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EXPERIMENTAL ANALYSIS OF A SHAPE MEMORY ALLOY
OSCILLATOR WITH DISCONTINUOUS SUPPORT

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Abstract. *Non-smooth nonlinearities are often in nature being linked to friction phenomena or discontinuous characteristics of intermittent contacts. Non-smooth systems occur in various physical scenarios, such as rotodynamic and oil drilling. Vibration control is an interesting application considering non-smooth systems, especially those using smart materials such as shape memory alloys (SMAs). In this regard, several studies on the use of shape memory alloys in vibration control systems have been proposed in recent years. The use of SMAs in these applications exploits the ability to dissipate energy due to hysteretic behavior and also property variations. This paper presents an experimental study of the nonlinear dynamics of a shape memory oscillator composed of a car, free to move over a rail, connected by two springs and an excitation system. The discontinuous support is built by a linear spring considering a gap to the oscillator position. The proposed experimental system is instrumented to obtain all system state variables. Different experimental configurations are of concern: a system with SMA springs, without and with support; a system with a combination of linear and SMA springs, without and with support. Results allow one to evaluate the influence of the SMA elements on the system dynamics for different assemblies and excitation conditions, showing a rich dynamical behavior.*

Keywords: *Shape memory alloys, dynamical systems, non-smooth systems, nonlinear dynamics, experimental observations.*

1. INTRODUCTION

Shape memory alloys (SMAs) are metals that belong to the class of smart materials that have many thermomechanical behaviors including pseudoelasticity, shape memory effect, internal subloops due to incomplete phase transformation, tension-compression asymmetry, and phase transformation due to temperature variation. These behaviors are associated with solid-solid martensitic phase transformations promoting a hysteretic response with large deformations and small volume changes (Yamauchi et al., 2011). These materials have been used in a large variety of applications in different areas including biomedical, aerospace, automotive, and robotics due to their remarkable properties (Machado and Savi, 2003; Petrini and Migliavacca, 2011; Mohd Jani et al., 2014; Nematollahi et al., 2019). Furthermore, due to their ability to dissipate energy and undergo significant deformations during the phase transformation process, shape memory alloys have great potential for vibration attenuation applications. This potential can be exploited in various mechanical equipment characterized by wide frequency ranges, devices subjected to impact loads, and earthquake-resistant structures (Saadat et al., 2002; Vignoli et al., 2020; Silva et al., 2021).

The use of SMAs in vibration control and vibration absorbers considers either stiffness changes due to temperature variations or energy dissipation due to hysteretic behavior. In recent years, several studies have investigated the potential of utilizing shape memory alloys to reduce vibrations in mechanical systems by manipulating the stiffness of SMA elements through temperature variations. Williams et al. (2002, 2005) and Savi et al. (2011) explored this concept by incorporating SMAs as tuning elements in adaptive vibration absorbers. Aguiar et al. (2013) experimentally examined one and two-degrees-of-freedom SMA oscillators, analyzing the impact of temperature variations on stiffness and hysteresis with their subsequent effects on the resonant conditions of the system. Silva (2013) analyzed the vibration control of a rotor-bearing system, comparing the behavior of the system under different temperature conditions. Enemark and Santos (2016) investigated the integration of pseudoelastic SMA helical springs into a rotor-bearing system for vibration attenuation through their mechanical hysteresis, and for adaptation of the dynamic behavior through their temperature-dependent stiffness properties. Alves et al. (2018) proposed a study of the influence of SMAs on the dynamic behavior of a rotor-bearing test rig suspended by shape memory alloy wires. The outcomes demonstrate the success of

shape memory alloy applied to the suspension of rotating machines as an interesting alternative for vibration control. Savi (2015) presented an overview of the nonlinear dynamics and chaos of smart material systems built with SMAs. In this sense, the main aspects involving oscillators, vibration absorbers, impact systems, and structural systems were analyzed.

