} \end{bmatrix},\; \hat{B}_f = \begin{bmatrix} 0 \\ 0 \\ b_\phi \\ 0 \end{bmatrix},\; \hat{C}_y = \begin{bmatrix} c_\phi & 0 & 0 & 0 \end{bmatrix}. \tag{6}$$

The modal displacements are such that $u = \phi\alpha$ and, for mass normalized vibration modes, $\Omega^2 = \phi^t K_m \phi$ and $\Lambda = \phi^t C \phi$. Ω is a diagonal matrix which elements are the undamped natural frequencies of the structure with piezoelectric patches in open-circuit. $\Omega_e^2 = L_c^{-1}\bar{K}_e$ and $\Lambda_e = L_c^{-1}R_c$ are both diagonal matrices which elements stand, respectively, for the squared natural frequencies of the electric circuits and the ratio between the resistances and inductances. The electromechanical coupling stiffness matrix projected in the undamped modal basis is defined as $K_p = \phi^t \bar{K}_{me}$. Input b and output c_y distribution vectors are also defined, with modal projections $b_\phi = \phi^t b$ and $c_\phi = c_y \phi$, and f is a vector of the amplitudes of each mechanical force applied to the structure (Santos and Trindade 2016).
A linear state feedback for the applied voltages V_c is assumed such that $V_c = -gz = -g_{dm}\alpha - g_{de}q_p - g_{vm}\dot{\alpha} - g_{ve}\dot{q}_p$, where g is a matrix of control gains for each state variable. Therefore, the state space equation (5) becomes

$$\dot{z} = (\hat{A} - \hat{B}g)z + \hat{B}_f f \;,\; y = \hat{C}_y z. \tag{7}$$

For a single-input mechanical excitation f, the closed-loop or controlled amplitude of a single displacement output y can be written such that $\tilde{y} = G_h(\omega)\tilde{f}$, where the FRF $G_h(\omega)$ is

$$G_h(\omega) = \hat{C}_y(j\omega I - \hat{A} + \hat{B}g)^{-1}\hat{B}_f, \tag{8}$$

which can also be derived from the second order equations of motion projected into the undamped modal basis leading to

$$G_h(\omega) = c_\phi\left\{-\omega^2 I + j\omega(\Lambda + K_p D_{cc}^{-1} g_{vm}) + [\Omega^2 + K_p D_{cc}^{-1}(g_{dm} - K_p^t)]\right\}^{-1} b_\phi, \tag{9}$$

where the closed-loop dynamic stiffness of the electric circuit D_{cc} is

$$D_{cc} = -\omega^2 L_c + j\omega(R_c + g_{ve}) + (\bar{K}_e + g_{de}). \tag{10}$$

In this work, the control gain g is calculated using the standard optimal LQR control theory applied to a single-input/single-output case, that is with only one active-passive patch-circuit pair for the control to minimize the vibration amplitude at one specific location of the structure, such that the following objective function is minimized

$$J = \frac{1}{2}\int_0^\infty \left(\dot{y}^2 + rV_c^2\right) t, \tag{11}$$

where $\dot{y}$ is the velocity at one location of interest and V_c is the control voltage applied to the active-passive shunt circuit in all cases following an iterative routine proposed in (Trindade *et al.*, 2001).

4. CONTROL METHODS

Even a minimal vibration is capable cause large destruction in mechanical systems, for that techniques to suppress or establish control over the system's vibration is widely researched. These researches generally presents two categories, the passive controls, as presented by the model used for passive control of the vibration and sound radiation from submerged shells (Oh *et al.*, 2002), and active controls, where we have structural active vibration control using active mass damper by block pulse functions (Younespour and Ghaffarzadeh, 2017), work that describe the concept of the using of a secondary system to absorbs the mechanical energy of the first one and consequently your vibration amplitude. Also is known the possibility of systems of control that merge these two categories of techniques, creating passive-active systems as its seen with the application of H∞ control technique in modeling and H∞ control of active-passive vibration isolation for floating raft system (Yang *et al.*, 2017). Inside the concept of an additional system designed for damping, stands out the usage of piezoelectrics as secondary system for vibration absorption as were made in experiments on optimal vibration control of a flexible beam containing piezoelectric sensors and actuators (Abreu *et al.*, 2003), where instead of transform the mechanical absorbed energy into the range of motion, the structure transforms mechanical energy into electrical and disperses it. A similar structure was adopted to this work, generally referenced as shunt control.

