

EXPERIMENTAL ANALYSIS OF VIBRATION REDUCTION IN SHAPE MEMORY ALLOY OSCILLATORS

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Abstract. *Smart materials have a growing technological importance due to their unique thermomechanical characteristics. Shape memory alloys (SMAs) belong to this class of materials being easy to manufacture, relatively lightweight, and able of producing high forces or displacements with low power consumption. These aspects could be explored in different applications including vibration control. Nevertheless, there is a lack in literature concerning the experimental analysis of SMA dynamical systems. This contribution deals with the experimental analysis of SMA dynamical systems by considering an experimental apparatus composed by low-fiction cars free to move in a rail. The system is excited by a shaker that provides harmonic excitation. Vibration analysis reveals that SMA elements introduce complex dynamical responses to the system and different thermomechanical loadings are of concern showing the main aspects of SMA dynamical response. Especial attention is dedicated to the analysis of vibration reduction that can be achieved by considering different approaches exploiting either temperature changes or vibration absorber techniques.*

Keywords*: Shape memory alloys, vibration reduction, experimental analysis, absorbers*

1. INTRODUCTION

The remarkable properties of SMAs are attracting much technological interest, motivating different applications in several fields of sciences and engineering. Aerospace, biomedical, and robotics are some areas where SMAs have been applied (Lagoudas, 2008; Paiva & Savi, 2006; Machado & Savi, 2002, 2003; Van Humbeeck, 1999; Pacheco & Savi, 2000). Dynamical systems are included among several applications that incorporate SMA elements to the system in order to explore their thermomechanical behavior. One possibility is to explore the high dissipation capacity related to the hysteretic behavior. Another interesting application is related to the temperature induced phase transformation that can be used to promote stiffness variations and, as a consequence, alters system dynamical characteristics. Both alternatives indicate SMA elements to be employed to promote vibration reduction in dynamical systems. Several research efforts presented different aspects of SMA applications in dynamical systems that include vibration absorbers and composite structures (Williams *et al.*, 2001, 2002, 2005, Rustighi *et al.*, 2005, Elahinia *et al.*, 2005; Nae *et al.*, 2004; Birman, 2008; Tiseo *et al.*, 2010; Savi *et al.*, 2011).

In general, dynamical behavior of SMA systems is related to complex behaviors, presenting periodic, quasi-periodic and chaotic responses. For details, see some of the references: Savi *et al.* (2011); Machado *et al.* (2009); Bernardini & Rega (2005); Savi *et al.* (2002); Savi & Pacheco (2002); Machado *et al.* (2003). Recently, SMAs are being used in impact systems where the dissipative characteristics of SMA can produce less complex behaviors when compared with elastic systems: Sitnikova *et al.* (2010) and Santos & Savi (2009).

This paper deals with an experimental analysis of the dynamical behavior of oscillators with SMA elements. An experimental apparatus composed by low-fiction cars free to move in a rail is attached to a SMA helical spring. The system is excited by a shaker that provides harmonic excitation. Vibration analysis for different thermomechanical loadings are of concern showing the main aspects of SMA dynamical response. Vibration reduction can be achieved by considering different approaches exploiting either temperature changes or vibration absorber techniques

2. EXPERIMENTAL APPARATUS

The dynamical behavior of SMA oscillators is studied with the use of the apparatus shown in Fig 1, composed by low-fiction cars free to move in a rail. The first car (car 1) is rigged-mounted to an electrodynamics shaker (LabWorks ET-126 with 58 N peak force capacity) and connected to a second car (car 2) through a tension helical spring (linear elastic). The second car (car 2) is connected to a SMA spring, which has the other end fixed to the load cell (Alfa SV-20 with 196 N capacity). The vibration system is mounted in a close-loop configuration controlled by a vibration controller system (LabWorks VibeLab VL-145s Digital Sine Controller) with sine-sweep controller capability. Cars are monitored by accelerometers transducers (Kyowa AS-10GB with 10g capacity) connected to a data acquisition system (HBM Spider 8) with 400 Hz acquisition rate. A laser sensor is also employed to monitor displacements (MicroEpsilon ILD 2220-100). Temperature variations are induced through joule effect by the application of an electrical current using a stabilized current source (Minipa MPL-1303). Temperature is monitored by an infrared camera FLIR A-320. Table 1 presents the technical specifications of laser transducer and accelerometers