Non-smooth nonlinearities are often in nature being linked to friction phenomena or discontinuous characteristics of intermittent contacts of some system components. Therefore, non-smooth systems occur in diverse physical scenarios, including rotodynamic systems, oil drilling operations, and manufacturing processes. Moreover, these nonlinearities are intimately linked to phenomena such as equipment chattering, which can cause serious problems in many industrial applications (Divenyi et al., 2008). Several non-smooth systems have been treated in the literature from different perspectives. Considering the numerical point of view, it is possible to highlight the works proposed by dos Santos and Savi (2009) and Sitnikova et al. (2010) that analyzed impact oscillators with SMA components. Results demonstrated the vibration reduction capabilities of the SMA oscillators when compared to an equivalent elastic device. The literature presents different references considering the experimental approach to analyze non-smooth systems from an experimental point of view and also to verify the proposed numerical methods. In this regard, Savi et al (2007) presented experimental and numerical studies considering a non-smooth system with discontinuous support. Divenyi et al. (2008) presented an experimental investigation considering different configurations of the experimental setup treated in the previous study to evaluate the influence of the internal impact on the characteristics of the system dynamics. Both studies showed a rich response that includes dynamical jumps, bifurcations, and chaos. Miranda et al. (2011) analyzed the dynamic response of a similar experimental apparatus, considering the use of different supports: one made from a linear spring, and another constructed with an SMA spring. Results demonstrated the significant dissipation capability of shape memory alloys with a reduction in the transient time and fewer amplitude behaviors. Other studies are available in the literature considering experimental and numerical approaches to evaluate the dynamics of non-smooth systems, for instance: Sitnikova et al. (2010) and Costa et al. (2020).

This paper aims to present an experimental study of the nonlinear dynamics of a single-degree-of-freedom oscillator with discontinuous support. The experimental apparatus is composed of a car, free to move over a rail, connected by two springs and an excitation system. Different experimental configurations are analyzed. A system with two SMA springs is treated, considering cases without and with support. Afterward, a system combining a linear spring with an SMA spring is treated, once again evaluating situations without and with support. The discontinuous support is built by a linear spring considering the oscillator separated by a gap to the car position. The proposed experimental system is instrumented to obtain all system state variables. From the proposed tests, it is possible to evaluate the influence of the SMA elements on the system dynamics for different assemblies and excitation conditions. In general, the results exhibit a rich dynamical behavior from the combination of geometrical and constitutive nonlinearities.

2. EXPERIMENTAL APPARATUS

The experimental analysis is performed by considering an SMA single-degree-of-freedom oscillator with discontinuous support represented by the schematic picture in Figure 1. The oscillator is composed of a car with a mass m (*PASCO ME-9430*), free to move over a rail. The mass is connected by two springs. The system excitation is assumed to be harmonic, provided by a DC motor (*PASCO ME-8750* with 0 – 12 V and 0 – 0.3 A) powered by a DC power supply (*Minipa MPL-3303M*) connected to one of the springs by an inextensible string. The parameter b measures the rotor arm, and its size can be adjusted to vary the excitation amplitude. The distance between the rotor and the guide is represented by a . It is assumed to be $b = 65$ mm and $a = 162$ mm.

The dissipation process can be modeled by a combination of dry friction with a coefficient μ and by viscous damping with a coefficient c . The discontinuous support is massless and composed of a linear elastic spring with stiffness k_s and the dissipation process is represented by a linear viscous damping element with coefficient c_s . Figure 2 shows the springs and support used in the experiment.

The car displacement is denoted by x , relative to the equilibrium position, while the support displacement is denoted by y . The distance between the mass and the support is defined by a gap g . Therefore, this system has two modes of operation, represented by a situation in which the mass makes contact with the support ($x \geq g$) and another in which there is no contact ($x < g$). The position and the velocity of the car are measured by a rotary sensor, *PASCO CI-6538* which has a precision of $\pm 0.25^\circ$, a maximum velocity of 30 rev/s, and a maximum sampling frequency of 1000 Hz. Furthermore, the angular velocity of the rotor is measured using the photogate sensor *PASCO ME-9204A*, and the induced force in the springs is estimated by the force transducer sensor *PASCO PS-2104*. The data captured by the sensors is sent to the *PASCO PS-2001 Powerlink interface*, connected to a computer, and processed by the software *PASCO Capstone*. Figure 3 illustrates the DC power supply, sensors, data interface, and acquisition software used in the experimental apparatus during the proposed tests.

