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USING A NEURAL NETWORK AND GENETIC ALGORITHM FOR A CANTILEVER BEAM WITH SHUNT CONTROL

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Abstract. *Smart techniques have been receiving widely attention in recent years as an alternative for solve engineering problems. Inside this concept, algorithms of optimization that seeks empirical connections between parameters of a systems stands out, mostly due its nature of dealing with data without constantly resort to complex equations. Therefore, this work aims to the usage of two categories of these algorithms, the Genetic Algorithm and Artificial Neural Network, in intention to establish vibration control in a structural set of a cantilever beam coupled to a piezoelectric layer in the piezo-beam configuration, doing a comparison between them focusing on time's execution and attenuation provided for the first natural mode of the beam. Were used piezoeletric ceramics of 10, 25 and 50mm of length, setted up since 5mm to 45mm from the crimp. The results shows that Genetic Algorithm and Neural Network presents close answers when they were configured to define electronic parameters for a shunt circuit, presenting average 23dB of damping, the larger difference comes in time of executions, where Genetic Algorithm presents average time of 1233,44s per execution and Neural Network presents 98,11s*

Keywords: *Vibration Control, Genetic Algorithm, Neural Network, Shunt Control, Piezoelectric Material . . .*

1. INTRODUCTION

The use of piezoelectric materials has become popular in many engineering applications. One of the most promising uses for piezoelectric materials is their incorporation into smart structures as combined sensor and actuators. In this role, the materials will be able to detect mechanical disturbances in their surroundings and adjust to these stimuli. There are basically two types of strategies adopted when it comes to integrating the piezoelectric sensors and actuators to flexible structures: bonding to the host structure's surfaces (or embedding into a laminate/composite structure) thin patches or layers of piezoelectric ceramics, polymers and/or composites. In both cases, the interface between the host structure and the piezoelectric device plays a decisive role in terms of mechanical strain and stress transfer mechanisms. A satisfactory interface ensures that effective actuation or sensing could be achieved, preventing the need of excessive voltages to be applied, in the case of actuators, and/or inaccurate output results, in the case of sensors, thereby increasing robustness of control systems.

Surface-mounted piezoelectric sensors and actuators are normally poled in the thickness direction so that the application of a through-thickness electric field forces an elongation or contraction of the actuators. Distributed sensors and actuators integrated with the flexible structure have been applied successfully in the closed-loop control. If the actuators are well-bonded to the surface of the host structure, their elongation or contraction causes a deformation of the host structure. That is why, surface-mounted piezoelectric sensors and actuators are also known as extension or extension bending sensors and actuators and were widely used on active (Sunar and Rao, 1999), passive (Reza Moheimani, 2003) and hybrid active-passive (Tang, Liu andWang, 2000; Trindade and Benjeddou, 2002; Santos and Trindade, 2011) control applications.

When in passive mode operation, piezoelectric materials act as energy converters, transforming strain energy into usable electrical energy. Therefore, when connected to properly designed electric circuits, they may be used for passive, semi-passive or active-passive vibration control (Hagood and von Flotow, 1991). The search for effective circuits to profit from the energy extracted from a vibrating structure by the piezoelectric device and either dissipate it into the environment or store it for future use. In both case, the energy extracted from the host structure leads to a reduction of vibratory energy and, thus, may be used for passive vibration control (Reza Moheimani, 2003). When combined to a voltage source aiming at actively control the host structure vibrations, these passive or semi-passive circuits, so-called shunt circuits, become active-passive shunt circuits (also known as active-passive piezoelectric networks). It was shown that, when properly designed, this combined solution not only allows to set either purely active or purely passive but also yields better performance than individual active or passive solutions (Tang, Liu and Wang, 2000; Santos and Trindade, 2011). In this papers was presented a comparison of two techniques for determinate components, resistance and inductance, of shunt control for a cantilever beam with focus in position and size of the patch piezoelectric.

FINITE ELEMENT 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: $\bar{C}^D_{11} = 97.767$ GPa, $\rho = 7500 Kg.m^3$, piezoelectric coupling constants $\bar{h}_{31} = 1.3520x10^9$ N.C^1, and dielectric constants $\bar{\beta}^{\varepsilon}_{33} = 57.830x10^6 m.F^1$. For the beam has: $\rho = 2700 Kg.m^{-3}$ and $E = 70x10^9 MPa$. (Santos, 2008).

