EXPERIMENTAL INVESTIGATION OF A SHAPE MEMORY ALLOY HELICAL SPRING SINGLE-DEGREE OF FREEDOM OSCILLATOR

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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 material being characterized by the capacity of undergoing large residual deformations, and then, after a proper thermal loading, recover its original shape. SMAs are easy to manufacture, relatively lightweight, and able of producing high forces or displacements with low power consumption. The dynamical response of systems with SMA actuators presents a rich behavior due to their intrinsic nonlinear characteristics. 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 focuses on the experimental analysis of a SMA helical spring single-degree of freedom oscillator. An experimental apparatus composed by a low-fiction car in a linear rail attached to a SMA helical spring is used to study the dynamical behavior of this oscillator. The car is excited by a shaker system providing harmonic excitation. Different sensors are used in order to establish proper filtering procedures that are calibrated from an equivalent elastic oscillator. 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.*

Keywords*: Nonlinear dynamics, shape memory alloys, experimental analysis.*

1. INTRODUCTION

Shape memory alloys (SMAs) present complex thermomechanical behaviors related to different physical processes. The most common phenomena presented by this class of material are the pseudoelasticity, the shape memory effect, which may be one-way (SME) or two-way (TWSME), and the phase transformation due to temperature variation. Besides these phenomena, there are more complicated effects that have significant influence over its overall thermomechanical behavior – for instance: plastic behavior, tension-compression asymmetry, plastic-phase transformation coupling, transformation induced plasticity, thermomechanical coupling, among others. All these phenomena give a general idea about the complex thermomechanical behavior of SMAs, as discussed by Matsumoto et al. (1987), Shaw & Kyriakides (1995), Otsuka & Ren (1999), Gall & Sehitoglu (1999), Patoor et al. (2006) and Lagoudas et al. (2006).

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; Pacheco & Savi, 2000; La Cava *et al.*, 2000; Garner *et al.*, 2001; Machado & Savi, 2002, 2003; Webb *et al* 2000; Denoyer *et al* 2000). Due to their high dissipation capacity related to hysteretic behavior, SMA elements are being used as damping elements in vibrating systems (Williams *et al.*, 2000, 2005). Moreover, the phase transformation induced by temperature variation can be used in order to alter their dynamic characteristics associated with stiffness. Dynamical behavior of systems involving SMA elements is investigated in different research efforts. For details, see some of the references: Savi *et al.* (2008), Machado *et al.* (2009), Savi & Pacheco (2002), Machado *et al.*, (2003); Sitnikova et al. (2008a,b), Santos & Savi (2009).

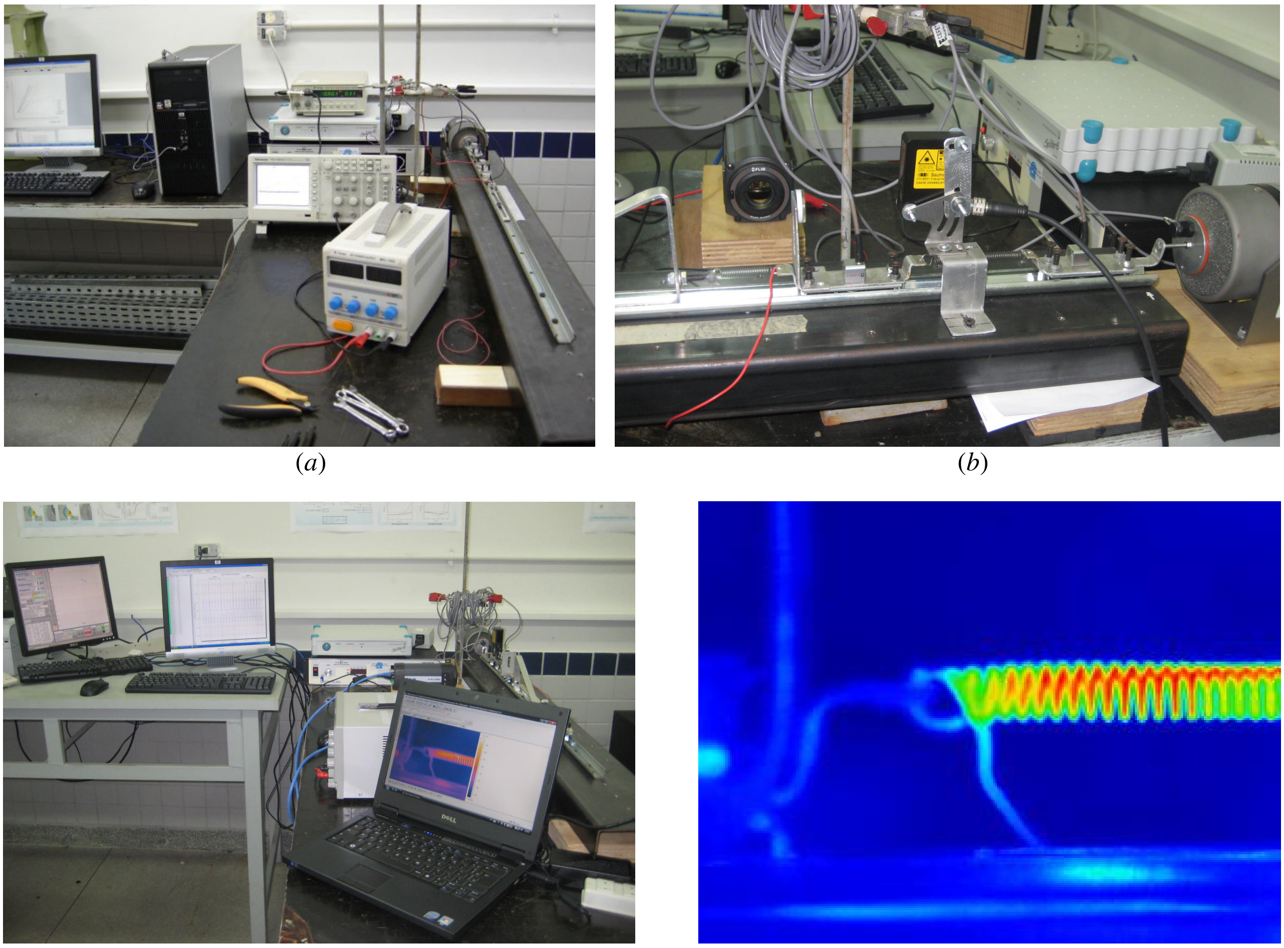
The study of the dynamical behavior of a single-degree of freedom SMA oscillator is carried out by considering an experimental analysis. An experimental apparatus composed by a low-fiction car in a linear rail attached to a SMA helical spring is used to study the dynamical behavior of this oscillator. The car is excited by a shaker system providing harmonic excitation. Different sensors are used in order to establish proper filtering procedures that are calibrated from an equivalent elastic oscillator. 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.