Different configurations are of concern, considering cases without and with support. One configuration uses two SMA springs and the other one considers a combination of a linear spring with a SMA spring.

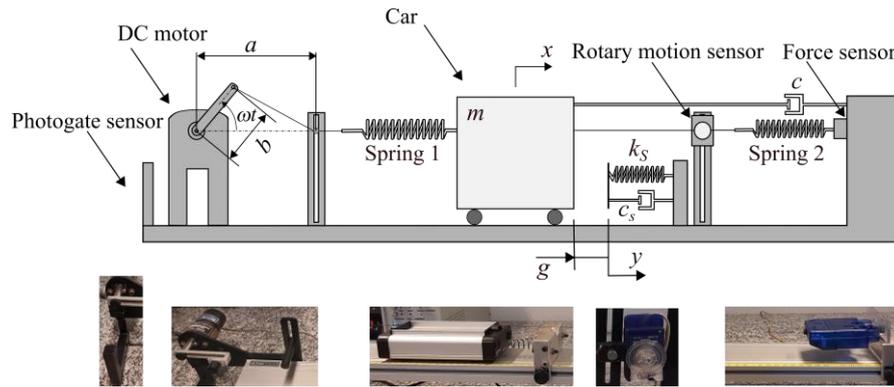


Figure 1. A non-smooth system with discontinuous support, schematic diagram.

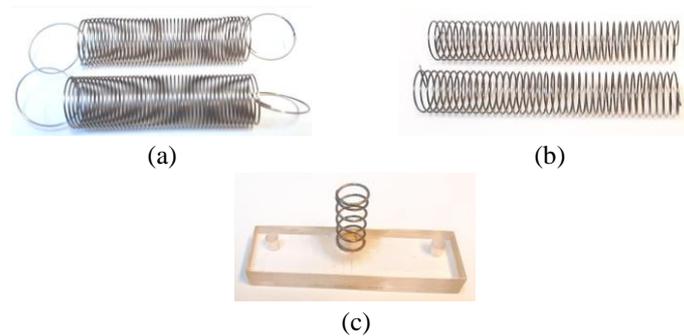


Figure 2. Oscillator components. (a) linear springs; (b) shape memory alloy springs; (c) discontinuous support.

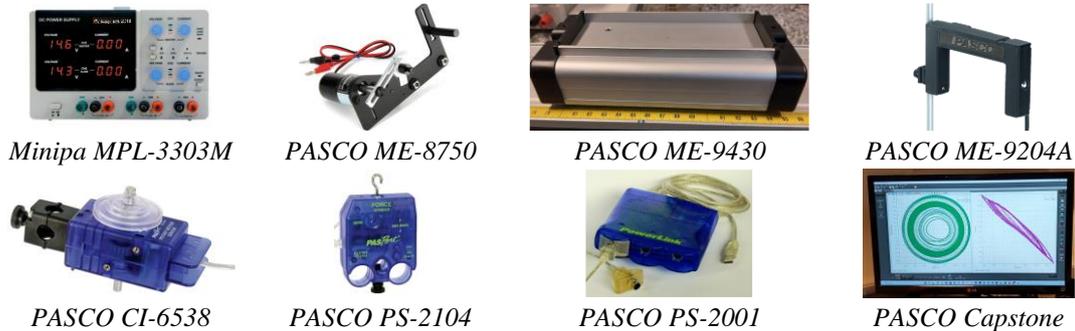


Figure 3. Experimental apparatus: DC power supply, sensors, data interface, and software.

3. SYSTEM WITH SMA SPRINGS

This section investigates the dynamic response of the system composed of two SMA springs without impact and subsequently with impact considering a gap $g = 3$ mm. Experimental tests are carried out considering different excitation frequencies to analyze the influence of forcing on the system dynamics and the dissipation characteristics of the SMA springs. In all tests, transient responses are neglected, which means that responses exclude the first 100 seconds.

