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EXPERIMENTAL INVESTIGATION OF SHAPE MEMORY ALLOY TENDONS APPLIED FOR ATTENUATION OF VIBRATIONS IN A PRISMATIC TABLE

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Abstract. *There are several applications for shape memory alloys (SMA), especially as thermomechanical actuators of low weight and moderate work capability compared to other conventional actuators. These characteristics of SMA actuators, among others, are desirable to attenuate vibrations in mechanical systems. In addition, it is known that mechanical systems can fail when subjected to excitation forces, especially in lightly damped systems, and near to resonance. The purpose of this paper is experimentally verifying the performance of SMA wire actuators applied as tendons to attenuate mechanical vibrations. For this, Ni-Ti SMA thin wires were installed in different configurations in a single-degree-of-freedom structure subjected to harmonic excitations. The obtained results demonstrate that the magnitude of the response can be significantly reduced by the use of the SMA wire tendons as vibration dampers. Interesting aspects are the low level of energy given off to dampen the system as well as a small electrical current intensity for activation of the SMA tendons. It believed to be possible to extend the analysis to various system settings damped, and the use of different shapes of SMA actuators.*

Keywords: *Shape memory alloys, Dynamic analysis, Vibration attenuation.*

1. INTRODUCTION

A significant amount of research on smart or adaptive systems has been developed during the last decades due to the growing demand for this technology in machinery and structures. These systems use sensors, actuators and control units, which are applied to conventional machines and structures with some specific purposes such as control or attenuation of mechanical vibrations, shape control, among others (FLATAU & CHONG, 2002; HURLEBAUS & GAUL, 2006; KORKMAZ, 2011).

The development of adaptive systems with high performance and at the same time with relatively low weight and volume is very important. In this context, this work presents a prismatic structure lightly damped with vibration control by SMA tendons activated using resistive heating. The structure is modeled as a mass spring damper system with one degree of freedom. Two DC motors with unbalanced masses are used as actuators for excitation of the structure. It was verified the change in stiffness of the activated tendons and performed an experimental investigation for various configurations of embedded SMA in the prismatic structure, being tested 15 activation combinations and assessed the influence on the natural frequency of the system and the structural damping. There were observed significant reductions in the level of vibrations when passing through the resonance region due to the change of stiffness and damping in the SMA-structure system.

2. EXPERIMENTAL PROCEDURE

The prismatic table for this study was designed to provide a natural frequency of approximately 1/3 of the maximum useful frequency from the miniaturized DC motor with rotating unbalanced mass used as a shaker for excitation of the structure. The frequency measured for this miniaturized motor is of about 50Hz. The displacement response of the prismatic structure under free vibration was measured by a Linear Variable Differential Transducer (LVDT) in two cases, with and without SMA tendons active in the prismatic structure. In addition, we can compute the damping ratio by logarithmic decrement from free response of the system in both cases. The logarithmic decrement represents the rate at which the amplitude of a free-damped vibration decreases. In addition, the displacement response of the prismatic structure under rotating unbalance (shaker) was measured by LVDT near to the resonance frequency in both cases. To quantify the excitation force due to the rotating unbalanced actuator, the value of eccentric mass was verified in a precision balance and its dimensions were measured. Furthermore, it was checked how the stiffness of the SMA tendons change with activation by Joule effect.

2.1 Thermomechanical characterization setup

The thermomechanical characterization using a universal testing machine (EMIC, model DL10000) to verify and quantify the change in stiffness of the SMA tendon (NiTi wire, 0.29mm in diameter) due to its activation by passing electric current is schematized in Fig. (1). For this purpose, the universal testing machine was set to a tensile testing and equipped with a load cell of 500N. To monitor the temperature of the SMA wire tendon during the test, a data acquisition (DAQ) system equipped with a thermocouple (type K, 100μm in diameter) added. For heating and consequent activation of the SMA tendon, a DC power supply is employed, as pointed out in Figure (1).