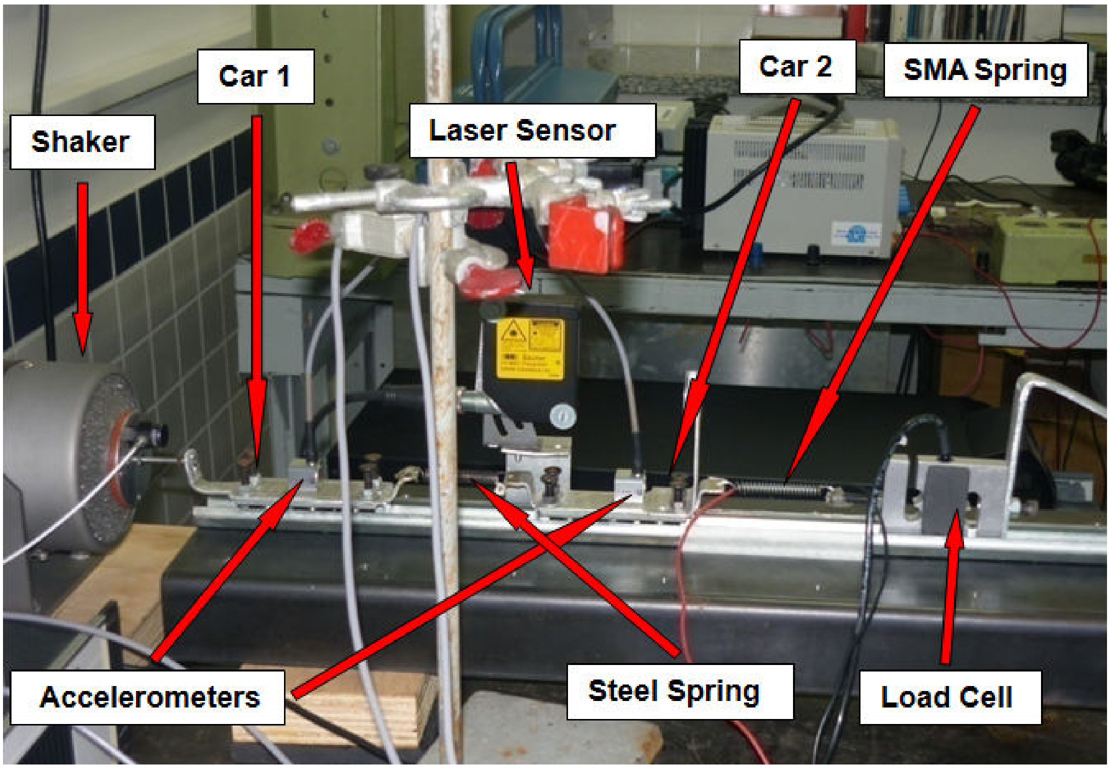


Figure 1. Experimental apparatus to study the dynamical behavior of one-degree of freedom SMA oscillators

Elastic and SMA springs are employed in experimental apparatus. Elastic tension helical springs are made of steel with an external diameter of 7.3mm, a wire diameter of 0.85 mm. Moreover, the system uses an SMA helical spring built with NiTi that presents martensitic phase at room temperature. This SMA spring has an external diameter of 6 mm, a wire diameter of 0.75 mm, 20 active coils, and an activation temperature in the range of 45-55°C. This spring has been purchased from Jameco's Robot Store. Table 2 shows the stiffness, k, of the elastic springs used in experiments. The thermomechanical analysis of the SMA spring is presented in Aguiar *et al.* (2010).

Table 1. Laser transducer and accelerometers technical specifications.

	Laser Transducer	**Accelerometers**
Resolution	1,5 μm	-
Linearity error	≤ 0.03% FSO	± 1.0% RO
Response time / release time	< 0,15 ms	-
Max. switching frequency	20 kHz	350 Hz
Hysteresis	-	± 1.0% RO

Table 2 - Stiffness of the springs.