3.1 Experimental results without impact

The system with two SMA springs without impact is now of concern. Three excitation frequencies are analyzed through phase-space and force-displacement curves as shown in Figure 4. The system response shows a steady state response where orbits visit two distinct behaviors, highlighted in the figure: high-level energy and low-level energy. The grayscale curves represent the phase-space for all the considered time (the same one presented in the curves on the left), with emphasis on the red curves that represent a lower energy orbit, and the blue curves representing a higher energy orbit. These orbits are estimated by observing the displacement time history response. The transit between high-energy and low-energy orbits is due to the hysteretic dissipation promoted by the SMA springs. In this regard, when the system has more energy, the SMA springs have a greater dissipation (represented by a larger area of the hysteresis loop). When

the dissipation reaches a limit value, the system transitions to an orbit of lower energy (represented by a smaller area of the hysteresis loop). Note that for all excitation frequencies analyzed, the system presents a complex dynamic response. It can also be observed that for excitation frequencies of $\omega = 3.43$ rad/s and $\omega = 4.36$ rad/s, the measured forces assume negative values. This occurs because the tests are performed with a pre-load on the springs, and therefore, the equilibrium position has an associated initial force. This force is set to zero for convenience in presenting the results. Thus, at certain moments, the system exhibits trajectories where the springs pass through a negative position relative to the measured equilibrium point, resulting in negative force values.

