

Experimental investigation of vibration control of flexible rotors using shape memory alloys

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Abstract. Vibration is an essential subject for the design of rotordynamic systems, being responsible for compromising the integrity and causing risks to operational functioning. This work deals with an experimental investigation of the semi-active vibration controller for a rotordynamic system using shape memory alloy (SMA) elements. SMAs are smart materials that present thermomechanical coupling represented by solid phase transformations that promote either stiffness change or hysteretic dissipation. In this regard, they are useful in controllers employing thermal actuation from electric current through the Joule effect. This paper presents a proof of concept of a controller using SMA elements. An experimental apparatus is proposed considering a typical rotor system using SMA wires at the bearings. In this regard, proper temperature variations allow the system to cross critical resonant conditions.

Keywords: Shape memory alloys, rotordynamics, flexible rotor, vibration control.

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1. Introduction

Rotor vibrations have been studied for years showing that the critical situations are related to resonant conditions, presenting high displacement amplitudes [1, 2]. The literature is vast in techniques to either mitigate or change critical behaviors. On this basis, vibration control is an essential subject and it is usual to employ passive and active controls to attenuate vibrations. An alternative to these two approaches is the semi-active approach that combines the advantages of both. In this regard, the properties of the primary system are modified, avoiding the excessive use of sensors and processing system [2, 3].

The use of smart materials has growing importance for the development of these controllers. In the last decades, shape memory alloys (SMAs) have been studied due to their remarkable properties. An essential aspect of SMA's thermomechanical behavior is the solid phase transformation that can be induced by either stress or temperature. When subjected to proper thermomechanical loadings, phase transformations occur producing different phenomena where it is important to highlight shape memory and pseudoelastic effects [4, 5]. These effects have several applications in distinct areas with extensive literature discussing the applications and their mathematical modeling [5–11].

The dynamical applications of SMA are particularly intriguing due to the unique combination of hysteretic dissipation and property changes resulting from phase transformations. Savi [12] provided a comprehensive overview of the main dynamical applications of SMA, including smart structures, rotor systems, among others.

Specifically related to rotordynamics, different rotor and bearing configurations were investigated considering distinct kinds of SMA elements. Lee et al. [13] employed a pedestal bearing with bundles of SMA wires heated by an electric current. The electric actuation changes the stiffness of the SMA wires, changing the system's properties. Borges et al. [14] reduced the rotor critical amplitude by 60% using SMA helical springs heated by the Joule effect. Enemark et al. [15] performed the vibration control of a vertical rotor using SMA helical springs heated by thermal blowers. The research sought to verify the effect of pseudoelasticity and stiffness variation considering different temperatures of the SMA elements, pointing out that amplitude can be reduced during resonant conditions.

Ma et al. [16] proposed a rotor bearing with an SMA metal rubber, a type of tangled metallic mesh. The material was heated in a thermal chamber at different temperatures, and the rotor presented variations in stiffness and energy dissipation. Alves et al. [2] presented numerical and experimental analyses of the influence of stiffness variation and pseudoelastic effect using SMA wires on flexible rotors. The SMA wires were arranged in one of the bearings and heated by thermal blowers. Due to the characteristics of the rotor, only horizontal displacements are of concern. It was presented that there was a shift of the critical velocity and a reduction in amplitude when reaching resonance, showing the feasibility of the vibration semi-active control. Braga et al. [1] introduced a novel configuration that incorporates SMA wires and considers the vertical displacement

of the rotor. They evaluated different SMA temperatures, demonstrating that an increase in temperature leads to a reduction in amplitude.

Feng et al. [17] developed an active foil bearing with SMA springs considering an effective cooling system to regulate the temperature. In this regard, results showed that phase transformations can control the system behavior altering system stiffness. Senko et al. [18] investigated the energy dissipation of pseudoelastic SMA bending elements placed in the rotor bearing. The study focused on the analysis of mechanical loads that induce pseudoelastic behavior, and two different models were explored: loads applied and removed; and a constant load. A comparative analysis showed that the first model was more efficient due to its higher dissipation capacity. The same device was used by Senko et al. [19] maintaining a constant pre-load throughout the test, reducing involved instabilities, and increasing the dissipation capacity without the use of an external source of energy.

This work deals with a rotordynamic system with a novel SMA-bearing configuration, inspired by the study of Alves et al. [2]. The system is composed of a rotor with SMA wires arranged in one of the bearings. This system works as a semi-active controller for flexible rotors, taking advantage of the changes in SMA stiffness and promoting hysteretic energy dissipation. The SMA properties are modified through electrical heating, utilizing the Joule effect, which defines the implementation of a compact heating system. The nonlinear dynamics of the system are assessed by monitoring the displacements of the bearings and the disc, as well as the critical frequency. Temperature changes provide a general overview of the influence of the SMA in the system responses.

2. Shape memory alloys

Shape memory alloys (SMAs) are metallic materials with thermomechanical couplings. The remarkable properties due to solid phase transformations are employed in several applications in different fields of human knowledge that include biomedicine [4, 20–22], dentistry, aerospace applications [4, 23–27], robotics [4, 28–31] and engineering [1, 2, 4, 14, 16, 32–34].

SMAs present two microscopic phases: austenite and martensite. Typically, austenite is stable at high temperatures and free of stress. On the other hand, martensite is stable at low temperatures and free of stress [12, 35–37]. The austenitic phase has only one variant while the martensitic phase can present 24 variants in three-dimensional media. Since austenitic and martensitic phases present different elastic moduli, phase transformations induce stiffness variations [16, 38]. Mechanical and thermal loadings induce phase transformations that lead to shape memory effect and pseudoelasticity. The first is related to the recovery of a defined shape if subjected to proper thermomechanical loadings. On the other hand, pseudoelasticity is characterized by hysteretic behavior in such a way that when an SMA sample is subjected to mechanical loads at a constant high temperature, direct and reverse phase

transformations occur without residual strains [12, 25, 35, 36].