Spring	Type	*k* [N/mm]
steel	Linear elastic	0.348
SMA	Non-Linear	Non-linear

3. DYNAMICAL ANALYSIS

The dynamical analysis of SMA system is analyzed by considering a one-degree of freedom oscillator (1DOF). This system allows one to have a general comprehension about SMA system dynamics. Forced vibration tests are conducted to evaluate the 1DOF response. Especial attention is dedicated to consider the possibility of vibration attenuation using the temperature variation of the SMA. Temperature variation promotes phase transformation that changes the system characteristics as the equilibrium points and the SMA helical spring stiffness. Several situations involving the influence of temperature on the system dynamics are explored.

At the beginning of each test, a standard procedure is considered. The SMA helical spring in load-free condition is heated, by applying an electric current of 0.8A in order to recover its original length. Afterwards, SMA helical spring is attached to the device in a high temperature condition, the SMA spring is subjected to an approximately 6N preload and the shaker provides an excitation with amplitude of 0.25g. Before the signal acquisition, a stabilization period of 60s is adopted. The system is subjected to sinusoidal excitation with a constant frequency. SMA helical spring temperature variation is obtained by changing the applied electric current.

Figure 2 shows experimental results involving SMA one-degree of freedom oscillator. Basically, the system is subjected to a sinusoidal excitation with 8.22 Hz that coincides with the resonant frequency for 0.8A. The test starts with an electric current of 0.8A and after 10s this value is increased and stabilized on four new electric current values: 1.5A, 2A, 2.5A and 3A. Two different signals are presented: acceleration measured by accelerometer (left panel) and displacement measured by the laser sensor (right panel). The accelerometer picture also presents the excitation of the system measured in car 1, connected to the shaker. Note that vibration reduction is achieved by the variation of SMA temperature

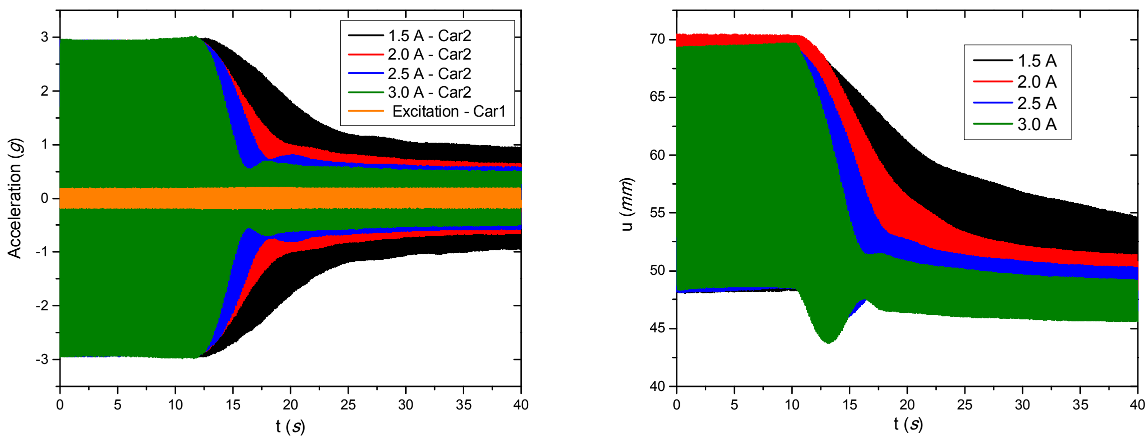


Figure 2. Vibration reduction promoted by SMA oscillator temperature variation.