2. EXPERIMENTAL PROCEDURE

The dynamical behavior of single-degree oscillator is studied with the use of the apparatus shown in Fig.1, composed by two low-fiction car in a linear track. The first car (car 1) is rigged-mounted to an electrodynamic shaker (LabWorks ET-126 with 58 N peak force capacity) and connected to a second car (car 2) through a tension helical spring. The second car (car 2) is connected to a second tension helical spring, which has the other end fixed to the rail. The vibration system is mounted in a close-loop configuration controlled by a vibration controller system (LabWorks VibeLab VL-145s Digital Sine Controller) with swept sine controller capability. Both cars are monitored by accelerometers transducers (Kyowa AS-10GB with 10 g capacity) connected to a data acquisition system (HBM Spider 8) with 400 Hz acquisition rate. Car 2 is also monitored by a laser displacement transducer (Baumer OADM 20I4460/S14C). Table 1 presents the technical specifications of laser transducer and accelerometer.

Two configurations are of concern considering different springs: *linear oscillator* and *nonlinear SMA oscillator*. The linear oscillator has tension helical springs made of steel with an external diameter of 7,3mm, a wire diameter of 0.85 mm, 40 active coils. In the nonlinear SMA oscillator, the second spring is substituted by a NiTi tension helical spring with an external diameter of 6 mm, a wire diameter of 0.75mm, 20 active coils and an activation temperature in the range of 45-55°C.

The *SMA oscillator* is subjected to temperature variations that are induced in the SMA helical spring through joule effect by the application of electrical current using a stabilized current source (Minipa MPL-1303). Four levels of electrical current are applied to the SMA helical spring: 0.6A, 0.8A, 1.0A and 1.2A. Figure 1d shows an infrared (IR) thermal image of the SMA spring obtained with a FLIR A-320 camera.



(*a*) (*b*) (*c*) (*d*)

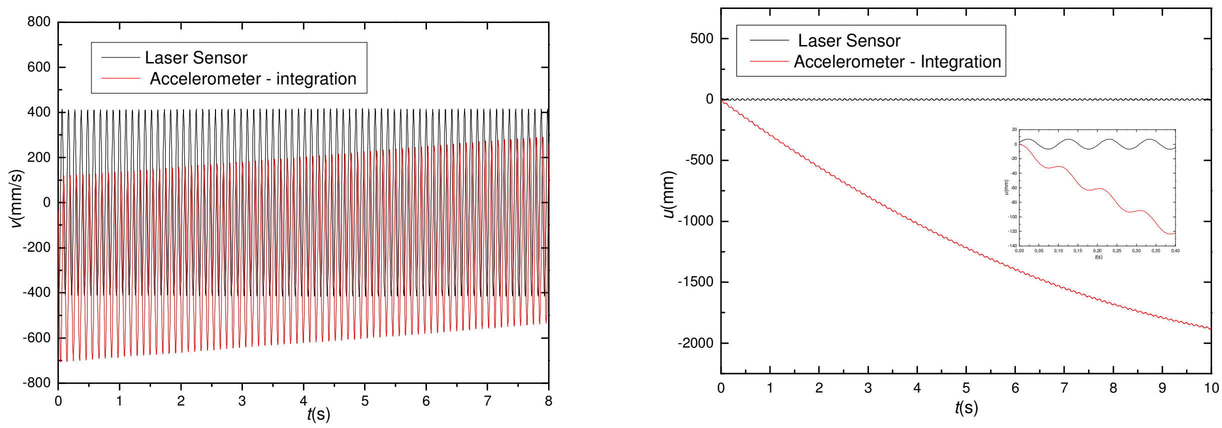
Figure 1. Experimental apparatus to study the dynamical behavior of linear oscillators at LACTM-CEFET/RJ (*a-c*). Infrared (IR) thermal image of the SMA spring subjected to a 1.2A electric current (*d*).