Pseudoelastic macroscopic behavior is schematically represented by considering the stress-strain curve of figure 1a. The SMA sample is initially in the austenitic phase when it is subjected to a mechanical loading. The phase transformation to the martensitic phase occurs and, upon unloading, reverse transformation occurs, making the sample returning to the previous shape, without residual strain. Temperature reduction can also induce phase transformation and, at low temperatures, the sample is in the martensitic phase. Under this condition, a mechanical load induces a martensitic reorientation and, if the mechanical load is removed, the reorientation does not take place, generating a residual strain. This residual strain can be eliminated by a temperature increase that causes a new phase transformation from martensite to austenite, characterizing the shape memory effect, figure 1b. It should be pointed out that the hysteresis loop is associated with an energy dissipation [4].

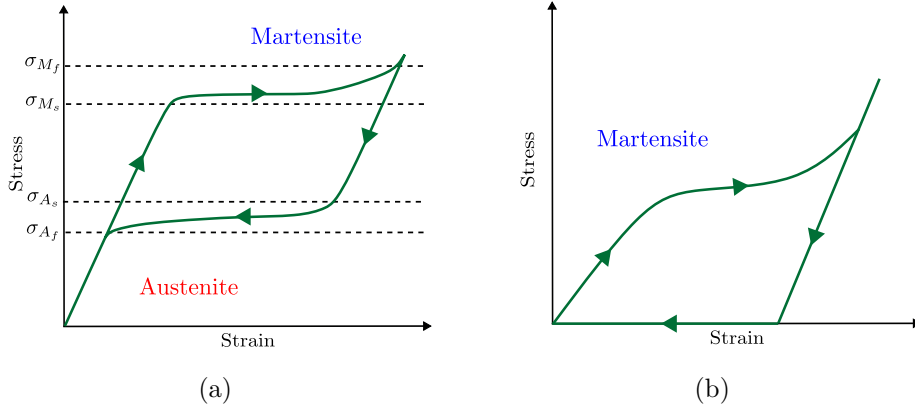


Figure 1. SMA macroscopic behavior represented by pseudoelasticity (a) and shape memory (b).

This work employs a Nitinol wire, NiTi (55%-45%), with a light oxide finish produced by the Forty Wayne Metals Research Products Corporation. Mechanical characterization involves tensile tests at various temperatures. On the other hand, thermal characterization utilizes Differential Scanning Calorimetry (DSC) to determine the phase transformation temperatures.

Figure 2 presents the results of the DSC test that heats and cools an SMA sample at a rate of 10°C/min, monitoring the heat flux. The peaks of this flux indicate phase transformations. The martensite transformation temperatures are determined through cooling, while the austenitic phase transformation temperatures are defined through heating. The tangent method is utilized to calculate the final and initial transformation temperatures of martensite (M_f , M_s) and austenite (A_f , A_s). Furthermore, an additional peak associated with the R phase is observed [39, 40].

The mechanical test is conducted by applying a constant tension while systematically varying the temperature to induce phase transformations. [4, 25]. Figure 3 shows the phase diagram that defines the phase transformation temperature for different

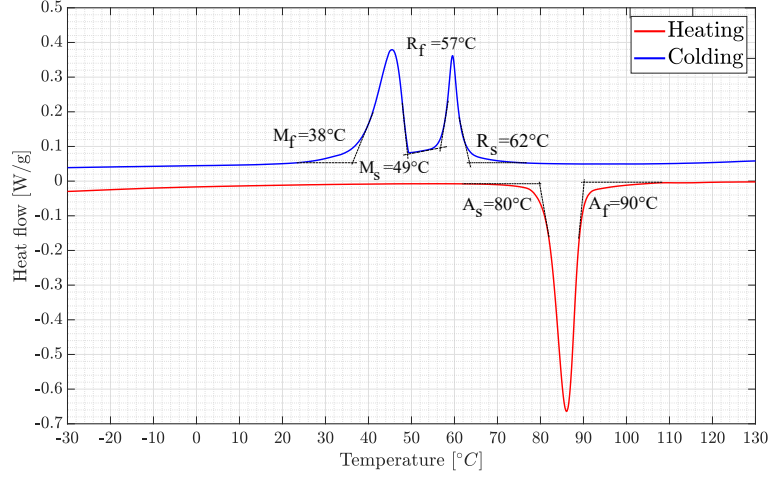


Figure 2. Results of the Differential Scanning Calorimetry test.

levels of an applied mechanical load built with a curve fitting. Three points of constant tension are evaluated following the same approach of reference [2]. Note that the slopes of the curves differ for the austenitic and martensitic phase transformations. Table 1 summarizes the main properties of the SMA based on these thermomechanical characteristics.

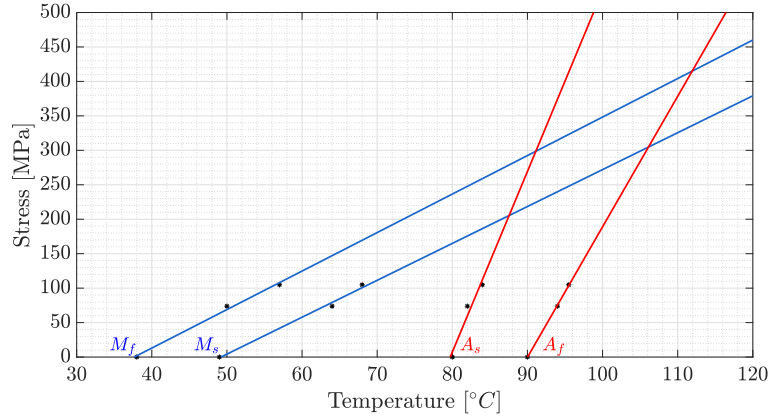


Figure 3. SMA phase transformation diagram: experimental result (*) and estimated curve (-,-).