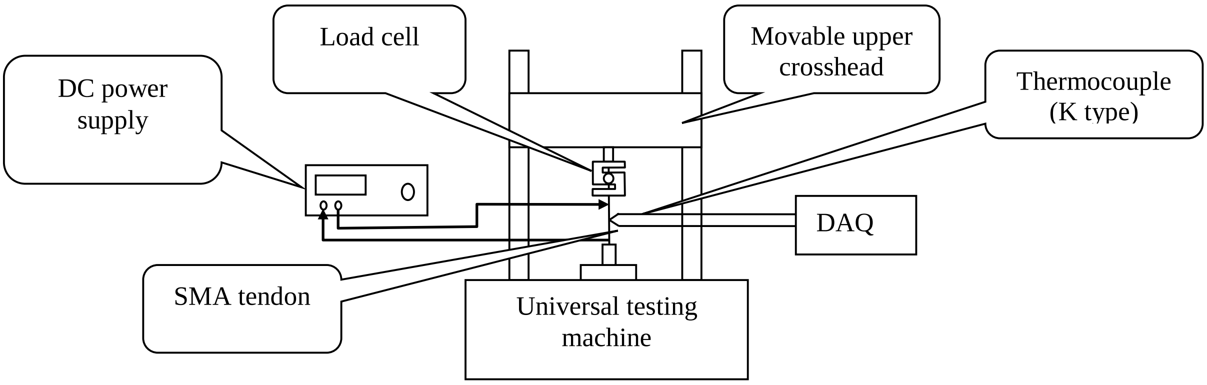


Figure 1. Experimental setup for thermomechanical characterization of the SMA tendons.

The experimental procedure consisted of tensile the SMA tendon in the following temperatures: 24, 26, 29, 40, 45, 50 e 60 °C. In the tensile test, the tendon pulled from zero strength until to reach 9N load at a displacement rate of 5.0 mm/min. After reaching this load level the test was stopped and the movable upper crosshead returning to starting. The deformation of the SMA tendon wire was recovered by heating after the tensile test, so it could be conducted another test. During each test, a different intensity of electric current is passed through the wire to promote heating, monitored by the thermocouple installed in the tendon, as above said.

2.2 Excitation force from two unbalanced DC motors

Physically, the two motors used as shakers are mounted on the frame so that the unbalance force acts predominantly in the direction of displacement represented by x in the Figure 4). These motors are installed as close as possible to the center of mass of the top structure. Electrically, they are connected so that a feeling had rotation contrary to other; to approximate rotational synchronism fed with two different adjustable voltage supplies. This idea is schematized in the simplified model defined in Fig. (2), where the forces perpendicular to the x direction cancel each other out, while add up in the x direction.

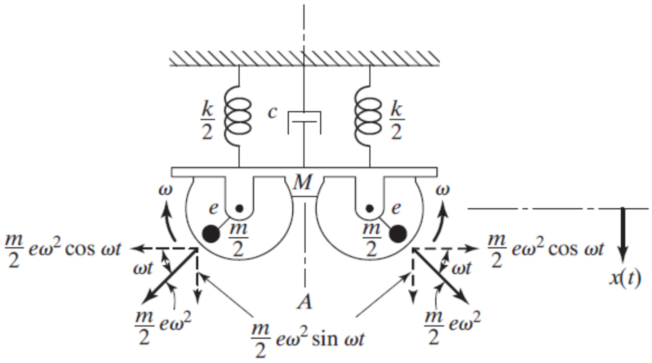


Figure 2. Simplified model of unbalance in rotating machinery (RAO, 2009)

From the representative scheme shown in Figure 2), the equation for the harmonic excitation force can be write as Eq. (1).

$$F(t) = 2\frac{m}{2}e\omega^2 sen\omega t \tag{1}$$

where m - eccentric mass (kg); e - eccentricity (m) and ω - rotating frequency (rad/s).

Each electric motor shown in Figure 3) has an eccentric mass measured using a precision balance and eccentricity (***e***) computed relative to the axis of rotation of each motor. The measured mass and eccentricity values are used to estimate the harmonic force produced by the rotation of the motors.

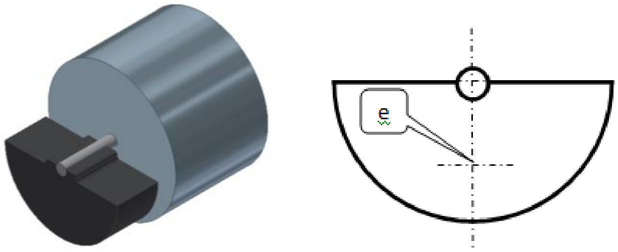


Figure 3. Illustration of the electrical motors used as shakers.