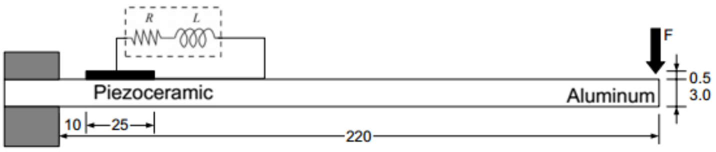

Figure 1: Representation of cantilever beam with bonded extension piezoceramic patch.

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, with can see in Figure 2.

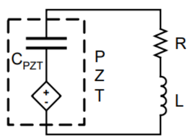

Figure 2: Configuration of the RLC circuit together with the piezoelectric.

EQUATION OF MOTION

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

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

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.

2. VIBRATION CONTROL ANALYSIS

For vibration control analysis, the proposed model (Santos and Trindade 2011) 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 and active-passive (hybrid) control performance.In this way, it became necessary to use the circuit that will dissipate the energy or to storage for later use.

2.1 Evaluation of mechanical output under mechanical excitation

How this work analyze a purely mechanical excitation, such as $V_c = 0$ and F = $bfe^{j\omega t}$, the amplitude of a displacement output y = c_yu can be written as $y = G_p\ (\omega)\, f$, where the FRF $G_p(\omega)$ is

$$G_p(\omega) = C_y\{\omega^2 M + J\omega C + K_m - K_{me}(\omega^2 L_c + J\omega R_c + k_e)^{-1} K_{me}\}^{-1} \tag{2}$$

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

$$G_p^{oc}(\omega) = C_y\{\omega^2 M + J\omega C + K_m\}^{-1} b \tag{3}$$

To the closed circuit

$$G_p^{sc}(\omega) = C_y\{\omega^2 M + J\omega C + K_m - K_{me} Ke\}^{-1} b \tag{4}$$

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.

2.2 Vibration control using piezoelectric actuators ans 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

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

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

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

where the closed-loop dynamic stiffness of the electric circuit $\underline{D}_{cc}$ 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 $\underline{g}$ 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

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

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, Benjeddou and Ohayon, 1999).

3. OPTIMIZATION BY SMART TECHNIQUES

Optimize is the act of creation the more favorable conditions for the development of something. When it is spoken in optimization of a circuit, it is sought to the best configuration of your passive elements to guarantee that this circuit do the best way what it was made to do, in case of a shunt circuit, we search for the best configuration to provide dispersion of energy and, consequently, damping of a structure. (Araujo, Prado, Santos, 2019). The usage of smart algorithm to solve this problems has been widely applied. To this work was adopted two classical smart techniques, the neural network and genetic algorithm techniques.

3.1 ARTIFICIAL NEURAL NETWORK

Artificial Neural Networks (ANN) are a set of computational techniques to obtain answers that present a mathematical model corresponding to the neural structure of living organisms, being able to learn and to improve their results with multiples training and applications. Neural networks have a large number of highly interconnected processing elements (nodes) that demonstrate the ability to learn and generalize from training patterns or data. They, like humans, can perform pattern-matching tasks, while traditional computer architecture, however, is inefficient at these tasks. On the contrary, the latter is faster at algorithmic computational tasks.Neural networks, like fuzzy logic control/decision systems, are excellent at developing human-made systems that can perform the same type of information processing than our brain performs.(Lin, 1991).

There are three typical steps for use 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 were saved as the Target data. The choose of the size of the vectors were think 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 the high speed answer of this function and the reliability associated with this back propagation algorithm, working in a maximum of 1000 epochs and 10 hidden layers. The error function used were the difference between of the peak amplitude frequency of first vibration mode for both open and short circuit.