To guide experimental tests, a constitutive model proposed by Brinson [6] is employed. By considering that σ is the stress, ϵ is the strain, and β represents the martensitic volume fraction, it is possible to write the following equation:

$$\dot{\sigma} = E\dot{\epsilon} + \alpha\dot{\beta} + \Omega\dot{T} \quad (1)$$

where Ω the thermal transformation coefficient and $\alpha = -E\epsilon_R$ with ϵ_R as the maximum recoverable strain coefficient. In addition, E represents Young's modulus and, since there are different values for austenitic and martensitic phases, it can be expressed as follows:

Table 1. Thermomechanical properties of nitinol.

Diameter (d)	0.635 mm
Young's modulus of austenite (E_A)	69.8 MPa
Young's modulus of Martensite (E_M)	30.4 MPa
Martensitic start temperature (M_s)	49°C
Martensitic finish temperature (M_f)	38°C
Martensitic start temperature (M_s)	49°C
Austenitic finish temperature (A_f)	90°C
Austenitic start temperature (A_s)	80 MPa/°C
Transformation coefficient of martensite (C_M)	5.6 MPa/°C
Transformation coefficient of austenite (C_A)	22.6 MPa/°C

$$E = E_A + \beta(E_M - E_A) \quad (2)$$

Based on that, it is possible to define the phase transformation region, describing its kinetics using the following equations [6, 41].

$$\beta = \beta_0 + (1 - \beta_0)f_M(\sigma, T) \quad A \rightarrow M \quad (3)$$

$$\beta = \beta_0 f_A(\sigma, T) \quad M \rightarrow A \quad (4)$$

where f_M and f_A are known hardening functions, usually assumed to be cosine functions.

Figure 4 shows stress-strain-temperature curves, for different temperature levels. It is noticeable the pseudoelastic effect at high temperatures while the shape memory effect is observed at low temperatures. It is also noticed that temperature increases move the hysteresis loop up.

3. Rotordynamical SMA system

Consider the experimental apparatus presented in figure 5 composed by an electric motor (1), two bearings (2 and 4), a disc (3), and four elements represented by helical springs (7) that are distributed considering an angle of 90° between each one of them in each bearing. Two different configurations are investigated considering an elastic configuration, without SMA wires, and an SMA configuration, introducing SMA wires. SMA configuration uses four load cells (5) in the bearing (4), four wires of 80 mm each, and a supply of direct current (8) that are responsible for heating the SMA wires.

The configuration of the wires within the bearing can be observed in figure 6. The wires are positioned at a 10° angle from the vertical axis, resulting in vertical and horizontal forces, with less intensity in the horizontal direction. Load cells are utilized to monitor the forces. SMA elements are subjected to a pre-load of 15 N. Table 2

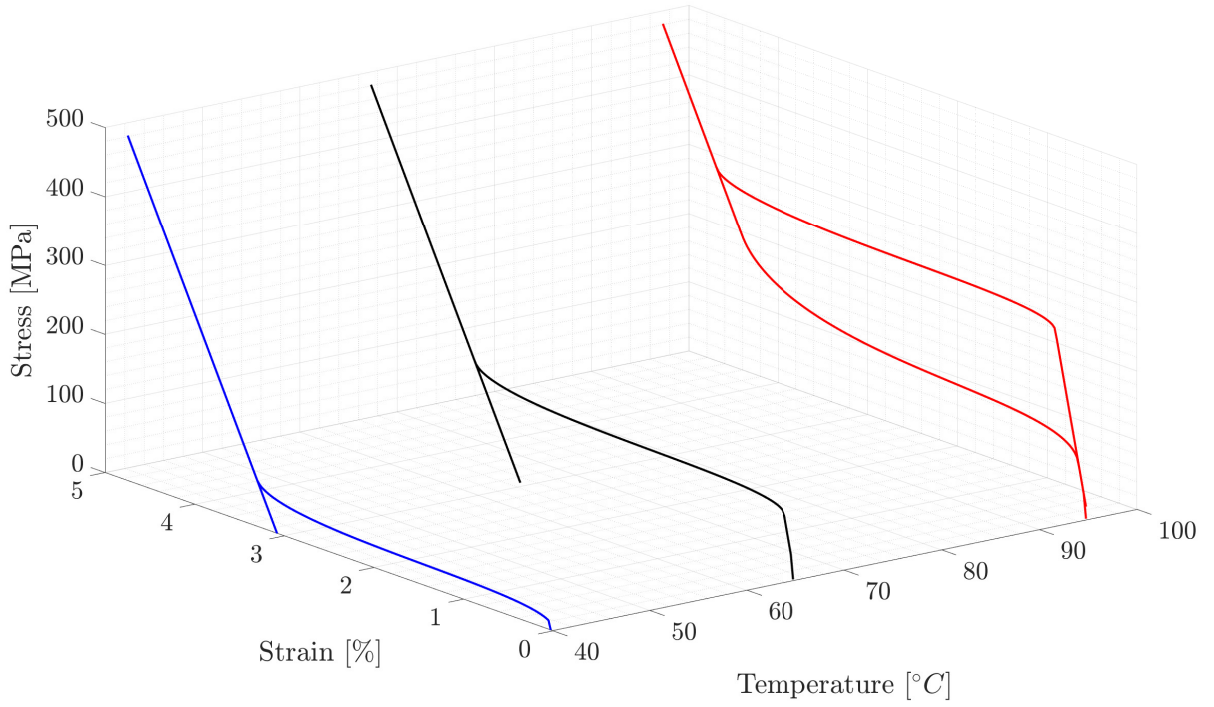


Figure 4. Stress-strain curves for different temperatures.