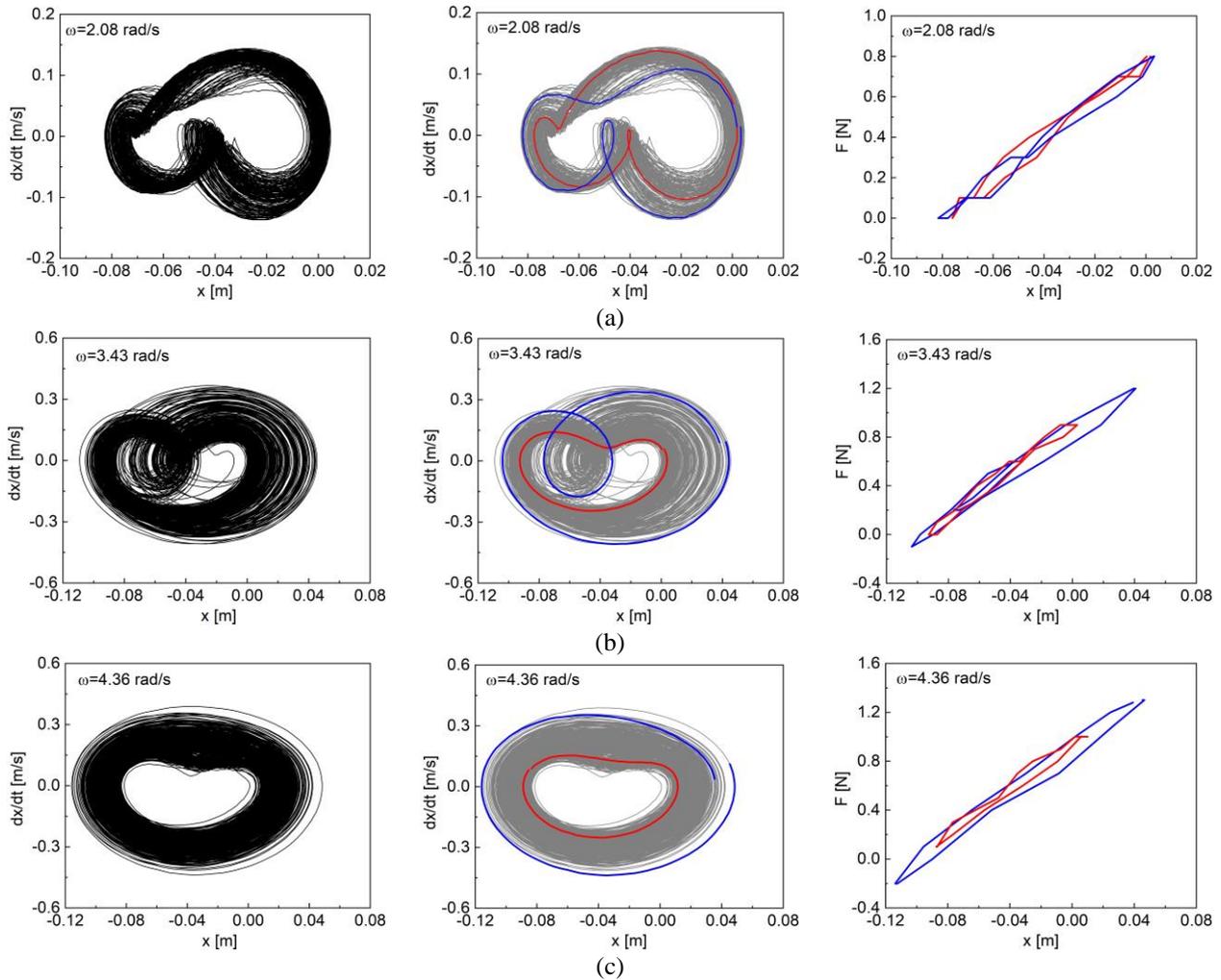


Figure 4. State space and force-displacement curves considering SMA springs without discontinuous support. (a) $\omega = 2.08$ rad/s; (b) $\omega = 3.43$ rad/s; (c) $\omega = 4.36$ rad/s.

3.2 Experimental results with impact

At this stage, the support is added, considering a gap of $g = 3$ mm, and three excitation frequencies are analyzed to represent the response of the system. Results are shown in Figure 5, following the same presentation approach previously performed. The results of the non-smooth system have a split of the state space, characterizing the contact and non-contact modes. Once again, it is possible to observe different dynamical behaviors as a function of the excitation frequency imposed on the system and the dissipation due to the support and the SMA springs. In this regard, for the excitation frequency of $\omega = 1.27$ rad/s, a complex response is observed when compared to the frequency $\omega = 4.07$ rad/s, where the system exhibits a periodic characteristic. Furthermore, an increase in the hysteretic dissipation of the SMA springs can be observed with the increase in the excitation frequency of the system.