Table 1. Laser transducer and accelerometer technical specifications.

	Laser Transducer	**Accelerometer**
Resolution	< 0.06 mm	-
Linearity error	± 0.2 mm	± 1.0% RO
Response time / release time	< 10 ms	-
Max. switching frequency	1000 Hz	350 Hz
Hysteresis	-	± 1.0% RO

Experimental tests are conducted by considering sinusoidal excitation in the frequency range from 7.5Hz to 11.5Hz. A vibration controller system (Lab Works VibeLab VL 145s) is used to control the imposed excitation to car 1. A closed loop system is adopted using an accelerometer to monitor the shaker head excitation frequency, acceleration and displacement amplitudes. Sine sweep tests are imposed to the system.

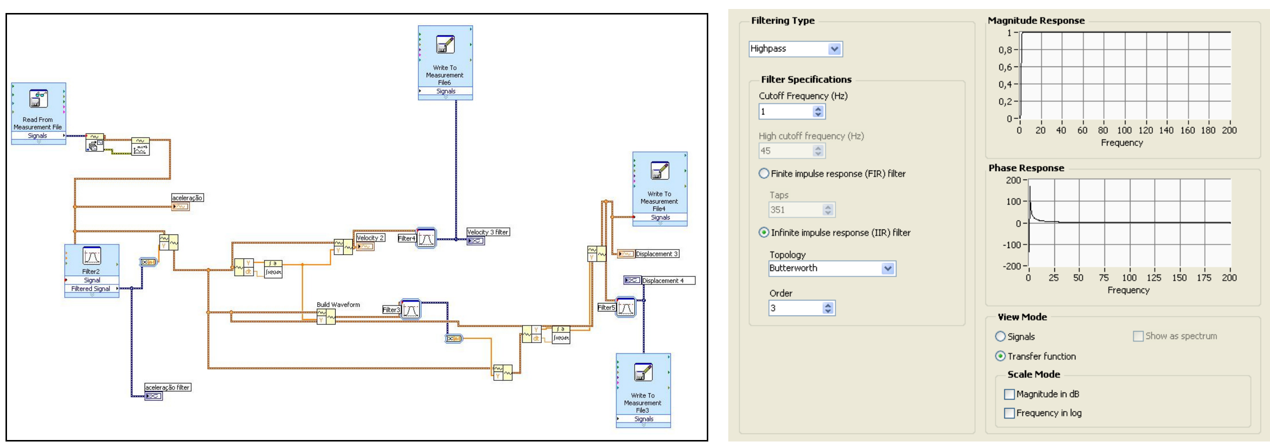
Laser sensor and accelerometer signals are analyzed together in order to calibrate the filtering procedures. Numerical derivation is employed to laser sensor signal in order to obtain velocity and acceleration. On the other hand, numerical integration is applied to accelerometer signal in order to obtain velocity and displacement. Labview routines are used in both cases. As it is well known, direct numerical integration of accelerometer signal to obtain velocity and displacement is not a trivial procedure. Slightest dc-offset in the original signal introduces a drift and double-integration makes it even worse. Some approaches consider the use of filters with a cut-off frequency to remove the dc-offset in the original signal (Ribeiro *et al.*, 1997, 1999; Slifka, 2004, Yanga *et al*, 2006, Tong *et al* , 2004). Figure 2 presents velocity and displacement signals obtained after direct integration of an experimental 9.6Hz acceleration sinusoidal signal. The presence of the slightest dc-offset in the original acceleration signal introduces a drift that can be observed in the integrated signals.



(*a*) (*b*)

Figure 2. Direct numerical integration of a 9.6 Hz senoidal accelerometer. (*a*) velocity and (*b*) displacement.

In this work a double integration procedure using LabView software is developed using an IIR (Infinite Impulse Response) digital filters with Butterworth topologic characteristics. The filters are adjusted for a highpass filter configuration with a cutoff frequency of 1 Hz and are applied to the signal before each integration step and to the displacement data obtained after the double integration. Tests with sinusoidal signals indicate that the proposed procedure furnish displacement data that presents a good agreement with the laser data. Figure 3 shows the block diagram, filter parameters and transfer function of the Labview integration procedure for accelerometer signal.



(*a*) (*b*)

Figure 3. Double integration Labview procedure for accelerometer signal: (*a*) block diagram and (*b*) filter parameters and transfer function.

3. LINEAR ELASTIC OSCILLATOR

The *linear elastic oscillator* is used in order to establish proper filtering procedure that will be used in the nonlinear SMA oscillator. Therefore, signals from accelerometers and laser displacement transducers are compared to capture the dynamical behavior of a single-degree oscillator. Initially, a sweep frequency analysis is performed using both transducers attached to car 2, while car 1 is harmonically excited with a 0.25g constant amplitude sinusoidal acceleration. The excitation frequency signal changes linearly during the test from 7.5 to 11.5Hz with 0.02Hz/s. Figure 4 shows displacement, velocity and acceleration time evolution considering two complete forward and backward sweep cycles. A good agreement is observed between the displacement and velocity signals obtained by laser and accelerometer transducers. Two peaks are associated with the resonance frequency (9.6Hz) where displacement and velocity values present larger values.