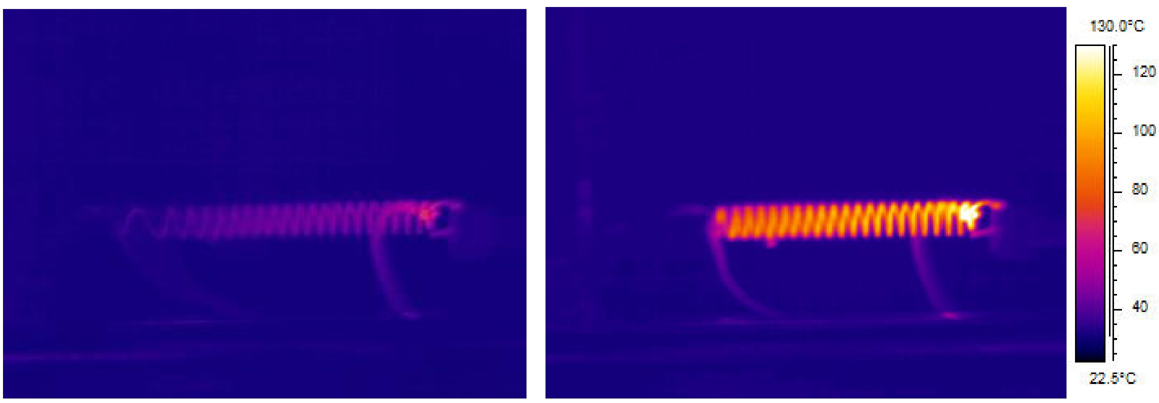
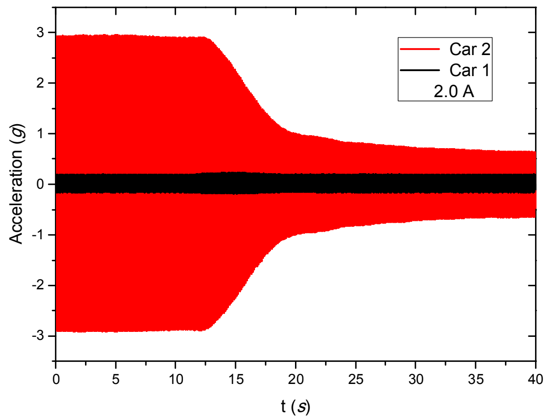


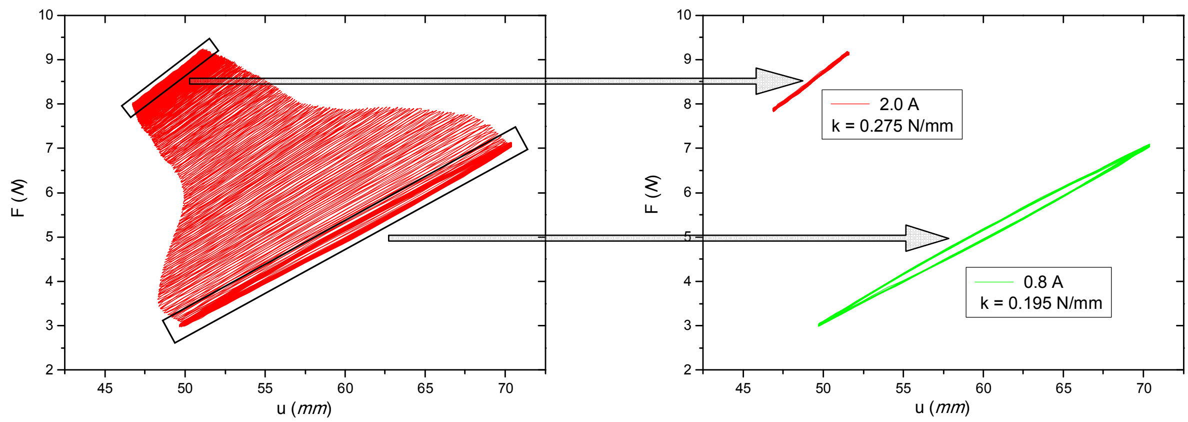
Figure 3. Thermal infrared image of the SMA spring submitted to a current of 0.8A (left panel) and 3.0A (right panel)

Temperature variation imposed by the electrical current is monitored by an infrared camera. Figure 3 shows an infrared thermal image of the SMA spring during the experimental procedure where temperature variation promotes vibration reduction. Left panel of Figure 8 is related to a current of 0.8 A while the right panel is associated with a current of 3.0 A.