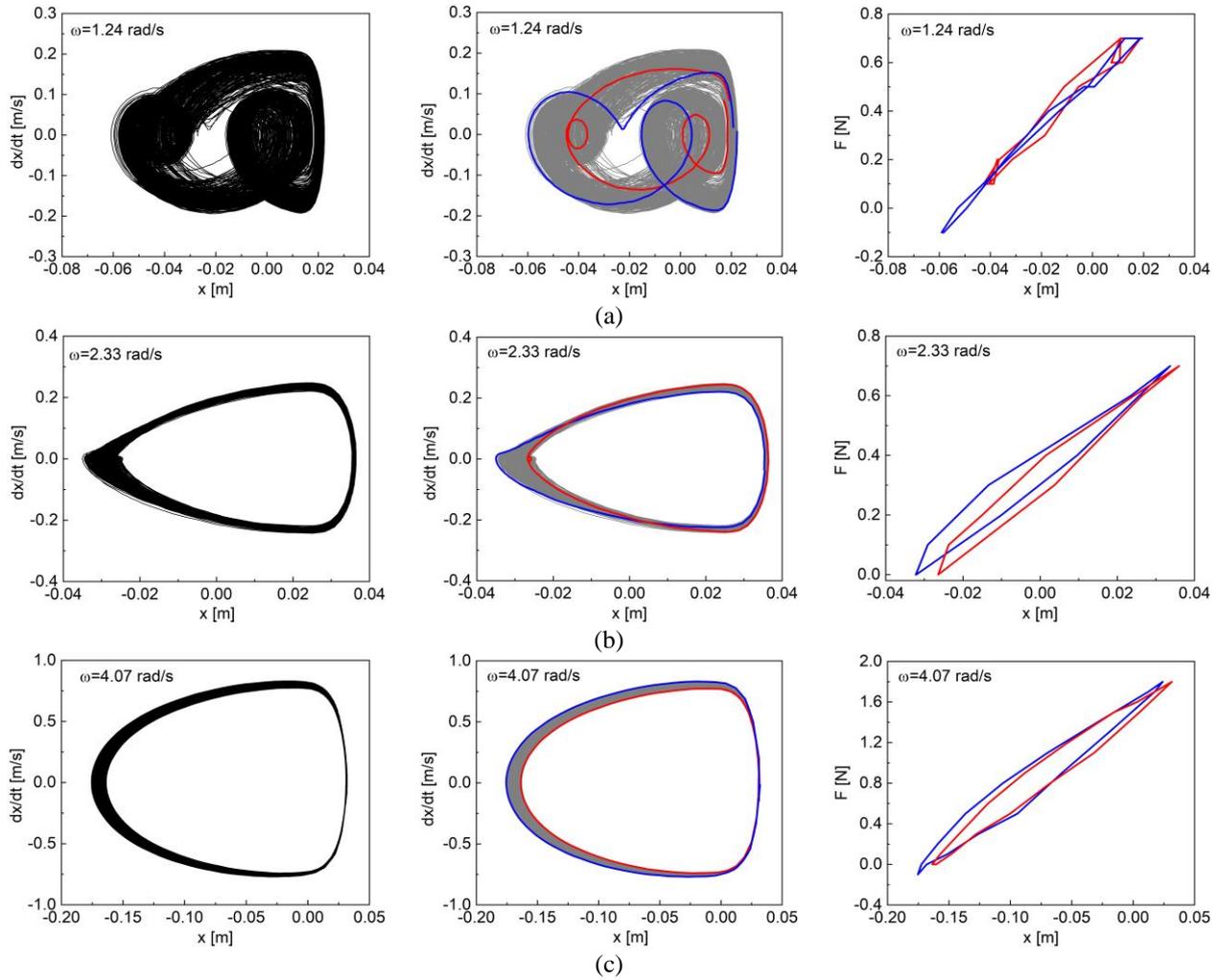


Figure 5. State space and force-displacement curves considering SMA springs with discontinuous support. (a) $\omega = 1.24$ rad/s; (b) $\omega = 2.33$ rad/s; (c) $\omega = 4.07$ rad/s.

4. SYSTEM WITH LINEAR-SMA SPRINGS

This section investigates the dynamic response of the system with a layout composed of linear-SMA springs without impact and subsequently with impact considering a gap $g = 3$ mm. Once again, different excitation frequencies are analyzed, and the transient responses were neglected.

4.1 Experimental results without impact

The system without impact is now of concern. Three excitation frequencies are analyzed through phase space and force-displacement curves as shown in Figure 6. Considering the arrangement composed of a linear spring and an SMA spring, it is possible to observe a change in the system's dynamical response when compared to the response of the system with two SMA springs, without support. Note that this configuration promotes a reduction in the complexity of the exhibited response. Nevertheless, the transit between high and low-energy orbits still persists, as can be observed through the highlighted orbits and the force-displacement curves.