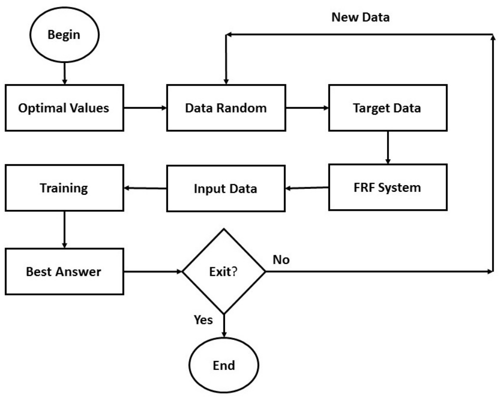

Figure 3: Neural Network Flowchart

3.2 GENETIC ALGORITHM METHOD

The Genetic Algorithm (GA) can be described as a family of computational models that are inspired by the evolution of species for problem solving. They incorporate potential solutions to a problem in species of chromosomes, or population,that pass through segregation and data crossing, applying a selection nature that seeks to filter the results that best match the solution of the problem, selecting them positively for future crossings and penalizing those that flee the possible solution of the problem, thus forcing the structure to converge to a single value that meets the nature of the formulation. This model has been recently adopted to solve a large scale of engineering problems of optimization in several areas as the optimization of laminate stacking sequence for buckling load maximization (Rifte, Haftka, 1996) or even the structural optimization of Lennard-Jones clusters. (Deaven, Tit, Morris, Ho, 1996).

In this work, the Figure 4 shows these both techniques were using aiming to optimize the parameters of Resistance and Inductance of the associated circuit, in intention to provide damping for the beam, with the piezoceramic layer in multiples positions, defining the best locale for the ceramic.

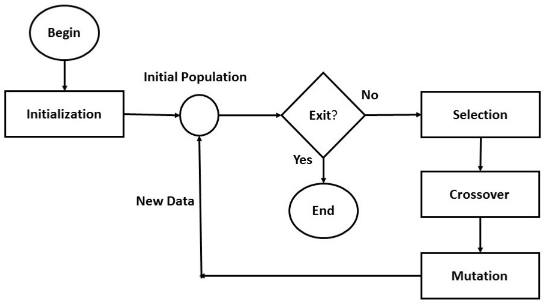

Figure 4: Algorithm Genetic Flowchart

4. RESULTS

The results for Neural Network and the Genetic Algorithm of damping for positions of 5 to 45mm from the crimp are shown in the (Figure 5), in a comparison with the three sizes of ceramic. It's seen a bit of distinction between values generated by both algorithms, and for both methods the piezoeletric with 10mm of length as the best in damping per area. Been the better chose for harvesting devices.

The behavior of three piezo sizes, 10, 25 and 50mm, and varying their positions from 5 to 45mm, were analyzed with each step of 5mm distance. Set in a 220mm beam that undergoes flexion and deformations in the piezo, in which the values of resistances and optimal inductances for each variation were obtained as results.

In Figure 6, it's seen the frequency response for the best and worst case of damping, with piezoceramics of 25 and 10mm of length, in the position 5 and 35mm from the crimp, respectively, showing the range of damping the algorithms can provide. It's seen that, even though not presenting the best damping per area, the piezo of 25mm of length presents the best global damping for the beam, been recommended for cases of control. By contrast the piezo of 10mm of lenght presents the worst global damping, even though it has the best damping per area.

The best global damping provided by the neural network and genetic algorithm, on the best position were, respectively, 24.34dB and 24.45dB for the piezo of 25mm. For the worst case, the neural network presents 15.4dB and the Genetic Algorithm 18.1dB, having too the larger distinction of amplitude of all configurations.

Figure 7 shows the damping for the optimal configuration of Resistance and Inductance for the position of 5mm from the Crimp for Figure 7(a) size of 10mm of length piezo and Figure 7(b) size of 25mm of length piezo. The figure 8 shows up a particular case for the piezo of 50mm of length setted up in 5mm from the crimp. For this position, and length, its seen a large distinction between the techniques, where the damping suggested by the Genetic Algorithm presents a feature of peak, not been recommended for cases of control, on the other side, the Artificial Neural Network can provide for the same and length and position a better shape of damping, as value, in the shape of valley, very useful for cases of control. This fact evidences certain superiority of this technique over Genetic Algorithm for control system applications.