At this moment, we consider the analysis of one temperature variation: from 0.8A to 2.0A. Figure 4a presents the accelerometer signal showing the details of the reduction that basically, is related to two essential issues: stiffness change and hysteresis. Mainly, the stiffness change is related to temperature induced phase transformation, basically from austenite to martensite and vice-versa. On the other hand, hysteresis is due to stress induced phase transformations. Therefore, the analysis of force-displacements curves allows one to get a better comprehension of the phenomenon. Figure 4b presents the force-displacement curve during all the process and highlights the behavior at the beginning and at the end of the process that, in principle, are related to steady state response. The analysis of the force-displacement curves shows that there is a stiffness change during the temperature increase. At the beginning of the test, when the current is 0.8A, the system presents k = 0.195 N/mm; at the end of the test, when the current is 2.0A, the stiffness is k = 0.275 N/mm. Notice however that, at the beginning of the process, there is a hysteresis loop that dissipates energy. Figure 5 presents the phase space of this response. The left panel shows all the process while the right panel presents the steady state response at the beginning and the end of the process.



(a)



(b)

Figure 4. Vibration reduction promoted by temperature change from 0.8A to 2.0A: (a) acceleration; (b) force-displacement.

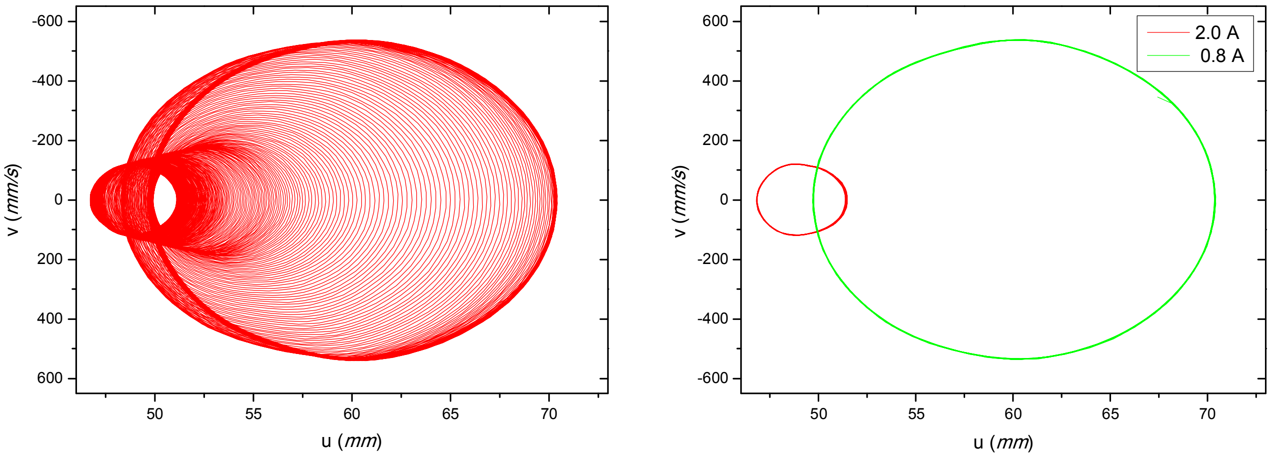


Figure 5. Vibration reduction promoted by temperature change from 0.8A to 2.0A: phase space.

Sweep tests are now performed trying to verify the influence of frequency on the vibration reduction. Basically, the car 1 is harmonically excited with a 0.25g constant amplitude sinusoidal acceleration. The excitation frequency signal changes linearly during the test from 7 to 11Hz with 0.02Hz/s. Different temperatures are also considered by assuming variation of the electrical current: 0.8A and 2.0 A. A frequency analysis is presented in the left panel of Fig. 6 considering the maximum amplitudes of the acceleration. Note that the peaks can change the position with temperature variation. This behavior defines an important characteristic of this system since it is possible to change the tuned frequency related to vibration reduction. The resonance frequency of the system at 0.8A is 8.23Hz and 2.0A is 8.84Hz. Concerning the vibration reduction it is clear that it depends on the frequency range. The right panel of Fig. 6 shows the force-displacement curve. Note that for 0.8A the system presents a smaller stiffness but presents a hysteretic behavior. When the temperature increases with 2.0A, the stiffness increases but the hysteretic behavior is strongly reduced. As a consequence, the system presents higher amplifications under resonant conditions