Shunt Control

Shunt control is a wide applied concept, used not only for vibration control, present in a large application of electronic systems. The main idea comes from the principle of energy conservation that establishes that the total quantity of energy in an isolated system remains constant, a concept associated with a large number of scientists along the years, since Thales of Miletus until James Prescott Joule, been even correlated with Newton. Starting from this principle, once you used the amount of energy in an isolated system, it has no longer driving source to realize any movement, therefore, in a vibration control, design a secondary system that consume the internal energy of the primary one, as the energy coming from any external excitement, results in your stabilization.

The basic way of using the energy of a system is converting this energy into movement, heat, electricity or any other energetic state. The most common way of conversion of energy is from work to thermal energy. A wide range of devices does this conversion accidentally, either by mechanical friction, joule effect or any other disturbances, using only part of their potential to perform its work, what is defined by his efficiency, losing the rest by this conversion. Other devices, on the other hand, produce this heat energy intentionally for multiples usages.

A conversion that still has no much highlight, but is increasingly applicable is the conversion from work to electrical energy, for this scenario piezoelectrics stands out. Ceramics piezoelectric is described as a ceramic set that has a natural dipole present on your structure. The existence of this dipole does that the structure deforms in the presence of an electrical field or produce an electrical dislocation with mechanical deformation. This singular characteristic makes these ceramics an interesting alternative to the conversion of energy without the need of dealing with punctual heat that could be harmful to the parts of the system exposed to it, once the heat can weaken or even force a change of phase in its structure. The application of ceramics piezoelectric as shunt circuits are present in a large scale of systems that used the concept of shunt control, as its seen in the work of structure control by a hybrid system in extension and shear (Santos, 2008), the similar idea was applied to reduce the error of the measure of high-speed nano-scale positioners that present a dominant first mode of vibration due harmonics of an input signal. (Aphale *et al.*, 2007). The usage of a piezoelectric for shunt with a parallel R-L circuit for structural damping (Wu, 1996) was an attractive model that we adopted for this work. The main idea of our research is demonstrating how efficient techniques of a neural network are to determine the resistance (R) and inductance (L) parameters for theses circuits when we compare with genetic algorithm techniques, aiming the best optimization.

5. NEURAL NETWORK AND SHUNT CONTROL

The main idea of shunt control comes from the principle of energy conservation that establishes the total quantity of energy in an isolated system remains constant. Once you used the amount of energy in these systems, it has no longer driving source to realize any movement, therefore, in an inertia system, design a secondary system that consumes any external excitement, results in your stabilization (Araujo *et al.*, 2019).

Smart alternatives were been widely applied to solve theses nature of problems once it presents a nature of self-learning very useful for dynamic solutions, the most used techniques are the genetic algorithm and the artificial neural network, used in similar research for Shunt Active Power Filter Control (Qasim and Khadkikar, 2014) for Smart Structures. This section presents a description of the neural network method.

Neural Network Method

Artificial Neural Networks(ANN) are a set of computational models used to obtain answers that try to reproduce the principle of animal thinking, learning by experience, through mathematical algorithms that seek the connection between received information, being able to learn and improve their results with multiples training and applications. There are three typical steps for using this model; the input of data, in general, is used arrays to organize this data. Training, the step where multiple data are crossed and analyzed according to stipulated conditions, producing increasingly accurate and close answers to the mathematical ideal, and data output. To create the input data, the values of resistance and inductance were randomly varied by a normal distribution centered on analytical optimal values in order to produce individuals for the training. The frequency response for these values was saved as the Target data.The choose of the size of the vectors were thinking aims to balance aspects of precision and execution time of the network, focusing on the converging line of the code. The training function of the network updates weight and bias values according to Levenberg-Marquardt optimization. The choose was due to the high-speed answer of this function and the reliability associated with this backpropagation algorithm, working in a maximum of 1000 epochs. The error function used were the difference between the peak amplitude-frequency of first vibration mode for both open and short circuit. The code objective was to minimize this difference, the flow chart for this technique can be seen in Figure 3.