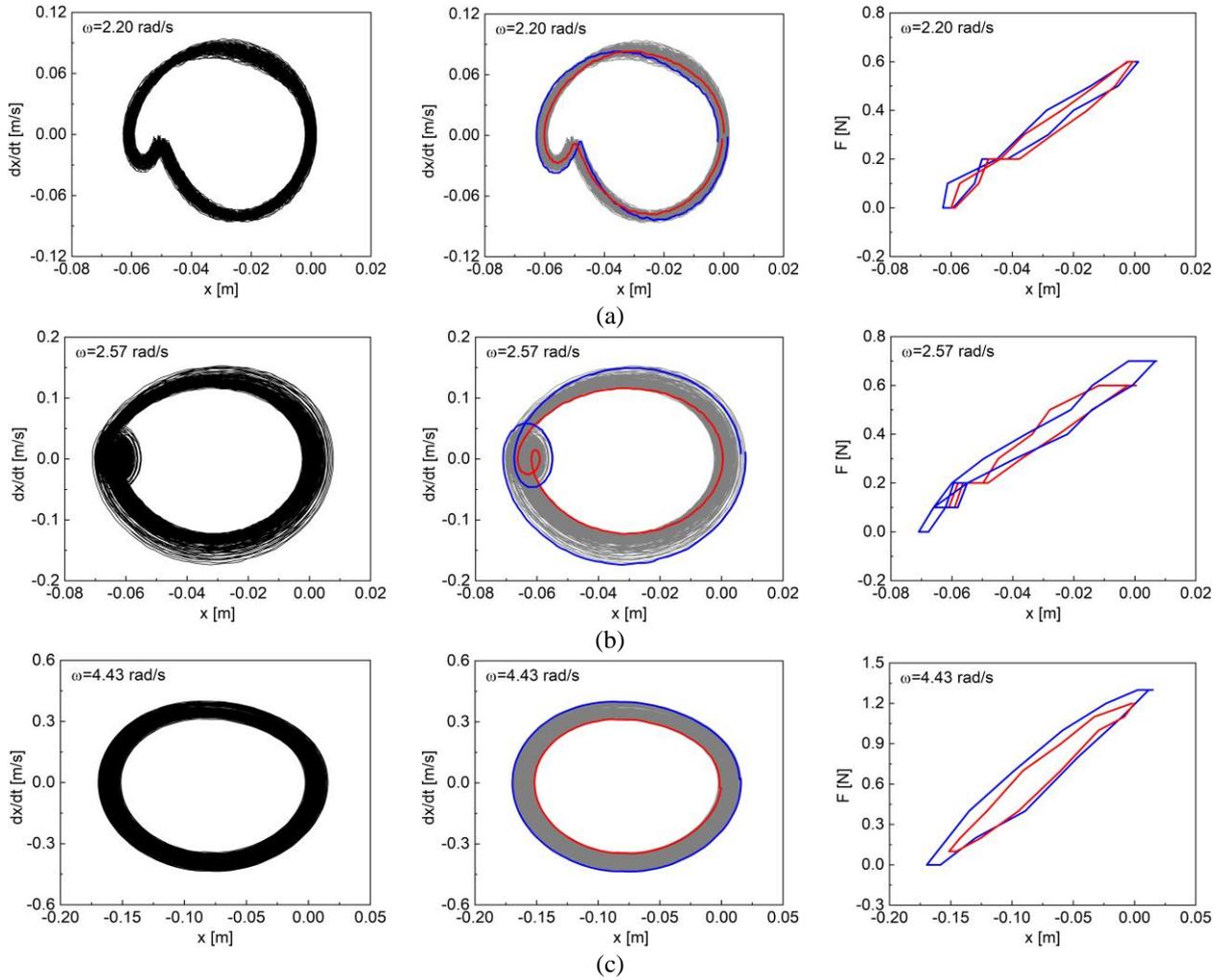


Figure 6. State space and force-displacement curves considering the association with linear-SMA springs without discontinuous support. (a) $\omega = 2.20$ rad/s; (b) $\omega = 2.57$ rad/s; (c) $\omega = 4.43$ rad/s.

4.2 Experimental results with impact

At this point, the dynamical response presented by the system is investigated considering the support with a gap of $g = 3$ mm. Once again, a change in the system's dynamic behavior can be observed in Figure 7 when compared to the response presented in Section 3.2 (two SMA springs with support). Furthermore, through the highlighted orbits, the transition between orbits of high energy to those of low energy due to the dissipation provided by the SMA spring is again verified.