2.3 Prismatc table

The idea was to design a structure that physically models a table with two tops; the lower is the fixing base of the columns to the ground and the upper lid with the fixed columns against rotation. Four steel blades represents the columns, two metallic plates compose the top and bottom. Figure 4) shows the physical model of the structure with the direction of displacement *x*.

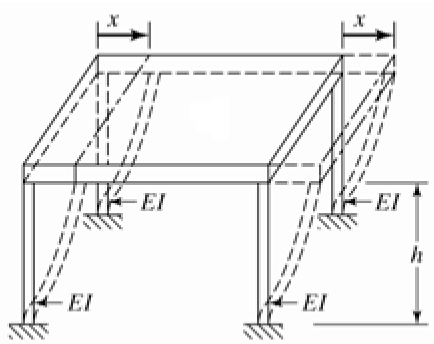


Figure 4. Physical model of the structure (RAO, 2009).

Considering that the columns behave like springs in elastic regime, it is possible to calculate the equivalent stiffness of the four columns by Eq. (2). The demonstration of Eq. (2) can be found in classical literature of mechanical of materials (HIBBELER, 2010).

$$k = \frac{48\,EI}{L^3} \tag{2}$$

where: E - Young's modulus of material (N/m^2); I - moment of inertia of the cross section (m^4); L - column height (m).

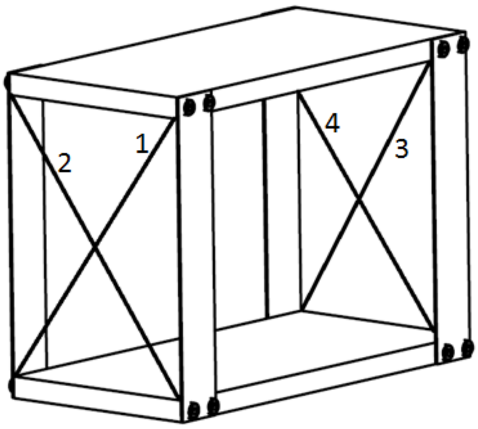
With the natural frequency set for approximately 34% of the maximum excitation frequency and ownership of the weight of the top head, now called the main mass M, the desired stiffness to the columns calculated by applying Eq. (3) where the stiffness of the equivalent columns, called k_1.

$$\omega_n = \sqrt{\frac{k_1}{M}} \tag{3}$$

2.4 Configurations of SMA tendons

The SMA tendons with an approximated total weight of 0.29g (four elements), diameter of 0.29 mm and length of 180 mm, installed in the structure and numbered nodal points according to the configuration shown in Figure 5). It was adopted a logical sequence for activation of the SMA tendons, so that 0 (zero) implies the tendon inactive and 1 (one) an activated tendon. Figure 5) shows the electrical activation scheme for the prismatic table. It is possible to activate one, two, three and four Ni-Ti SMA tendons simultaneously.

Note that the configuration 0000 means that none of the tendons is active. In the configuration 0010 the tendon number 3 is turned on and the rest are off. Remember that when a tendon is active means that electrical current passes through it for heating.



1	2	3	4	Number tendons active
0	0	0	0	none
0	0	0	1	One #4
0	0	1	0	One #3
0	0	1	1	Two #3,4
0	1	0	0	One #2
0	1	0	1	Two #2, 4
0	1	1	0	Two #2,3
0	1	1	1	Three #2,3,4
1	0	0	0	one #1
1	0	0	1	two # 1,4
1	0	1	0	Two #1,3
1	0	1	1	Three #1,3,4
1	1	0	0	Two #1,2
1	1	0	1	Three #1,2,4
1	1	1	0	Three #1,2,3
1	1	1	1	Four #1,2,3,4

Figure 5. Scheme of the prismatic table with embedded SMA tendons and different modes for electrical activation.

2.5 Experimental setup for vibration tests

The assembly used for the experiments is showed in Figure 6), with all described instruments. Note that the framework bolted on the bench, and the existence of two unbalanced motors for rotating eccentric mass, one set on top of the structure, and another at the bottom, which does not appear in the picture. This assembly is used for both experiments, related to free vibration and forced vibration. For forced vibration, motors are used to excite the structure, while for free vibration structure was excited by impact with hammer.