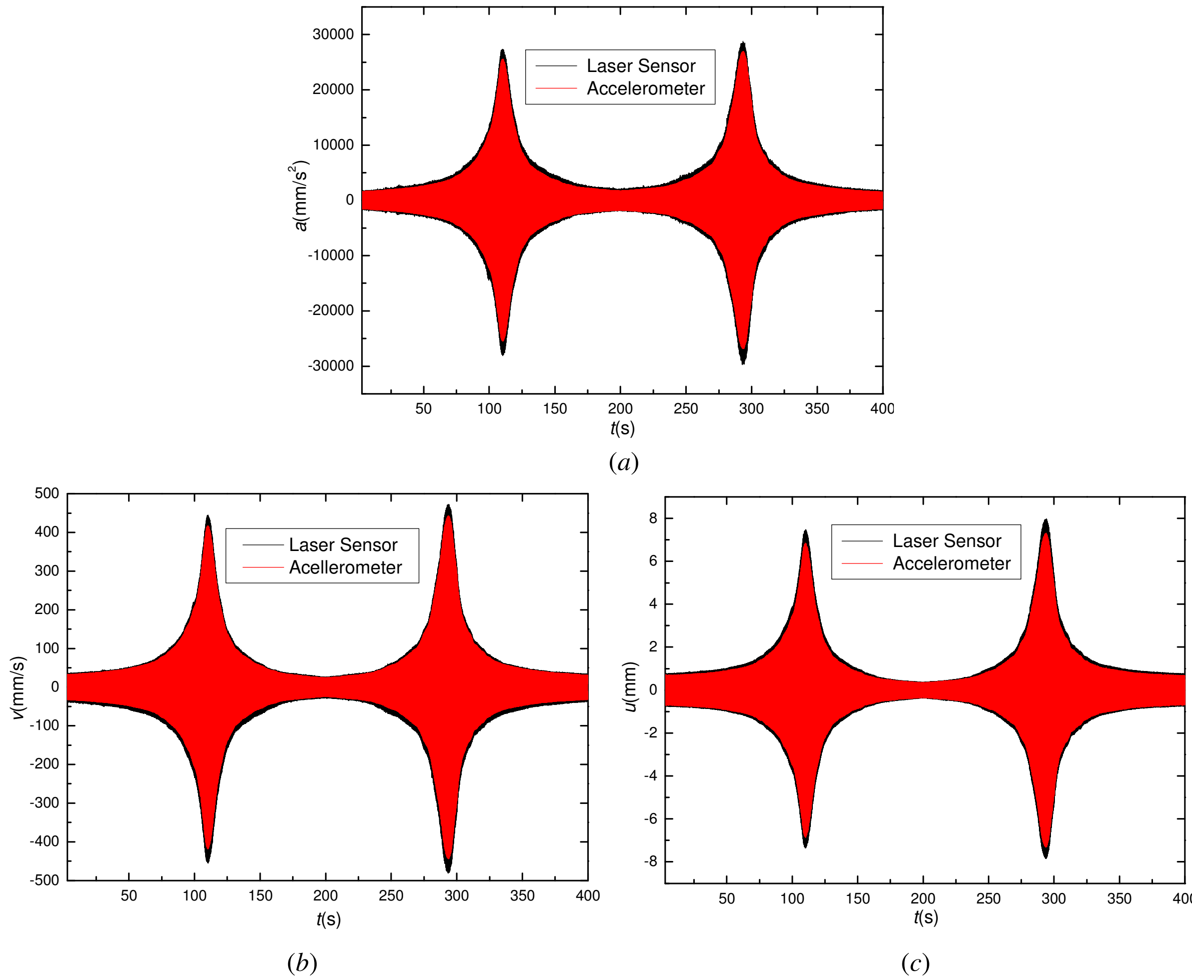


Figure 4. *Linear elastic oscillator:* acceleration (*a*), velocity (*b*) and displacement (*c*) time evolution considering two complete forward and backward sweep cycles (7.5Hz to 11.5Hz and 11.5Hz to7.5 Hz).

Figure 5 presents the phase space for three different excitation frequencies: 8.5, 9.6 and 10.5Hz. For 9.6Hz, the system is under resonant conditions related to large values of displacement. This situation is related to larger discrepancies between accelerometer and laser transducer signals.