The time of execution for these both techniques is the most evident distinction between them, the Table 1 shows up the suggested configuration with respective time and damping provided by the Genetic Algorithm for the piezo of 25mm of length fixed in 5mm from the crimp. The Table 2 has the results for the same conditions provided by the Neural Network, where can its seen close values such for configuration as damping, but a large distinction in time. The average time for Artificial Neural Network and Genetic Algorithm, were, respectively, 139.1472 and 1628.3270s. To define the configuration for the entire beam were needed 18348 seconds for the Artificial Neural Network, and 2306634 seconds to

Resistance(Ω)	Inductance (H)	Damping(dB)	Time(s)
27801	387,8843	23,9	1693,206567
30320	386,8901	23,19	1665,991664
29075	387,0866	23,5	1669,642542
23606	388,1002	25,23	1650,33263
33081	386,0969	22,49	1629,328715
30132	386,5428	23,24	1642,51844
28468	385,5762	23,23,7	1397,632765
28598	387,0412	23,66	1614,253078
28292	387,6802	23,75	1692,274854
28976	387,3765	23,56	1628,088528

Table 1: Results for Genetic Algorithm

Resistance(Ω)	Inductance (H)	Damping(dB)	Time(s)
30296	397,3777	23,27	107,3682
30239	392,5947	23,3	109,8399
30271	382,4379	23,15	137,2556
30264	372,0686	23,12	140,7768
30473	378,3703	23,22	110,4075
30266	381,3045	23,21	132,0642
30274	392,4681	23,29	135,6881
30256	370,7726	23,4	139,8354
30290	397,1577	23,27	138,6904
30249	383,66	23,2	99,7105

Table 2: Results for Artificial Neural Network

Genetic Algorithm, to produce the configuration for all positions for the beam. Or, 5h for Neural Network, and almost 3 days for Genetic Algorithm.

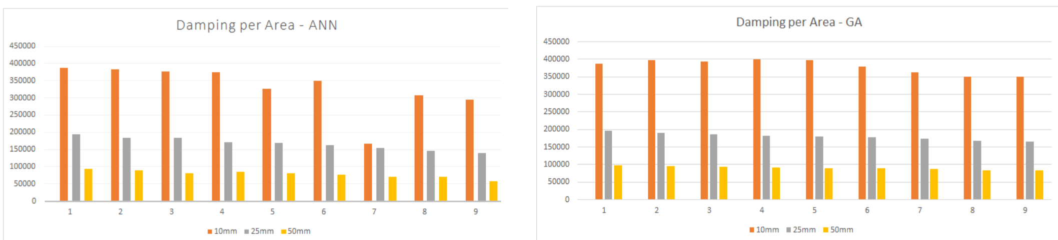

Figure 5: Damping per Area using ANN and GA.