This technique creates a Neural Network capable of define parameters of Resistance and Inductance for a resonant circuit and provides respective damping for the beam, with the piezo layer in a fixed position. However, practical applications could demand to move the piezo layer to another position and it would require new training for the network. To avoid the time would lose in this process a secondary Network was created to define R and L configuration based on the

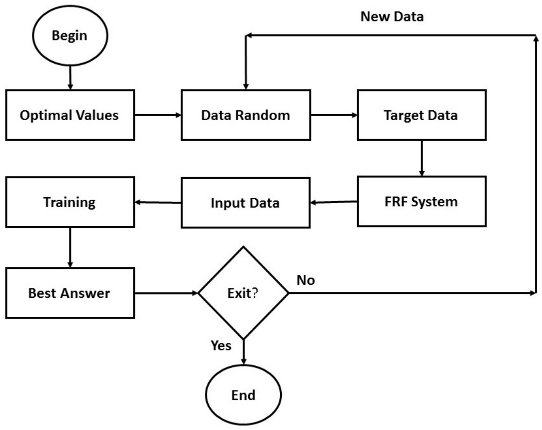

Figure 3. ANN's Flow Chart

position of the piezo-layer, using the position as Input data, and R and L configuration as Target data.

6. RESULTS

The Figure 4 presents the results for three size of piezoelectrics with configurations of Resistance and Inductance defined by this technique, for the piezo layer setted up from 5 to 45mm from the crimp, in a damping per area comparison, showing that, for both vibrations modes, the 10mm layer has the best results in almost all the positions, being the better choice if you are looking for damping efficiency. The frequency response for averages configurations suggested for the first and second vibration mode are shown in a comparison with a short circuit in Figure 5, showing damping superior to 23dB for both natural modes. Figure 6 presents the range of values for damping that both vibrations modes demonstrate with the piezo layer set up in 5 to 45mm from the crimp, showing a low variation of amplitude, and high damping in this range.

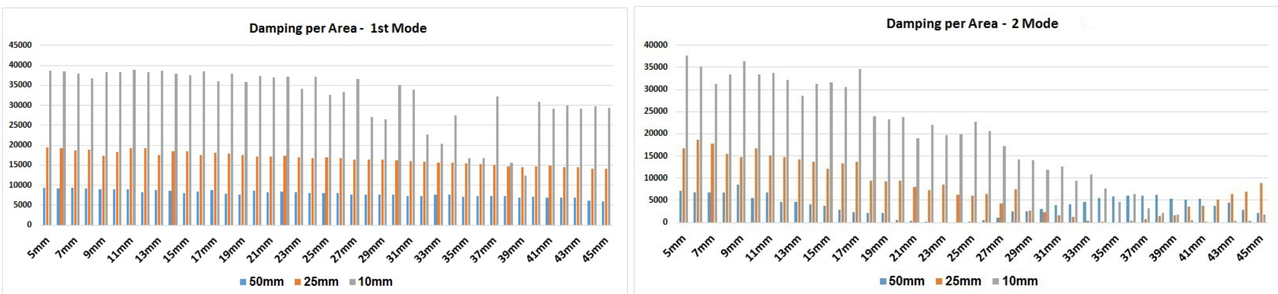

Figure 4. Damp per Area - Piezos of 10, 25 and 50mm of Length

The Figure 7 presents the frequency response for the beam with two piezoelectric layers, each one set up to provide damping for a vibration mode of the beam, showing that technology can be used simultaneously for multi-modal damping. The range of values for this multimodal configuration in the range of 5 to 45mm from the crimp is shown in Figure 8 for both natural modes of vibration.