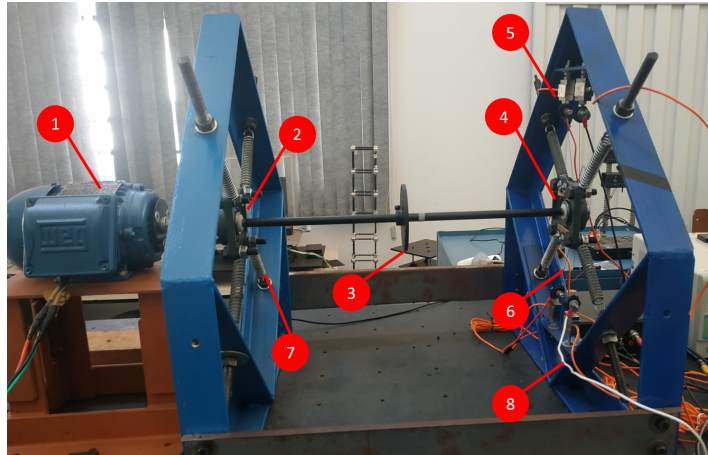


Figure 5. Experimental apparatus: (1) Electric motor, (2) First bearing, (3) Disc, (4) Second bearing - SMA, (5) Load cell, (6) SMA wire, and (8) Supply wire.

provides information on the dimensions, materials, and rotor unbalance utilized in the tests. Additionally, table 3 displays the stiffness and mass values for both bearings and the coupling.

Experimental tests are performed assuming that the electric motor imposes a speed ramp presented in figure 7, adopting a smooth rate of 100 rpm/s. A maximum angular rotation is assumed to be 2400 rpm. The test considers that the system is held on

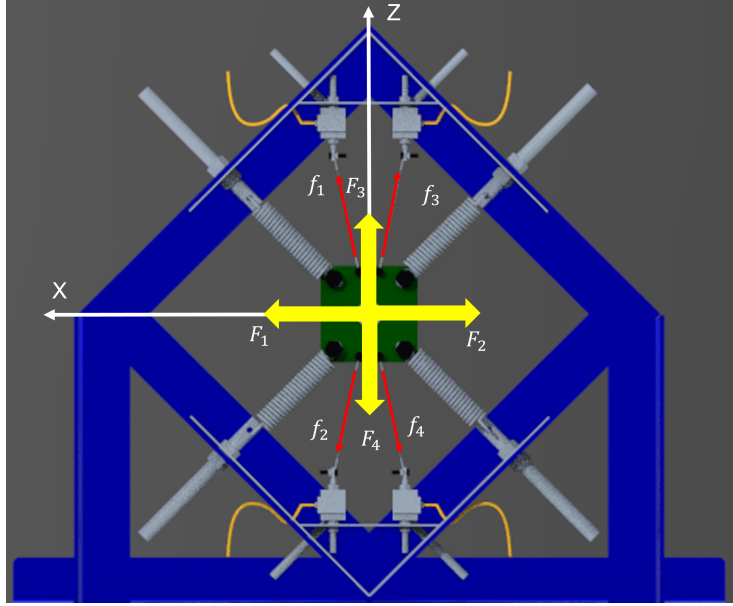


Figure 6. Representation of the arrangement of the wires and the forces acting in the load cell (f_i) and principal forces (F_i).

Table 2. Rotor properties.

Shaft diameter	12.5 mm
Shaft length	575 mm
Shaft mass	0.516 kg
Disc outside diameter	100 mm
Disc thickness	5.0 mm
Disc mass	0.306 kg
Young's modulus of shaft and disc	200 GPa
Density	7800 kg/m ³
Unbalance	0.2475 g.m

Table 3. Bearing and coupling properties.

Parameter	Bearing 1	Bearing 2	Coupling
Mass [kg]	0.670	0.568	0.01
Horizontal stiffness (x) [kN/m]	34.8	34.8	20
Vertical stiffness (z) [kN/m]	21.9	21.9	26

standby for 1 second at the maximum speed, and afterward, it is decelerated.

The bearing displacements (4) are measured using two uniaxial ICP accelerometers by PCB, one mounted vertically and the other horizontally. The horizontal displacement of the disc is measured using the vibrometer controller OFV-5000. However, the vertical

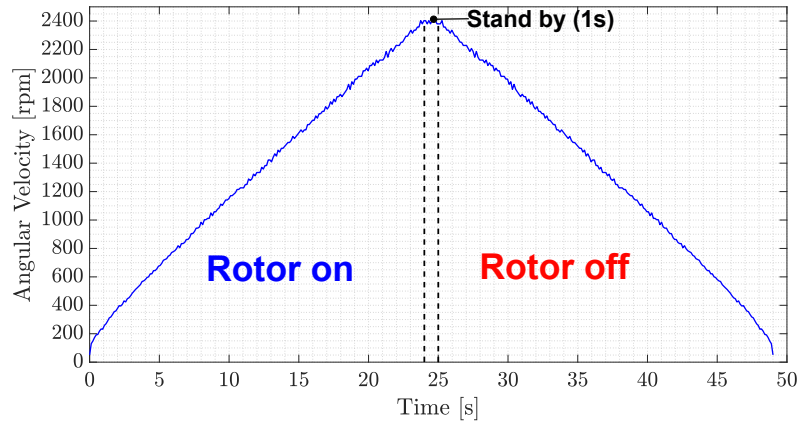


Figure 7. Rotor speed ramp.

displacement cannot be measured due to interference conditions.