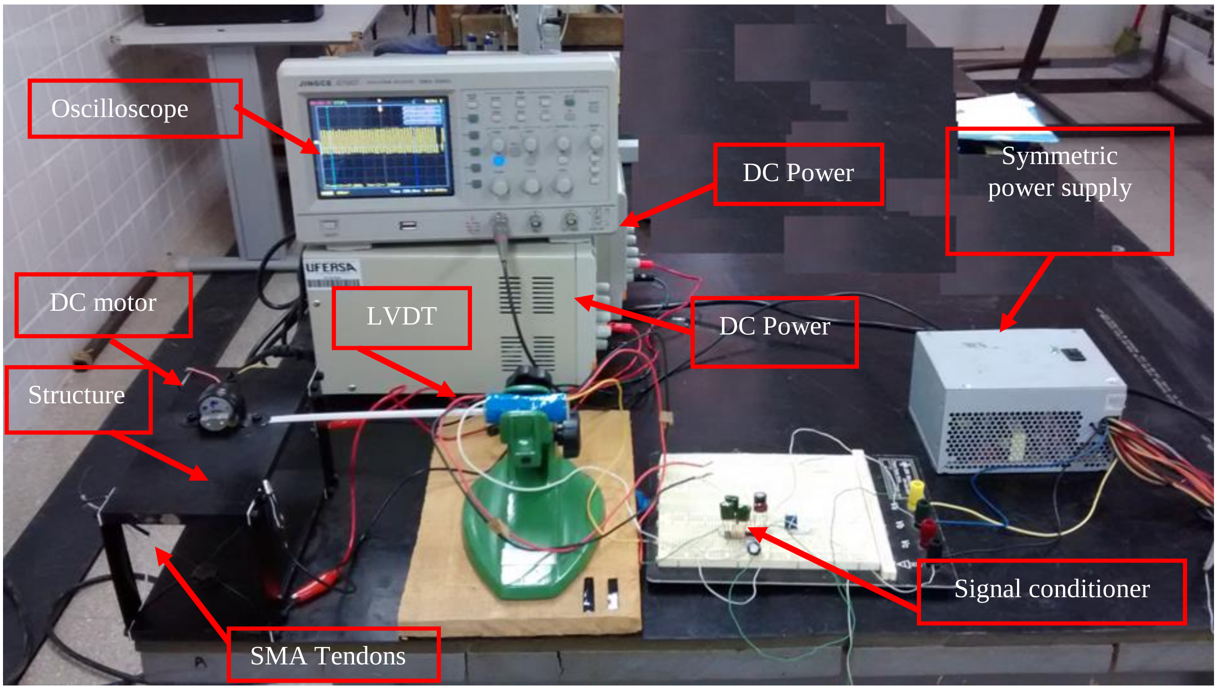


Figure 6.Photograph of the experimental setup.

The main parameters and natural frequency of the system summarized in Table1).

Table1. General characteristics of the prismatic table.

Length of the columns [m]	110.0E-3
Thickness of the columns [m]	1.0E-3
Width of the columns [m]	28.5E-3
Top head thickness [m]	10 E-3
Top head width [m]	100 E-3
Top head length [m]	200 E-3
Mass of the top head [kg]	1.54
Young's modulus [Pa]	200.0E+9
Moment of inertia [m^4]	2.38E-12
Natural frequency [Hz]	16.79
Stiffness system [N/m]	17.13E+3

3. RESULTS AND DISCUSSIONS

3.1 Thermomechanical characterization of SMA tendons

As described previously, thermomechanical characterization was performed only in a small region of stress-strain curve in order to verify the change of curve slope (stiffness) as a function of tendon temperature, revealing this way the thermoelastic property of the tendon (OTSUKA &WAYMAN, 1998; LEO, 2007). It can be verified from Figure 7 that the slope changes by varying the current applied to the SMA tendon corresponding to a monitored temperature with the thermocouple.