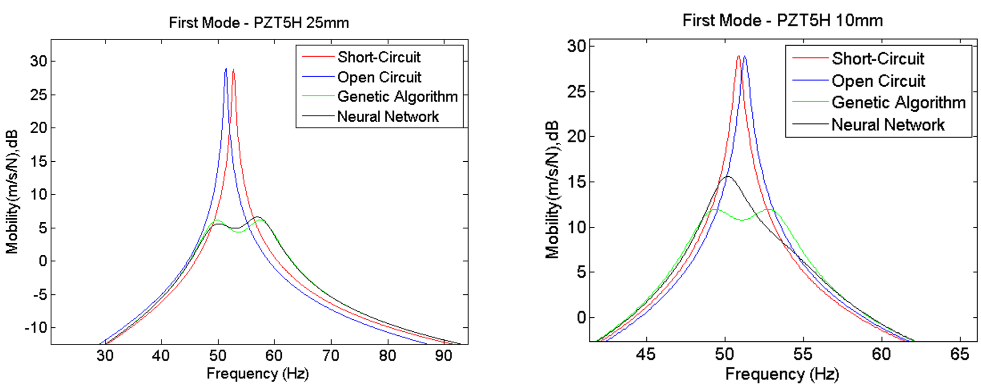

Figure 6: A) FRF - Position 5mm from the Crimp B) - Position 35mm from the crimp

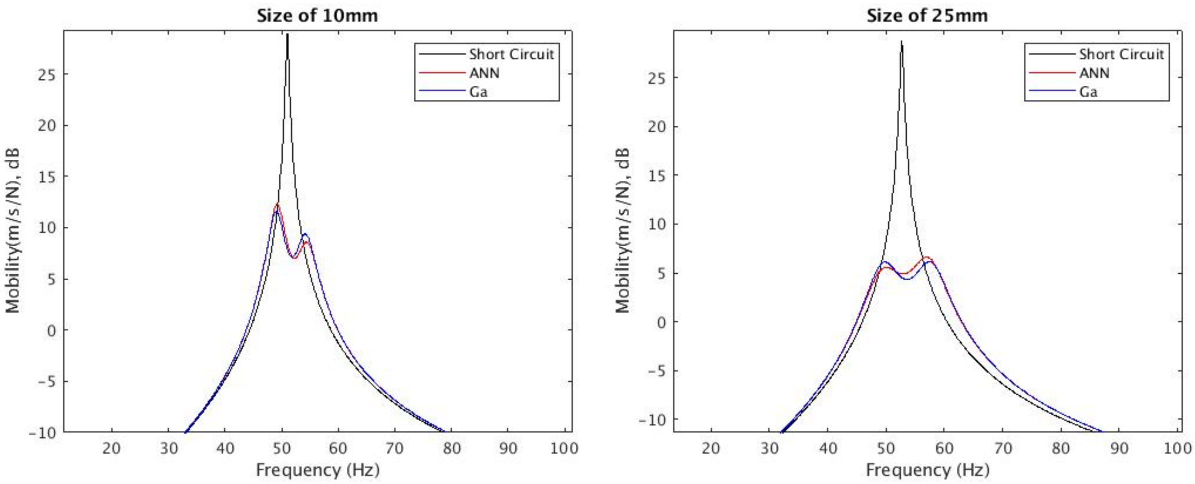

Figure 7: FRF - Position 5mm from the crimp

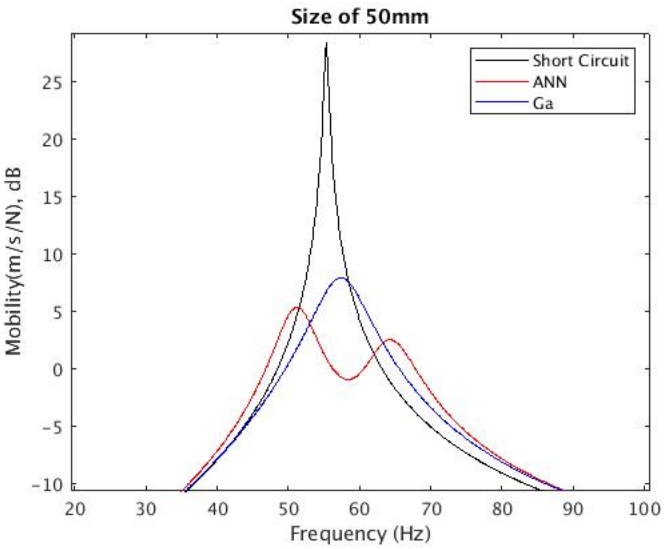

Figure 8: FRF - Position 5mm from the crimp

5. CONCLUSION

The algorithm which use artificial neural network, even with poor training, obtain results close if compare with a genetic algorithm, but so much faster, having respectively the average time processing of 139.1472s, while Genetic Algorithm demands 1628.3270s to provide a close configuration.

To define parameters for the entire beam 2649s were used for the Artificial Neural Network, and 33303 seconds to Genetic Algorithm, showing that even in a continuous case, the neural network outperforms the genetic algorithm when the metric is the time.

The damping provided by the neural network and genetic algorithm, on the best position were, respectively, 24.34dB and 24.45dB. For the worst case, the neural network presents 15.4dB and the Genetic Algorithm 18.1dB, having, in this position, too the larger distinction of amplitude of all configurations, but not that much, proving to be relevant only for more precise control cases.

Between the three size of piezo layers its seen that the piezo of 10mm presents the better damping per area, but worst in global damping. On the other hand, the piezo of 25mm of length presents the best global damping, but not the best in damping per area. The choice between them should be decided by thinking about the type of application.

For the particular case of the piezo with 50mm of length its seen that Neural Network provides a better shape of damping than Neural Network, presenting a Frequency Response in shape of Valley, instead of Peak as presented by the Genetic Algorithm.

For theses presented data, the ANN shows up a better choice for the shunt control of smart structures, once this technique demonstrates a fast response and close results than Genetic Algorithm, even thogh the Genetic Algorithm in almost all cases a better global damping. The choice between these technique, therefore, should be considered for harvesting or control cases.

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