Data acquisition is performed using the Q8-USB Quanser board and transmitted to the computer via Simulink. The acquired data is then processed and analyzed using the Matlab software. Figure 8 provides a comprehensive overview of the data acquisition methodology, illustrating the flow of the measured signals from acquisition to treatment and processing stages.

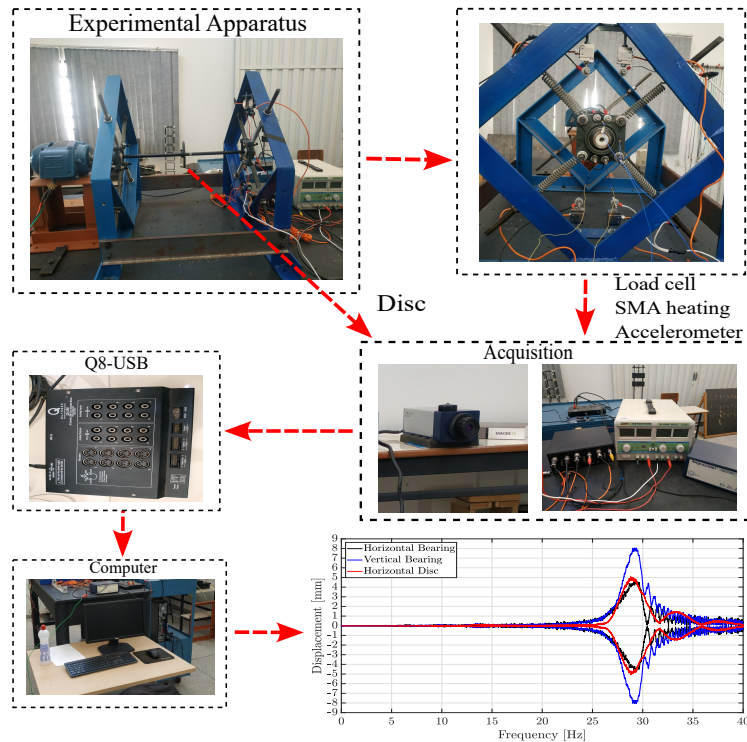


Figure 8. Graphical abstract of data acquisition methodology.

3.1. SMA Wire heating

The heating of the SMA wires is induced by the Joule effect generated by the potential difference in the Nitinol material. A k -type thermocouple with low thermal inertia and the MGCplus HBM acquisition system is employed to measure the temperature. The Nitinol wire is fixed at its ends, with one end connected to the rigid structure and the other end attached to a load cell for measuring pre-load. The electrical source is activated for 100 seconds and subsequently turned off. Consequently, the electrical voltage in the wire is related to the temperature and the applied force. Thus, it is verified the heating and cooling behavior and the natural convection influence. Figure 9(a) presents a schematic picture of the test, while figure 9(b) shows the acquisition system for the analysis of parameters, temperature, and load.