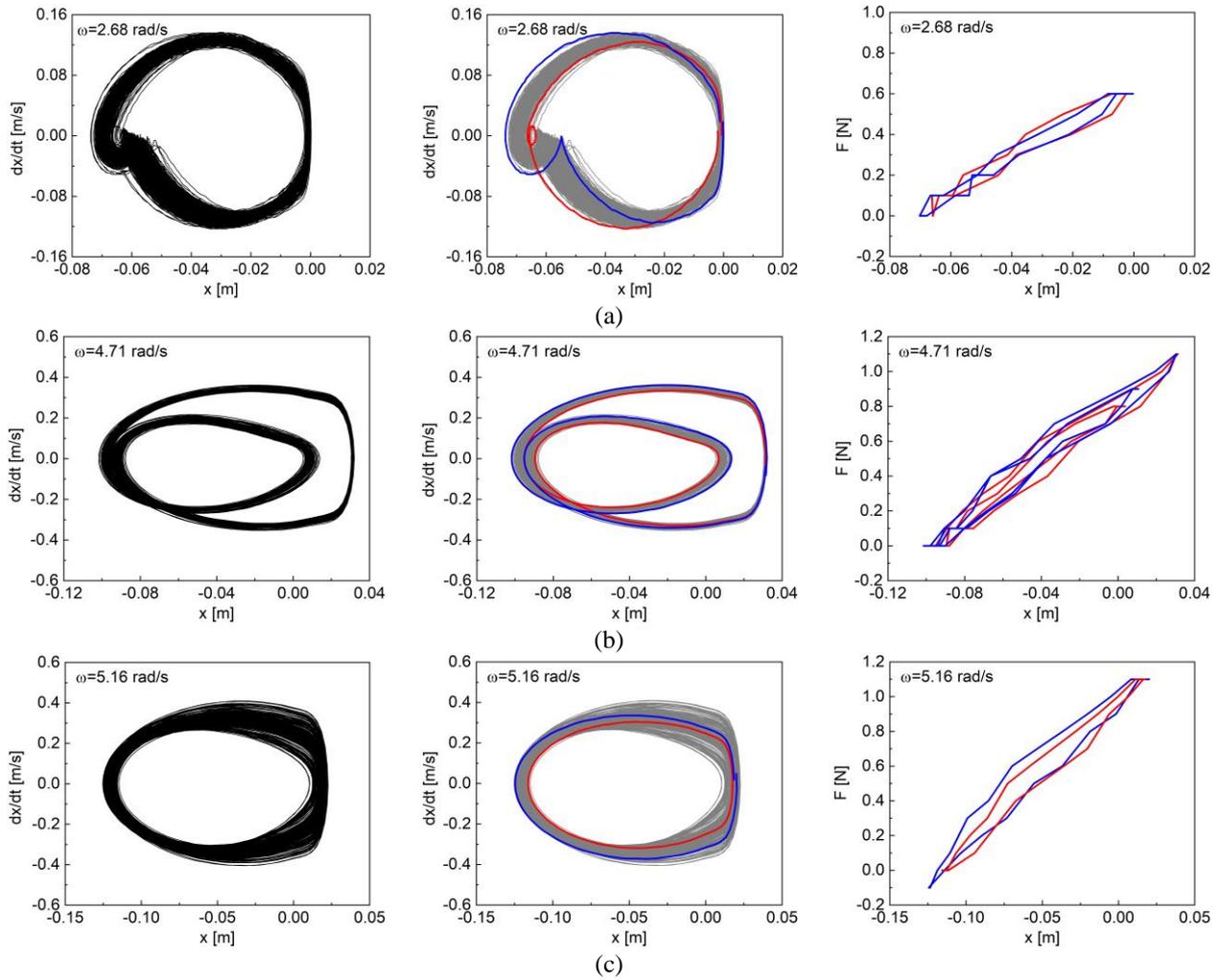


Figure 7. State space and force-displacement curves considering the association with linear-SMA springs with discontinuous support. (a) $\omega = 2.68$ rad/s; (b) $\omega = 4.71$ rad/s; (c) $\omega = 5.16$ rad/s.

5. CONCLUSIONS

This contribution deals with the experimental analysis of shape memory alloy oscillators with discontinuous support. The oscillator is a single-degree-of-freedom system composed of a car, free to move over a rail, connected with two springs, and an excitation system provided by a motor and a string-spring system. The discontinuous support is built by a linear spring separated by a gap to the oscillator position. The experimental system is instrumented to obtain all system state variables. Different configurations are analyzed considering, initially, two SMA springs and then, an arrangement with an SMA spring and a linear spring. Both configurations are analyzed without support and with support. Based on the results, the system composed of two SMA springs without impact exhibits the highest complexity in the dynamic responses. When the support is added, due to its dissipation characteristic, a reduction in the complexity of the dynamic responses is observed, particularly for higher excitation frequencies, and the system begins to exhibit periodic characteristics. The system composed of a linear spring and an SMA spring displays less complex dynamic responses for all analyzed frequencies. In general, the dynamical response presented by the system is directly linked to the dissipation of the SMA springs. Furthermore, when the linear spring is added, the system's ability to dissipate energy through hysteretic dissipation is reduced. The most interesting characteristic of the system response is related to a steady state associated with high-energy and low-energy orbits due to SMA dissipation.

6. ACKNOWLEDGEMENTS

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