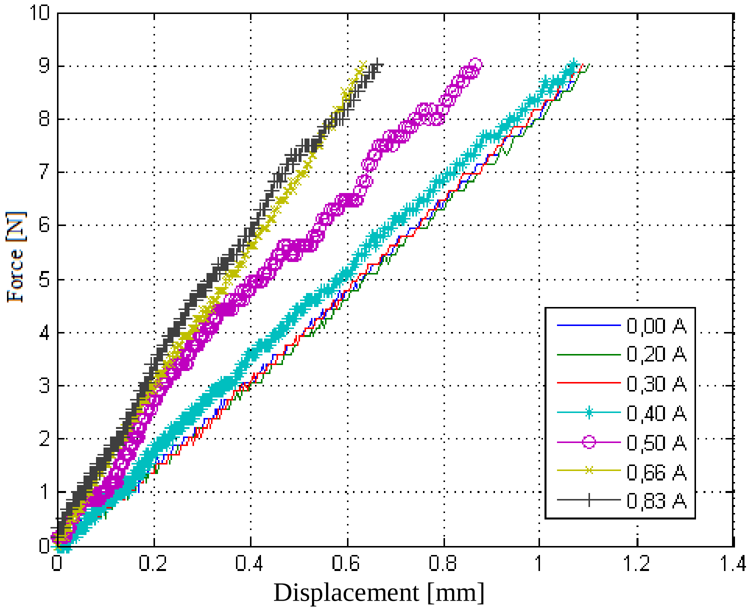


Figure 7. Force vs displacement behavior of the SMA tendons as a function of applied current.

The slope values of the force vs displacement behavior (stiffness) are presented in Table 2). It can be observed a variation in the stiffness of the SMA tendons of the order of 60% between the tendon condition not active (room temperature 24°C) and fully active (60°C).

Table 2.Change of SMA tendon's stiffness during heating.

Electric current (A)	Temperature (°C)	Stiffness (N/mm)
0.00	24.0	8.06
0.20	26.0	8.08
0.30	29.0	8.28
0.40	40.0	8.61
0.50	45.0	10.50
0.66	50.0	13.67
0.83	60.0	13.69

3.2 Estimation of the excitation force from unbalanced rotating motors (shakers)

The designed frequency for the structure was 34% of the maximum excitation frequency (50Hz in this case) implying a value of f = 17 Hz, corresponding to approximately 106.03 rad/s. Substituting the values of the unbalanced mass, eccentricity and ω in Eq (1), leads to Eq. (4):

$$F(t) = 0.512 \text{ sen} 106{,}03t \qquad (4)$$

where: m_e = 9,76 g; $\omega = \omega_n$= 106.03 rad/s; e= 0.00233m.

3.3 Free vibration tests

The displacement of the *x* direction in response to free vibration of the system in the time and frequency domain is presented in Figure 8). Figure 8(a) shows the displacement response at free vibration in time domain with none tendon active, while Figure 8(b) reveal this response for the tendon number one active (electric current of 0.6A). There has verified a decrease in the time required for the system to come to rest after the excitement. This fact leads to the conclusion that there was an increase in structural damping with the activation of the SMA tendon. Figure 8(c) show the response of displacement in frequency domain with none tendon active while Figure 8(d) show the free response in frequency domain with tendon #1 active. It is confirmed that there is a change in the frequency and amplitude of the response.