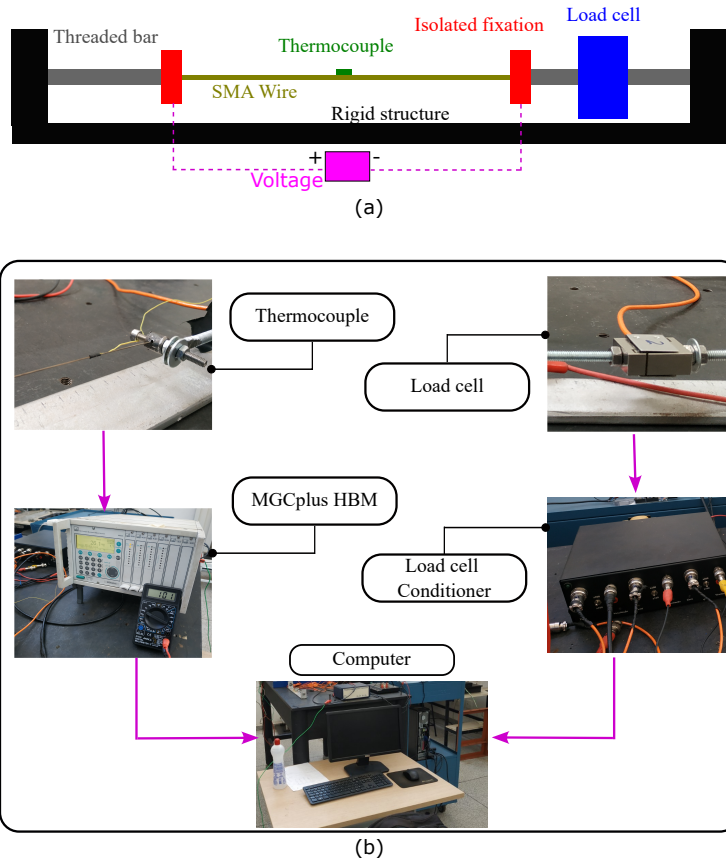
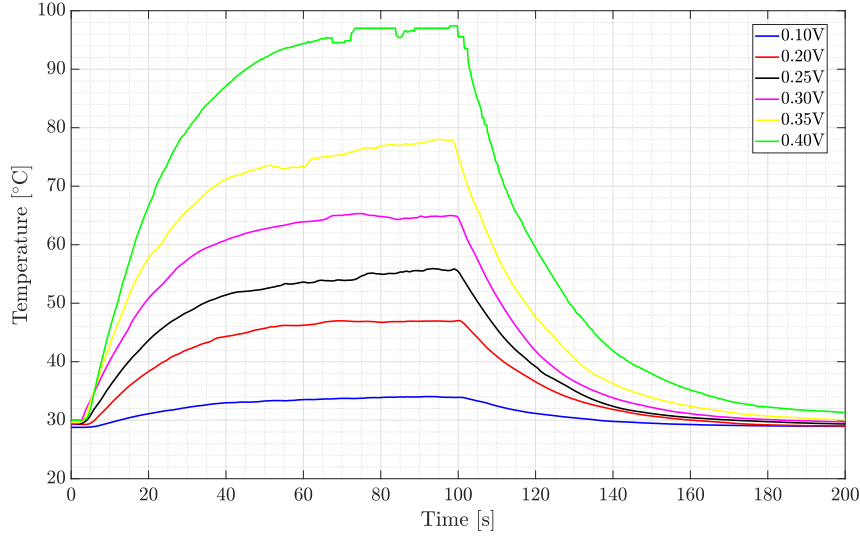
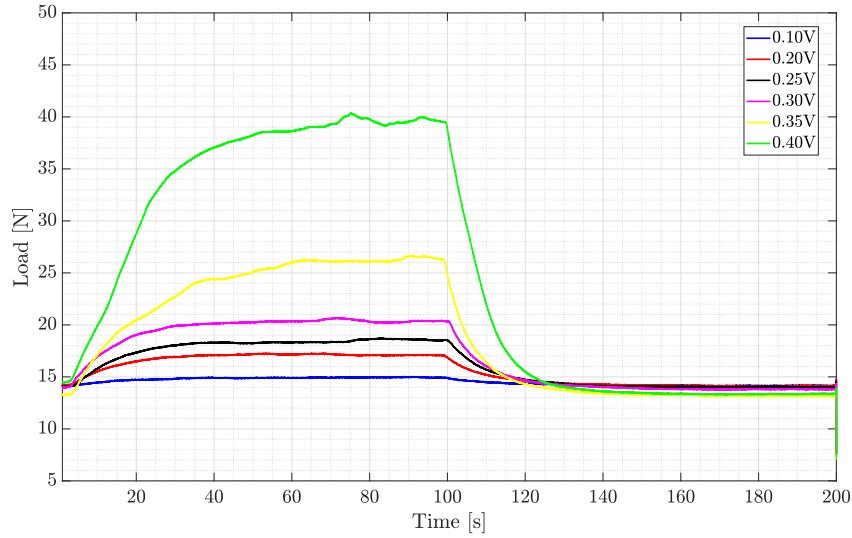


Figure 9. **a** Schematic of wire heating system and temperature measurement, **b** temperature (left) and load (right) acquisition system.

Figure 10(a) presents the temperature variation induced by electric voltage, considering different maximum values. The voltage is applied using a linear increase and subsequent decrease pattern. It is important to note that the voltage increase leads to an increase in wire temperature, which stabilizes at a specific level. The voltage is then removed, causing the temperature to decrease due to convection.



(a)



(b)

Figure 10. Results of heating wires SMA. **a** Temperature evolution due to voltage, **b** Force evolution due to voltage.

The force generated by the wire during the heating and cooling process is shown in figure 10(b). The behavior is qualitatively similar to that of temperature and when the temperature increases, the force applied to the wire also increases. The charge generated by the wire decreases rapidly after the heating system is turned off, ensuring a fast action of the SMA actuator.

4. Results and discussion

Rotordynamics is evaluated considering two different configurations: elastic and SMA. Figure 11 shows the bearing and disc horizontal displacements and the bearing vertical

displacement for the elastic configuration, without SMA wires. The Hilbert transform is used for visualization. The horizontal displacements present similar amplitudes, around 5 mm, whereas the vertical amplitude on the bearing occurs at the largest amplitude, reaching 8 mm. Results indicate the same critical resonant frequency that is employed as the reference for the analysis.

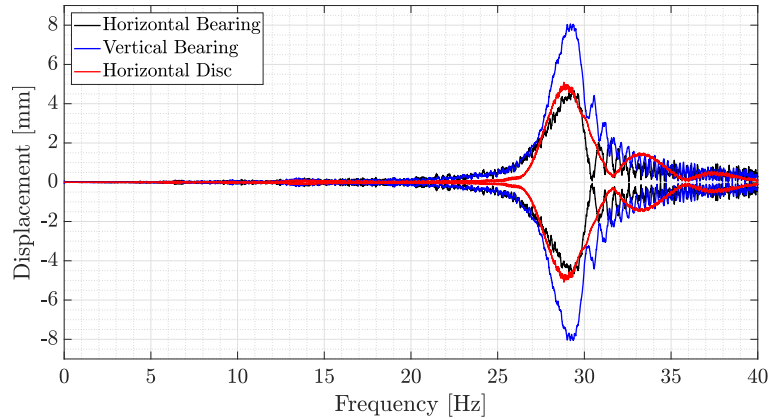


Figure 11. Elastic configuration: displacement of the bearing and the disc.