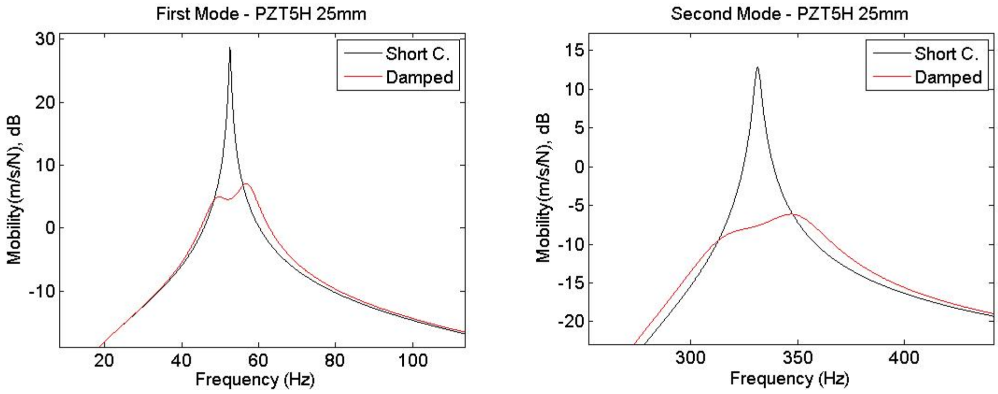

Figure 5. A) FRF 25mm - First Mode B) FRF 25mm - Second Mode

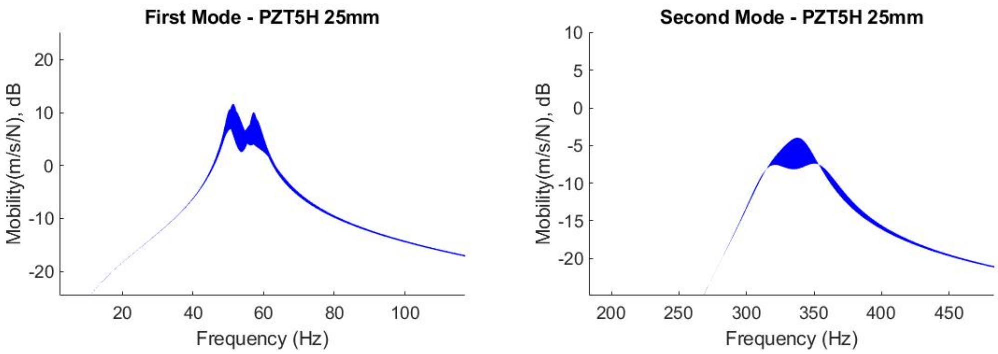

Figure 6. FRF A) FRF 25mm - First Mode B) FRF 25mm - Second Mode

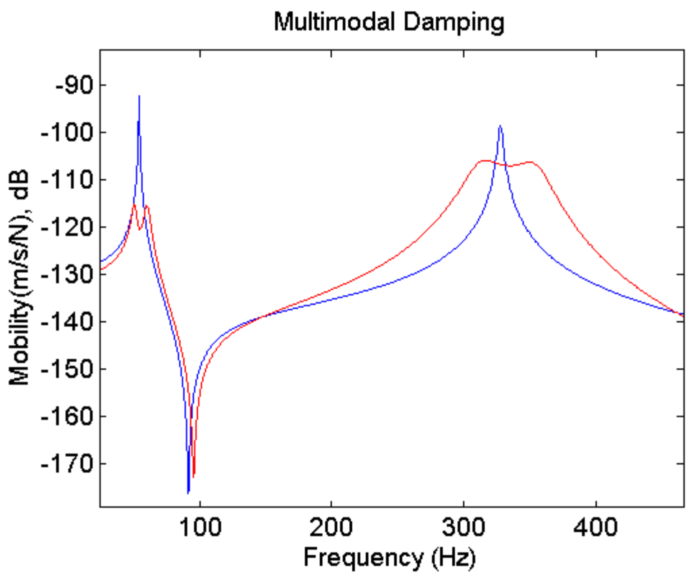

Figure 7. Frequency Response for First and Second Mode Using Shunt Control (Red) and Open Circuit (Blue)