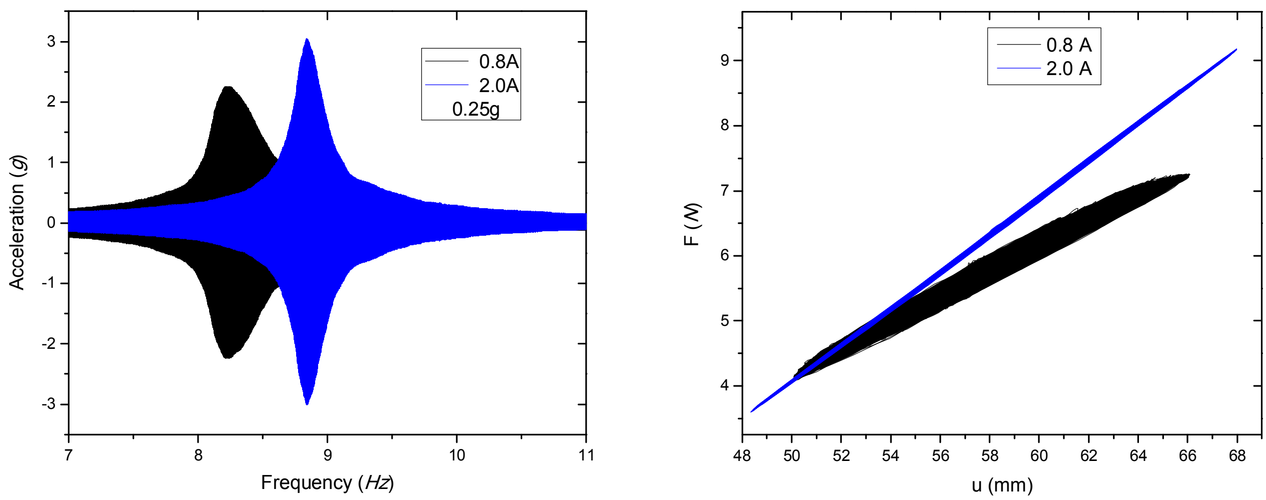


Figure 6. Sine-sweep tests for different temperatures.

Based on the previous conclusions, stiffness and hysteresis plays a competition to define the vibration conditions. The hysteretic behavior of the system can be altered by preloads and this effect is now investigated by considering different preload conditions in a sine-sweep test performed with 1.2A (Fig.7) and 2.0A (Fig.8). The car 1 is harmonically excited with an amplitude 0.25g, and two different preload conditions are of concern: 6 N - 9 N (1.2A) and 6N - 14N (2.0A). The increase of the preload induces the system to stay in a position that is more inside the hysteresis loop in the force-displacement space. Figure 7 and Fig.8 shows the sine-sweep response of the SMA oscillator. It is clear that the increase of the preload is associated with the decrease of the amplitudes under resonant conditions. This effect can be explained by considering the force-displacement curved that shows the increase of the hysteretic behavior with the increase of the preload value. This behavior increases the dissipation and therefore, decreases the amplitude gain under resonant conditions.