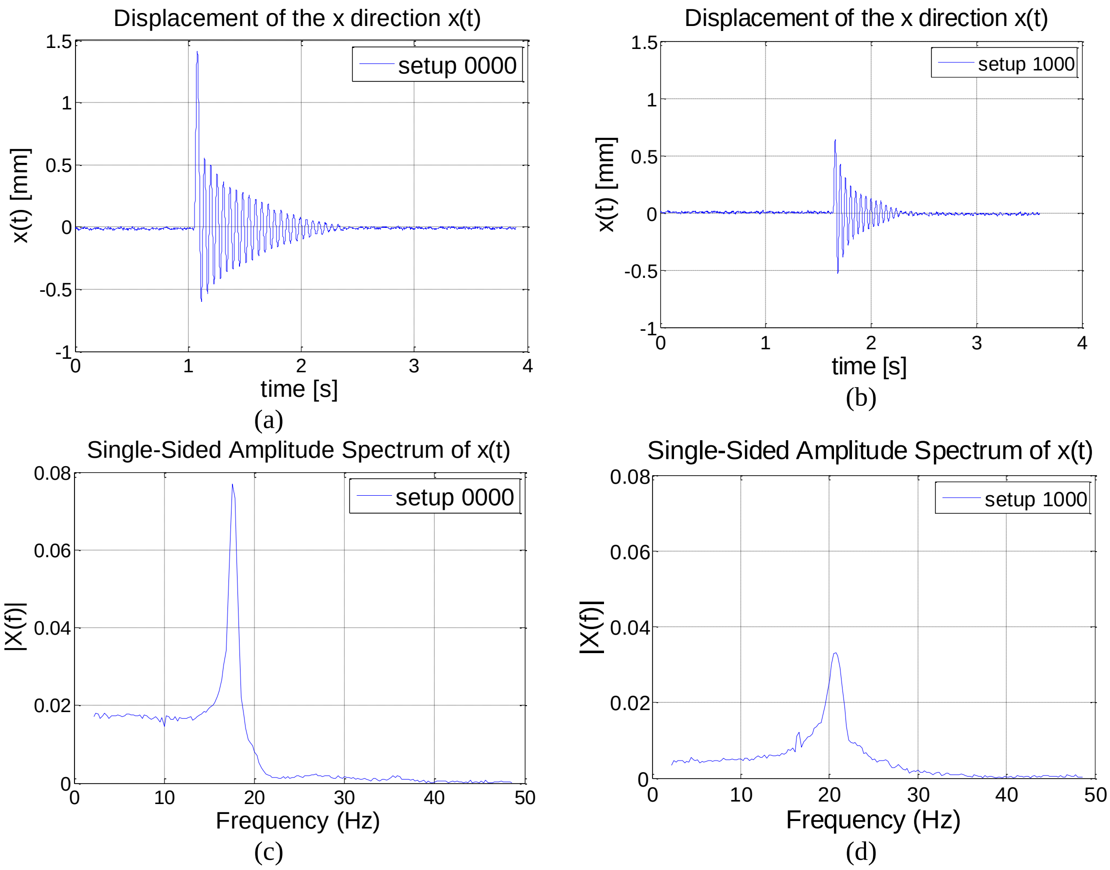


Figure 8. Free vibration tests. (a) None tendons active in time domain. (b) Tendon # 1 active in time domain. (c) None tendon active in frequency domain. (d) Tendon # 1 active in frequency domain.

Figure 9 shows a comparison between the response of free vibration for the system with none active tendon and all active tendons with current of 0.4A. Note that frequency of system without active tendons is close to the designed frequency (17.69Hz), calculated and presented in Table1). It can be also observed that the system frequency increased to 29.05Hz, corresponding to an increase of about 34.2N/mm in the system stiffness.

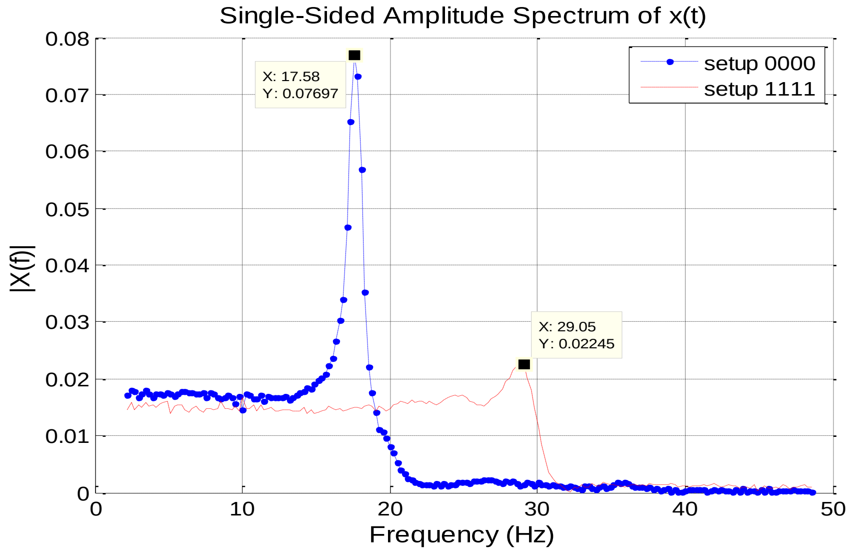


Figure 9. Comparison of the responses with and without all tendons activated at 0.4 A.