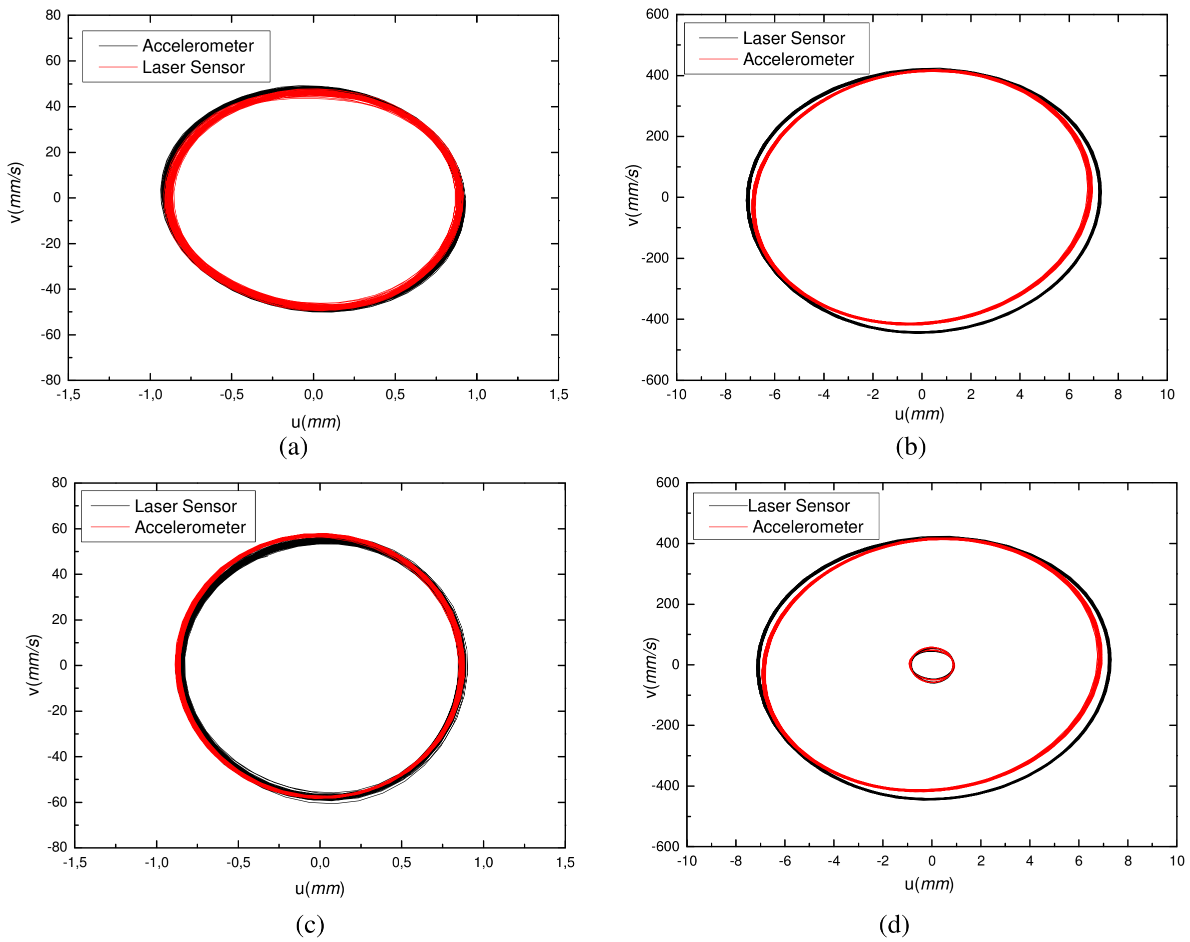


Figure 5. *Linear elastic oscillator* phase space: (*a*) 8.5Hz, (*b*) 9.6Hz, (*c*) 10.5Hz and (d) 8.5, 9.6 and.10.5Hz.

4. NON-LINEAR SHAPE MEMORY ALLOY OSCILLATOR

The *SMA oscillator* is now focused on. 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.

Experimental tests use a standard procedure. At the beginning of each test, a standard procedure is done. The SMA helical spring in load-free condition is heated, by applying an electric current of 0.6A in order to recover its original length. Afterwards, SMA helical spring is attached to the device in a high temperature condition and the shaker provides an excitation with amplitude 0.25g. Before the signal acquisition takes place 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.

Initially, a sweep frequency analysis is performed using both transducers attached to car 2, while car 1 is harmonically excited with a 0.25g constant amplitude sinusoidal acceleration. This situation is the same as the one treated in the preceding section for the *linear oscillator*. The excitation frequency signal changes linearly during the test from 7 to 11 Hz with 0.02Hz/s. The SMA helical spring is heated, by applying an electric current of 0.8A during the test. Figure 6 shows displacement, velocity and acceleration time evolution considering two complete forward and backward sweep cycles. A good agreement is observed between the displacement and velocity signals obtained by laser and accelerometer transducers. Two peaks are associated with the resonance frequency (8.9 Hz) where displacement and velocity values present larger values. It should be highlighted that the system presents different peaks during the increase or decrease of the frequency.