A traditional way to define parameters for vibration control is the usage of algorithms that reproduce the principle of natural selection, as the genetic algorithm. These techniques even capable of providing respective damping and been very interesting in problems of shape and nonlinearities, usually demands more computational power and time than neural networks. The Figure 9 shows a comparison of runtime between Artificial Neural Network and Genetic Algorithm techniques for ten experimental tests in same conditions, where the Genetic technique presents the average time of 1628.3272 seconds to provide a configuration, and the Neural Network presents 52.8519 seconds of average, showing up much

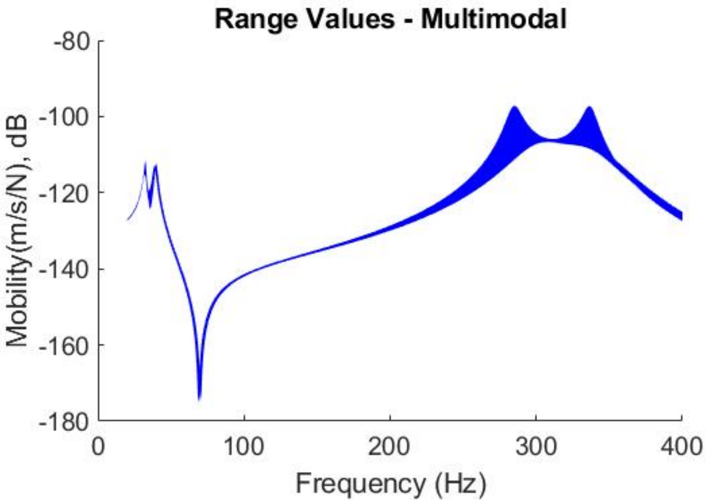

Figure 8. Range of Values for Multimodal Damping

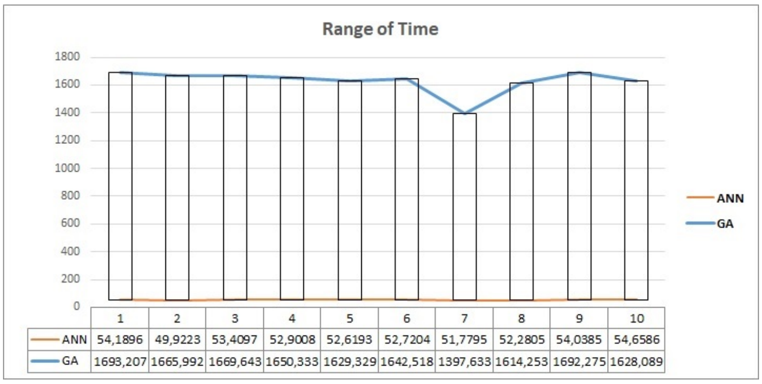

Figure 9. Time Comparison of Artificial Neural with Genetic Algorithm

superior.

7. CONCLUSION

An analysis of performance, with a focus in a time of processing and attenuation of the amplitude for frequency tuned, show Neural Network as a great alternative when compared with traditional techniques. The results, the ANN shows up a better choice for the shunt control of smart structures, once this technique demonstrates the answers in order of 50 seconds, having the average time and gain in damping, respectively, 52.8519s and 23.38dB for both vibration modes.

This technique demonstrates large possibilities of applications into practical problems, once it has parameters not fixed and a model of solution that includes various types of dynamic problems.

An additional advantage of this technique is your adaptive learning characteristic, that allows your structure goes through complex changes without demand additional computational cost to adapt to the new conditions. This technique can be used for active and passive vibration control systems or a quick answer from the controller, as for the monitoring and decision-making on smart structures.

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