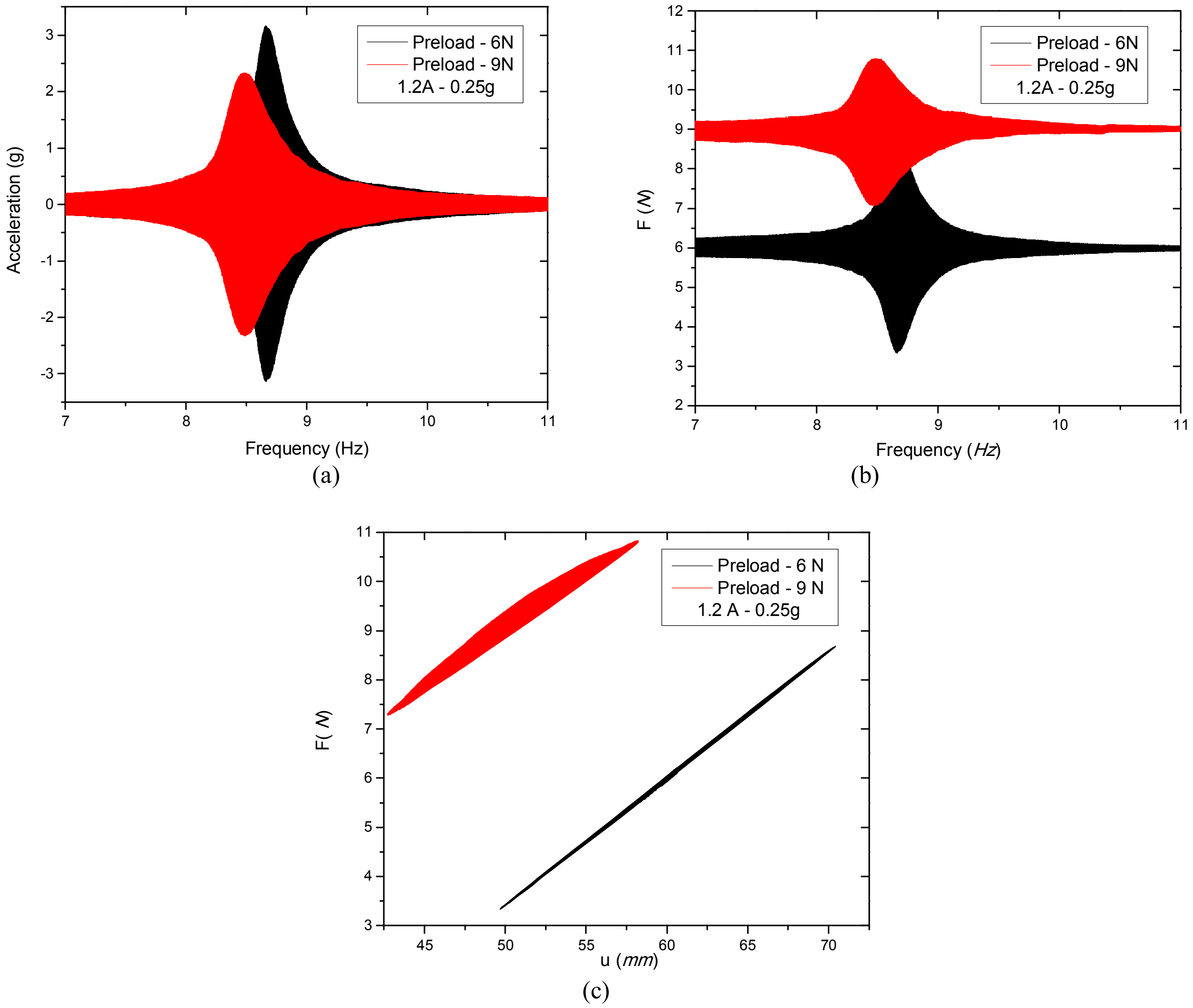
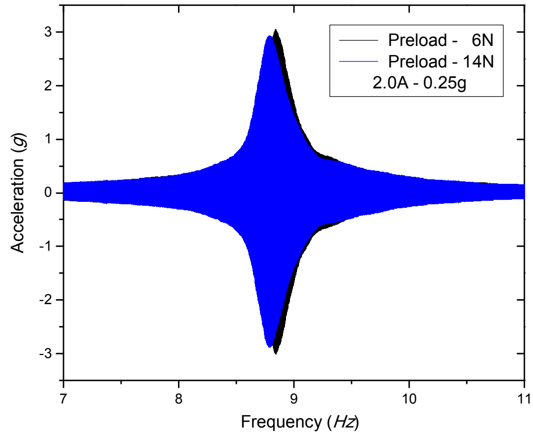
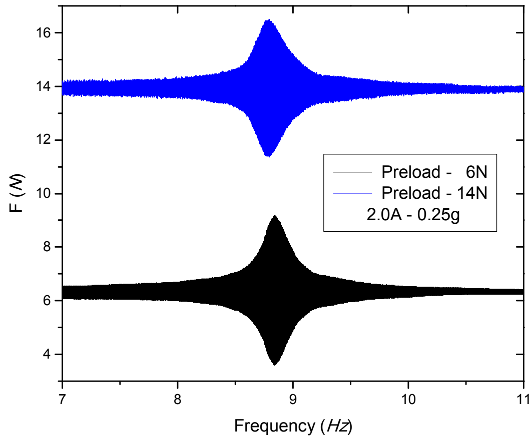


Figure 7. Effect of preload conditions in sine-sweep tests performed with 1.2A:
(a) acceleration; (b) force; (c) force-displacement.