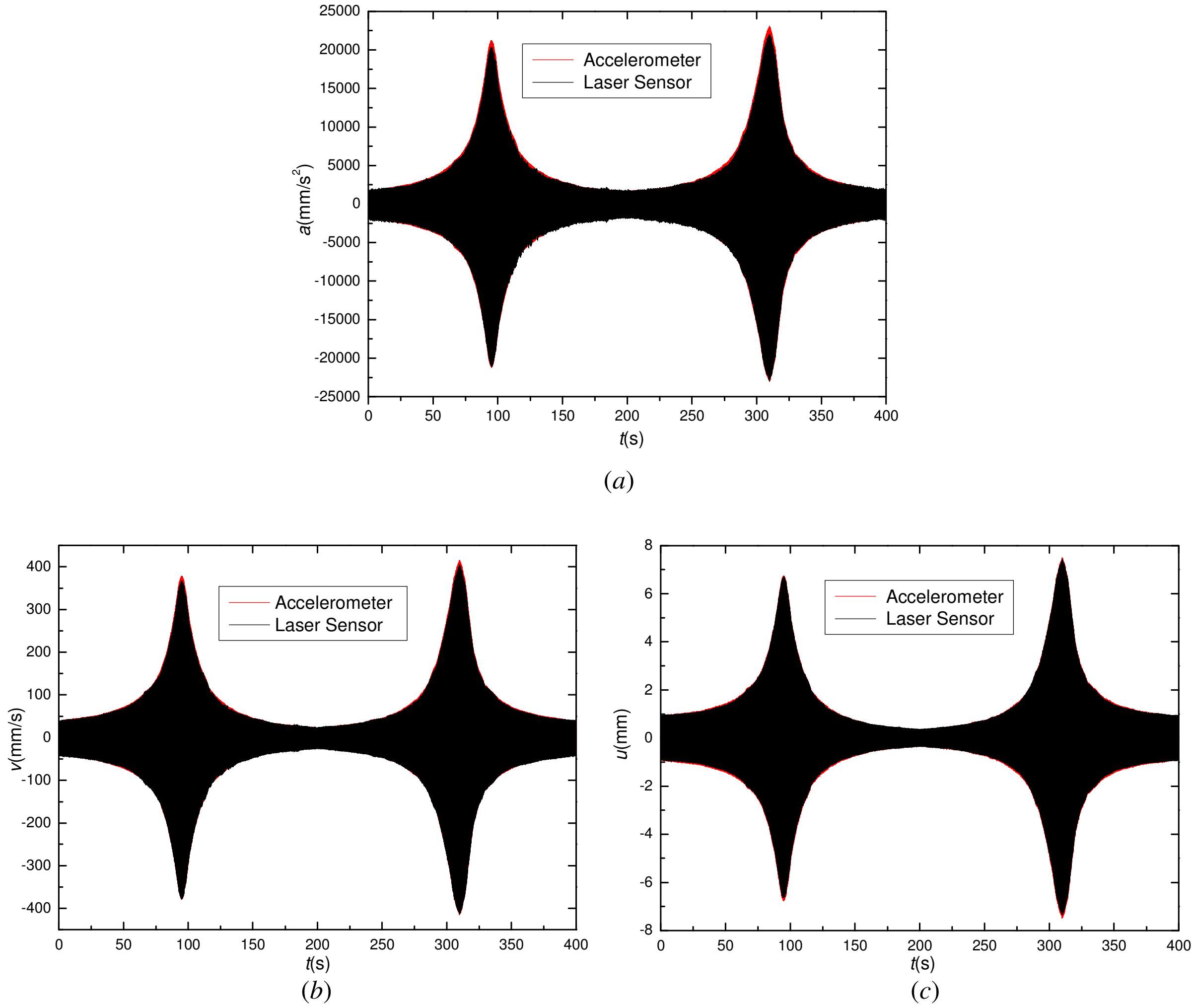
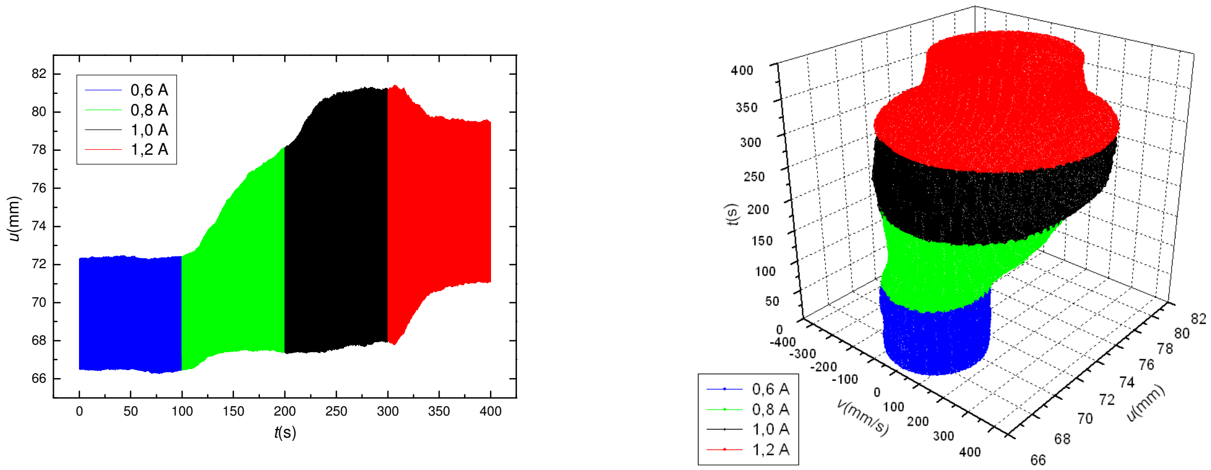


Figure 6. *SMA oscillator*: acceleration (*a*), velocity (*b*) and displacement (*c*) time evolution considering two complete forward and backward sweep cycles (7Hz to 11Hz and 11Hz to 7Hz).