From the responses in the time domain, it was also possible to estimate the damping factor of the structure for each launch configuration of SMA tendons presented in Figure 5(5). The 3D graphic generalized response of the system as a function of the ratio of frequencies and damping factor ζ is show in Figure 10). It is possible to observe that with all the tendons active the damping factor increase from 0.0172 with none tendons active to 0.0963. This means about 450 % of increase.

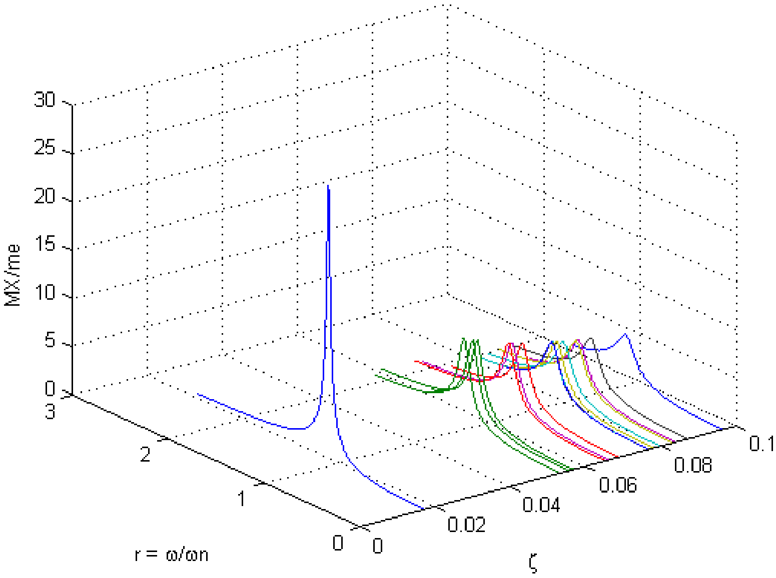


Figure 10. Generalized response of the system as a function of the ratio of frequencies and damping factor.

3.4 Forced vibration

For the forced vibration tests, the system was excited harmonically by DC motors with unbalanced mass (shakers) tuned to the calculated natural frequency (f =17 Hz) and the response with and without activation of the SMA tendons was monitored. The displacement response without any activated tendon and with activation of tendon #1 and #2 using 0.5A is shown in Figure 11). It was observed a significant reduction in the amplitude of the displacement, of the order of 70%.

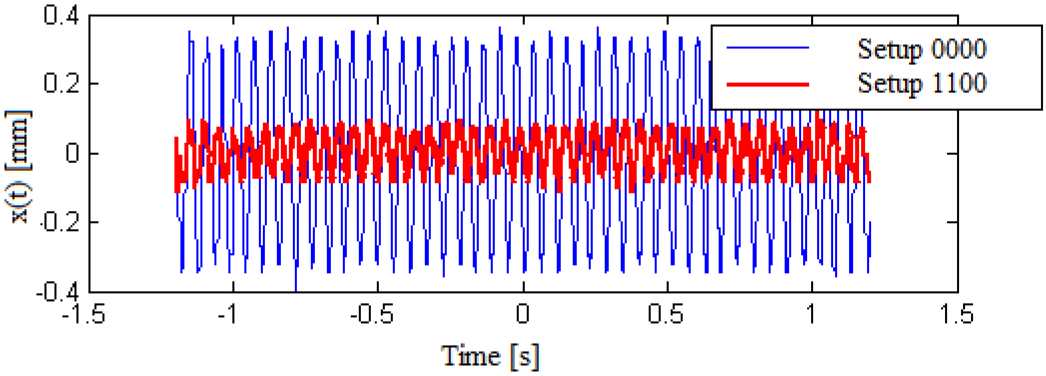


Figure 11. Forced vibration response of the system for the cases 0000 (without activation) and 1100 (activation of tendons #1 and #2) defined in Fig. (5).

4. CONCLUSIONS

The effect of SMA tendons embedded in a prismatic table structure was studied by means of experimental tests of free and forced vibrations. The results show that there is a change in stiffness of the system after activation of SMA tendons, moreover, an increase in damping of the structure. A reduced quantity of tendons with very small mass compared to the mass of the system is enough to reduce by 70% the amplitude of the vibration. This is a great advantage compared to other damping means. From these observations, we concluded that applying an appropriate setup of SMA tendons, as function of position and temperature, can lead to successful applications with respect to the damping capacity.

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