(a)



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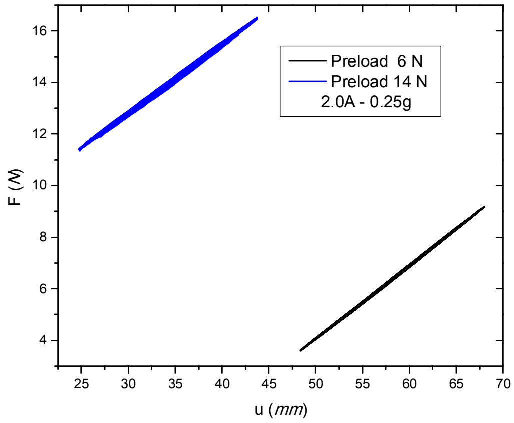
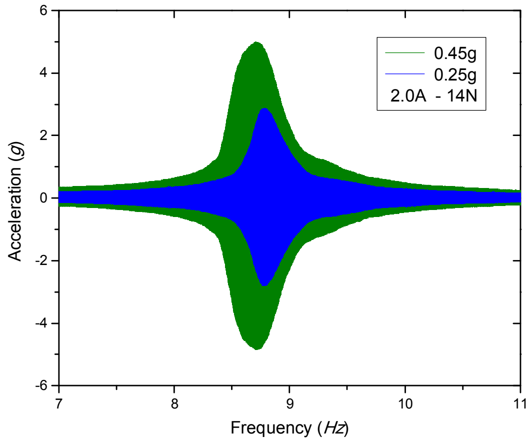


(c)

Figure 8. Effect of preload conditions in sine-sweep tests performed with 2.0A:
(a) acceleration; (b) force; (c) force-displacement.

An important aspect related to hysteretic dissipation is that it can be considered as a smart dissipation in the sense that the more amplitude increases, the more dissipation increases. Figure 9 shows the sine-sweep test performed with 2.0A and a preload of 14N. But now, two different excitations conditions are of concern: 0.25g and 0.45g. By observing the force-displacement curve it is possible to verify a higher dissipation due to hysteretic behavior when the excitation is greater (0.45g).



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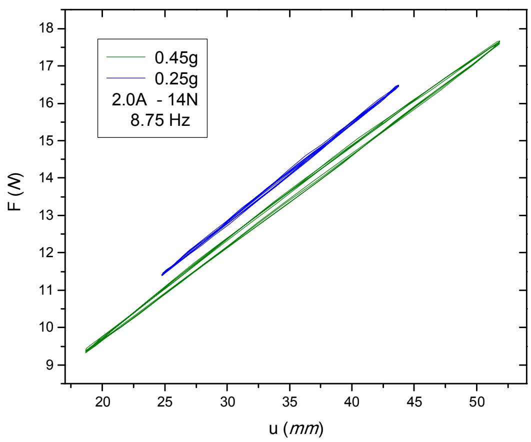

(b)

Figure 9. Effect of different excitation conditions in sine-sweep tests performed with 2.0A and 14N of preload:
(a) acceleration; (b) force-displacement.

4. CONCLUSIONS

This paper deals with an experimental investigation of nonlinear dynamics of shape memory alloy systems. The system is composed by low-fiction cars free to move in a rail. The main objective is the investigation of the vibration reduction exploring the SMA behavior due to temperature variations imposed by electric current. Sensors are employed to monitor the main system variables. Two different aspects influence the system response: stiffness change and hysteretic response. Basically, the temperature change can alter system stiffness changing the resonant condition. Nevertheless, this change can also alter the hysteretic response of the system. Therefore, it is important to evaluate both things in order to verify proper conditions for vibration reductions. In this regard, it is important to note that the hysteretic behavior reduce vibration amplitudes under resonant conditions.

5. ACKNOWLEDGEMENTS

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