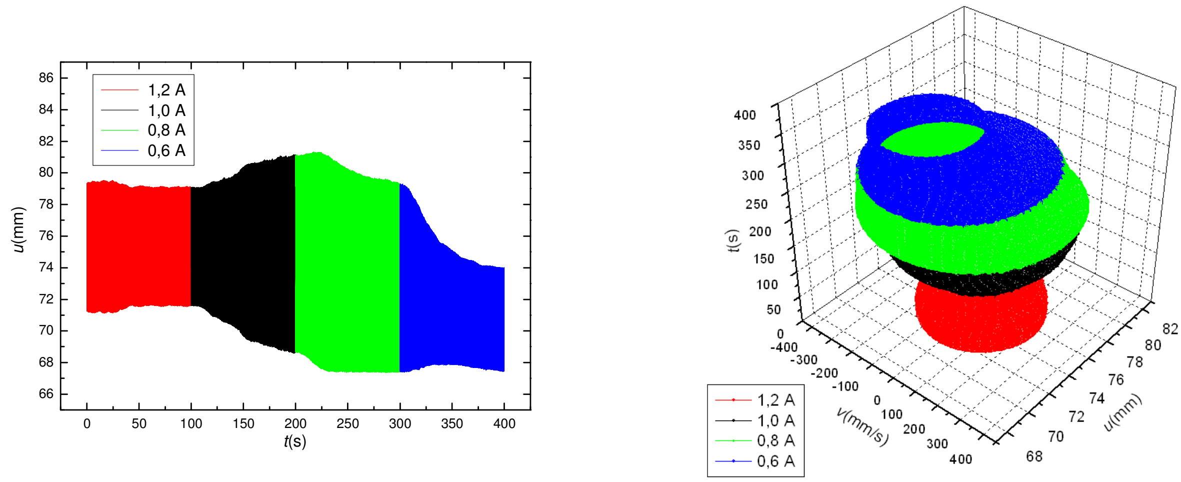
At this point, the system is subjected to four electric current steps, whose value changes from 0.2A at each 100s, resulting in steps of 0.6, 0.8, 1.0 and 1.2A. A smooth current variation is prescribed for the first 20s of each step. Two excitation frequencies are considered: 8.9 and 9.2Hz. The first one is the resonance frequency for a condition between 0.6 and 1.2A. On the other hand, the second one is the resonance frequency for 1.2A. Two cases are analyzed: heating (0.6 → 0.8 → 1.0 → 1.2A) and cooling (1.2 → 1.0 → 0.8 → 0.6A) of the system.

Figures 7 and 8 show data from the laser transducer for the tests involving the heating and the cooling of the SMA helical spring, respectively, considering an excitation frequency of 8.9 Hz. Figures 9 and 10 show data from the laser transducer for the tests involving the heating and the cooling of the SMA helical spring, respectively, considering an excitation frequency of 9.2 Hz. This analysis reveals the complex behavior of SMA helical spring dynamical response where the displacement amplitude can be controlled/modified by varying the temperature of the device. It should be highlighted the change of the equilibrium point due to temperature variations.



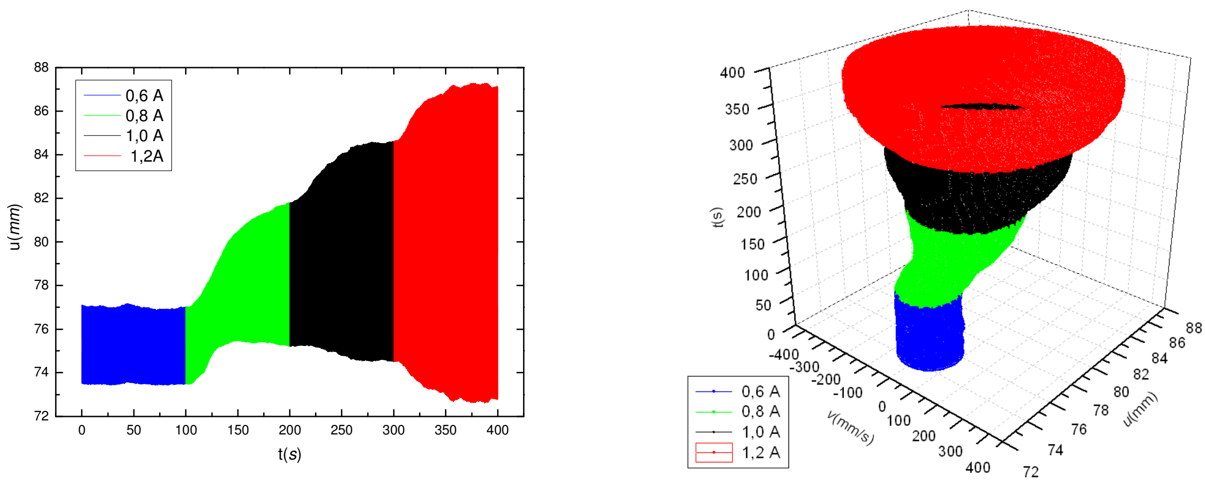
(*a*) (*b*)

Figure 7. *SMA oscillator* dynamics from laser transducer signal: displacement evolution of car 2 (*a*) and phase space (*b*) during heating (0.6 → 0.8 → 1.0 → 1.2A) for 8.9Hz.