The SMA rotordynamic system is now of concern incorporating the SMA wires. Figure 12 shows the horizontal bearing displacement at different temperatures (40°C, 65°C, and 95°C). Note that each one of these temperatures is related to different behaviors, as can be observed in figure 4 that presents quasi-static stress-strain curves. The higher temperature presents pseudoelastic behavior and clearly presents both austenitic and martensitic phases. On the other hand, lower temperatures present a typical behavior of martensitic phase, which means that the dissipation is predominantly due to martensitic reorientation. A comparison is conducted with the elastic configuration, emphasizing the adaptive behavior of the SMA rotor configuration. The amplitude tends to decrease with the temperature increase, promoting the shift of the critical frequency. The disc exhibits similar behavior when subjected to the same temperature conditions, as depicted in figure 13.

A frequency response function (FRF) of vertical displacements is constructed by conducting an impact test using the LMS Scadas system. The average of ten tests is used to create figure 14, which displays the FRF of the rotor. Once again, it is evident that the SMA configuration causes a frequency shift in comparison to the reference rotor represented by the elastic configuration.

It is worth mentioning that the installation of the wires leads to an increase in stiffness, manifested by an elevation in the critical frequency. Additionally, the initial amplitude of the system with SMA is smaller compared to the system without SMA. As temperature varies, the curves exhibit slight divergence in amplitude, which can be attributed to phase transformations. In this case, It is not feasible to analyze the pseudoelasticity using the impact test as it does not induce such behavior. Additionally, due to the limitations of the dynamic analysis, which is restricted to 40 Hz, it is not

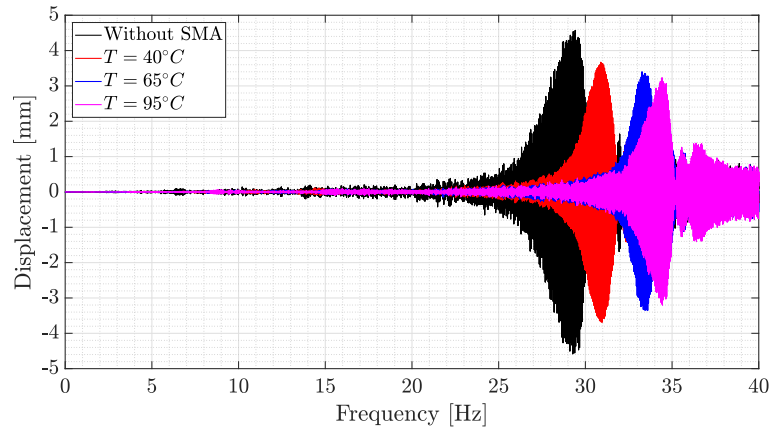


Figure 12. Horizontal displacement of the bearing to different temperatures.

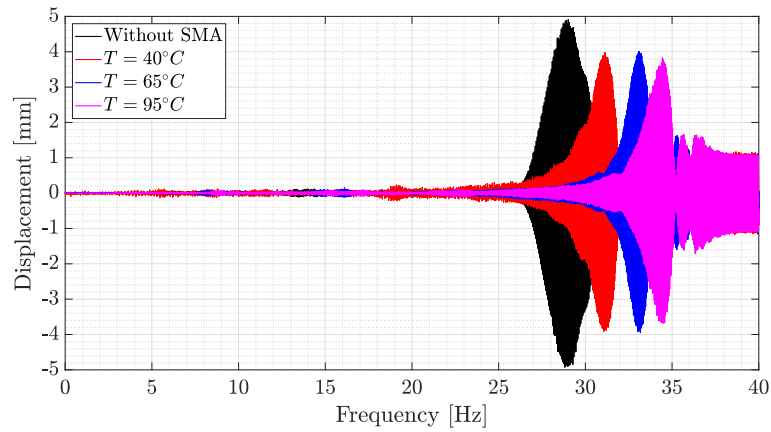


Figure 13. Horizontal displacement of the disc at different temperatures.

possible to identify the critical frequency of the vertical displacement in the bearing, as depicted in figure 14, since it exceeds this frequency.

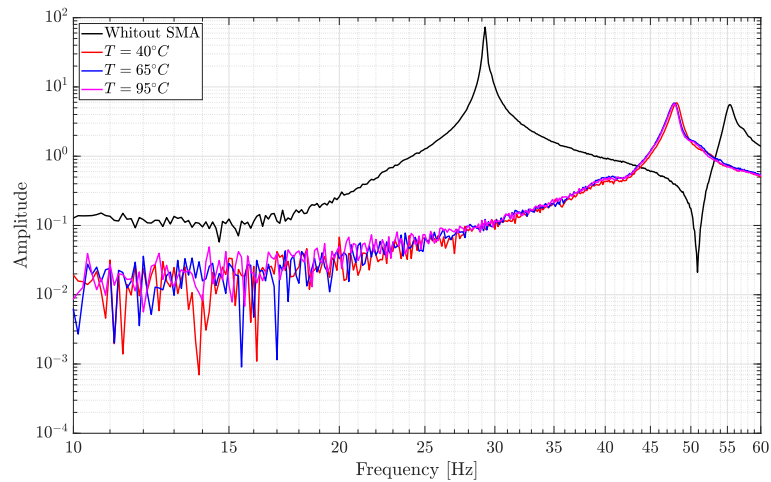


Figure 14. Bearing FRF for vertical displacements in the bearing.

The quantitative analysis of the effect of the SMA in the rotordynamic behavior is now in focus, being restricted to the disc and bearing horizontal displacements. Table 4 establishes a comparison of the displacements among the elastic configuration (without SMA) and the SMA configuration at different temperatures. It should be noted that significant reductions can be achieved, ranging from 20 to 30%. The amplitude reduction is due to two effects: stiffness change and hysteretic dissipation. Both behaviors establish a competition to define the rotordynamic behavior.

Table 4. Comparison of the displacement of the bearing and disc for different configurations and temperatures.