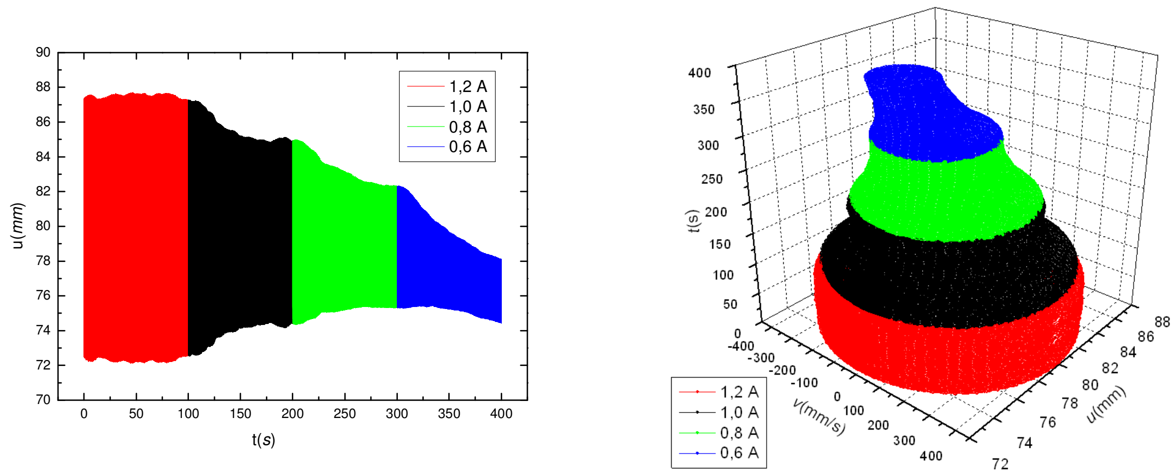
(*a*) (*b*)

Figure 8. Displacement evolution of car 2 (*a*) and phase space (*b*) during cooling (1.2 → 1.0 → 0.8 → 0.6A) for 8.9Hz. Laser transducer signal *SMA oscillator*.



(*a*) (*b*)

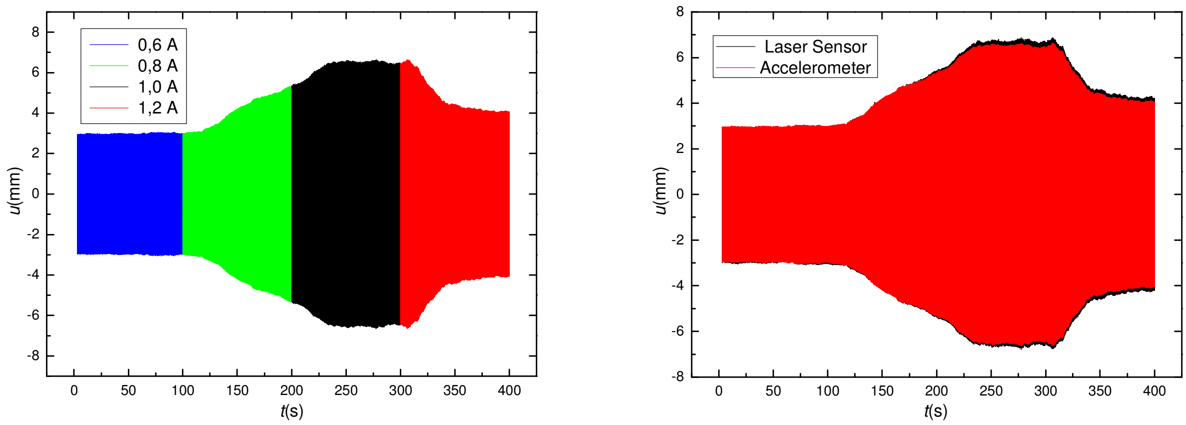
Figure 9. *SMA oscillator* dynamics from laser transducer signal: displacement evolution of car 2 (*a*) and phase space (*b*) during heating (0.6 → 0.8 → 1.0 → 1.2A) for 9.2Hz.



(*a*) (*b*)

Figure 10. *SMA oscillator* dynamics from laser transducer signal: displacement evolution of car 2 (*a*) and phase space (*b*) during cooling (1.2 → 1.0 → 0.8 → 0.6A) for 9.2Hz..

The use of accelerometer as a sensor is related to a proper methodology for the double integration of the signal. Here, a highpass band filters are employed promoting the loss of dc signal information. Therefore, this technique is critical for the dynamical analysis of the SMA oscillator. The following example illustrates compares signals from laser and accelerometer sensors by using an IIR (Infinite Impulse Response) digital filter in the laser signal. Figure 11*a* shows data obtained from accelerometer while Fig. 11*b* shows a comparison between both transducers where dc signal is eliminated for laser transducer signal in order to permit a direct comparison. This data is associated with an excitation frequency of 8.9 Hz involving the heating of the SMA helical spring by applying four levels of electrical current: 0.6 → 0.8 → 1.0 → 1.2 A, as in Fig. 7. Despite the loss of dc signal information that the proposed methodology presents since the highpass band filters cut the dc signal during integration, results indicate that accelerometers can be used to assess some dynamical parameters of oscillators as their amplitude.



(*a*) (*b*)

Figure 11. *SMA oscillator*: displacement evolution of car 2. Accelerometer (*a*) and comparison between accelerometer and laser signals (*b*) during heating (0.6 → 0.8 → 1.0 → 1.2 A) for 8.9 Hz.

5. CONCLUSIONS

An experimental analysis of the dynamical behavior of a single-degree of freedom SMA oscillator is carried out. An experimental apparatus composed by a low-fiction car in a linear rail attached to a SMA helical spring is employed. The car is excited by a shaker system providing harmonic excitation. Laser and accelerometer sensors are employed for data acquisition and filtering procedures are developed being calibrated from an elastic oscillator. Different excitation tests are carried out considering sweep frequency variations and temperature changes induced by electric currents. In general, it is possible to conclude that accelerometer signals is only useful for specific purposes since the dc signal filtering eliminates important information related to equilibrium point position induced by temperature. In this regard, laser sensor furnishes better results providing a better comprehension of the system dynamics.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Brazilian Research Agency CNPq.

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