Condition	Amplitude Bearing horizontal [mm]	Variation [%]	Amplitude Disc horizontal [mm]	Variation [%]
Elastic, without SMA	4.61	—	5.00	—
SMA 40°C	3.66	20.6	3.99	20.2
SMA 65°C	3.36	27.1	3.94	21.2
SMA 95°C	3.21	30.4	3.81	23.8

The critical condition is another essential piece of information that can be quantified by phase transformations. The maximum displacement analysis allows one to estimate the critical frequency of the rotordynamic system. Table 5 shows the critical frequencies evaluated in the time domain using the speed ramp test. The maximum amplitude of the disc and bearing is considered to be corresponding to the critical frequency. Since martensitic and austenitic properties are different, stiffness tends to change with high temperatures.

The greatest effect occurs at the highest temperature, particularly when the material undergoes pseudoelastic behavior. The influence is smaller at low temperatures since martensite reorientation is the preponderant behavior and, therefore, there is not a stiffness change.

Table 5. The analysis of the critical frequency in the bearing and disc.

Condition	Frequency Bearing horizontal [Hz]	Variation [%]	Frequency Disc horizontal [Hz]	Variation [%]
Elastic, without SMA	29.5	—	29.3	—
SMA 40°C	31.1	5.4	30.9	5.5
SMA 65°C	33.1	12.2	33.3	13.7
SMA 95°C	34.1	15.6	34.1	16.4

Figure 15 shows the relationship between SMA force and bearing displacement through the orbital of the critical frequency. The energy dissipation can be estimated through the area of the curves. In this regard, table 6 presents the estimated average area of each orbital. The temperature increase is responsible for reducing the estimated area since there is a change on the hysteretic behavior. The 95°C temperature has the

smallest estimated average area, indicating the lowest energy dissipation. Since the cases related to 40°C and 65°C do not involve complete phase transformations, the stiffness change is reduced under these conditions. On the other hand, the pseudoelastic case at 95°C promotes austenite-martensite phase transformations, which change the stiffness during the process. Therefore, both stiffness change and dissipation are present, which justifies the interesting results previously presented. This points to the importance of the competition between dissipation and stiffness change for the determination of the dynamical response.

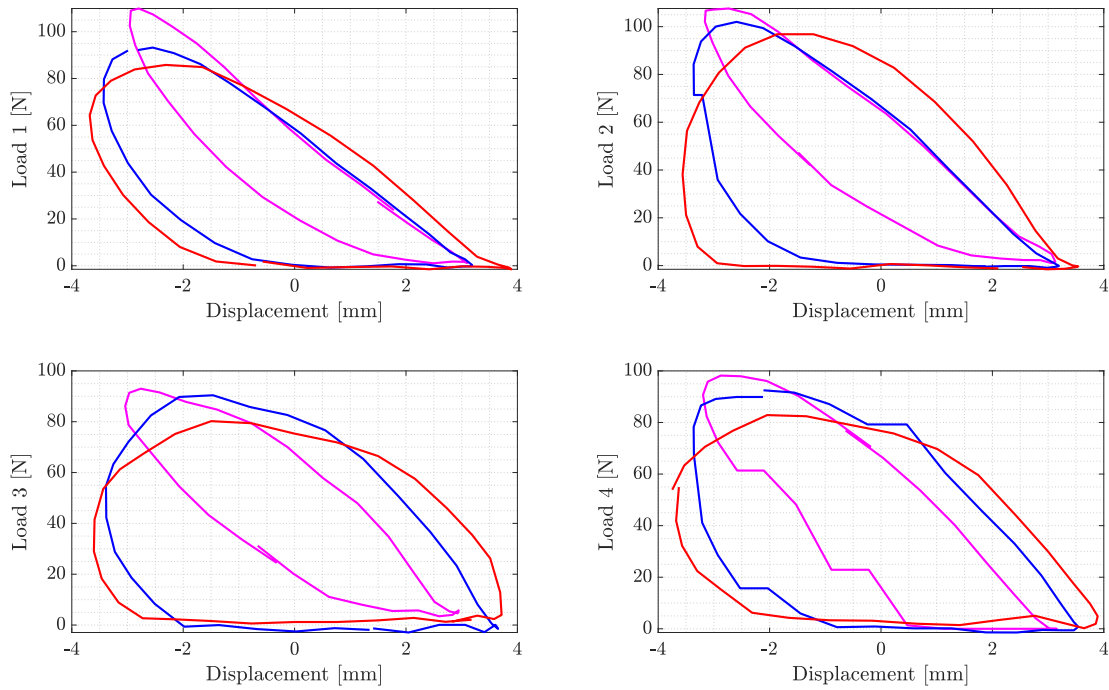


Figure 15. Relationship between force and bearing displacement at the critical frequency for temperatures of 40°C (-), 65°C (-) and 95°C (-).

Table 6. The analysis of the orbital area.

Load cell	Estimated area 40°C (N mm)	Estimated area 65°C (N mm)	Estimated area 95°C (N mm)
1	366	304	170
2	452	351	202
3	449	443	199
4	433	414	232
Average	425	378	201

5. Conclusions

This work proposes a novel experimental configuration of an SMA flexible rotor system, taking advantage of the SMA properties to perform semi-active vibration control. Phase transformations induced by stress and temperature can reduce vibration amplitudes and also shift resonant conditions. Both stiffness variation and hysteretic dissipation are important for this interesting behavior. The heating of the SMA elements is efficient for the phase transformation, resulting in a variation of the critical frequency and a reduction of the amplitude of the bearing and disc horizontal direction. Results show that compared with the elastic configuration, without SMA, there is a reduction between 20 and 30% of the displacements for the analyzed cases.

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