Dynamical behaviour of a shape memory alloy torsional pendulum

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Summary. The non-linear dynamical behaviour of a shape-memory alloy (SMA) device is investigated experimentally. The experiment consists in a torsional pendulum involving a pseudo-elastic wire made of nickel-titanium (NiTi). The wire is forced at its upper end by a servomotor. An inertial load is attached at the bottom end of the pendulum in order to tune the first eigenfrequency of the wire in a frequency range of interest for dynamical measurements. The set-up allows measurements of the quasistatic behaviour of the SMA wire by fixing the end mass, as well as dynamical response by freeing the inertial load. Frequency-response curves are systematically measured for varying excitation amplitudes, in the vicinity of the first eigenfrequency. As expected by the decreasing stiffness of the SMA under martensite forward transformation, a softening behaviour is clearly evidenced by the experiment.

Introduction

The dynamical behaviour of shape-memory alloys (SMA) has received great attention in the last years for their potential use for mitigating undesirable vibrations. As a large amount of energy can be dissipated due to the hysteretic pseudo-elastic martensitic transformation, these alloys are natural candidates for designing innovative efficient passive vibration isolation devices.

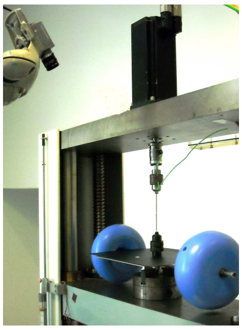
The pseudo-elastic effect is characterized by a decreasing stiffness of the material due to the forward transformation from the austenite to the martensite phase of the alloy. When the transformation is completed, the effective stiffness increases to the value of the martensite phase. This non-linear behaviour is awaited to result in a classical softening behaviour for a SMA device excited harmonically in the vicinity of its eigenfrequency. Although this behaviour has been clearly evidenced by numerical models, see *e.g.* [1, 2], experimental measurements still remain seldom seen. To the authors' knowledge, the most convincing experimental measurements of non-linear frequency-response curves of harmonically forced SMA have been reported by Li and Feng [3] on a tensile vibration bar, and by Collet *et al.* [4] on a cantilever beam. But in both cases, only a shift in the resonance frequency was observed, without the jump effect of non-linear oscillators that was certainly hidden by the increasing damping of the material.

In this paper, a torsional pendulum consisting of a NiTi wire with an end-mass, is used to investigate experimentally the dynamical behaviour of a single degree of freedom (DOF) shape memory oscillator. This set-up allows both measurements of quasi-static and dynamic responses. The frequency-response curves exhibit a clear softening-type behaviour with jump phenomena.

Experiments

A photograph of the experimental setup and its schematic view are given in Fig.1. The above part of the setup consists in a servomotor which angle position is imposed by its tension input. The SMA wire under study is fixed between two grips. The upper one joins the wire to the motor transmission shaft rigidly, while the bottom one joins the wire to the inertial mass rigidly. A torque sensor is inserted between the upper grip and the motor transmission shaft.

The test specimens are 2 mm diameter polycrystalline NiTi wire with a chemical composition of 56.1% Ni, obtained from AMF-France. The material has the following experimentally determined temperatures: A_f=24 °C, A_s=9 °C, M_f=13 °C and M_s=23 °C. Two samples of 150 mm length, with a 85 mm test length, were tested. The weight of the sample is 3.10g and the density of the material is $\rho \approx 6600\, kg/m^3$.



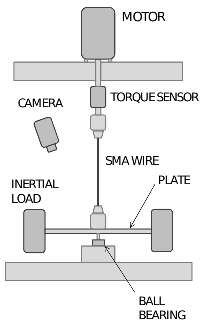


Figure 1: Photograph of the experimental setup (left) and schematic view showing the main components (right).

Quasi-static experiments

Quasi-static measurements are performed by fixing the bottom end mass. A rotation angle path is then imposed at the above end of the wire. Position angle of the above end and torque are recorded. Examples of such measurements are given in Fig. 2, where the nonlinear torque-angle relation is plotted for two different wires, and three different amplitudes of rotation. For the two tested wires, the martensitic transformation sets in for forcing angles above 100 degrees. The characteristic loop of the pseudoelastic behaviour is clearly recovered. The torque-angle relationship is clearly symmetric for positive and negative angles, as expected from the symmetric torsional behaviour of the wire. This is markedly different from what is observed in tensile tests. Another peculiar feature of torsion is that the martensitic transformation should occur from the outer ring of the wire and grow continuously to the center. Consequently, the elastic rigidity of the martensitic phase should be reached asymptotically at high angles, what is observed for the two specimens.

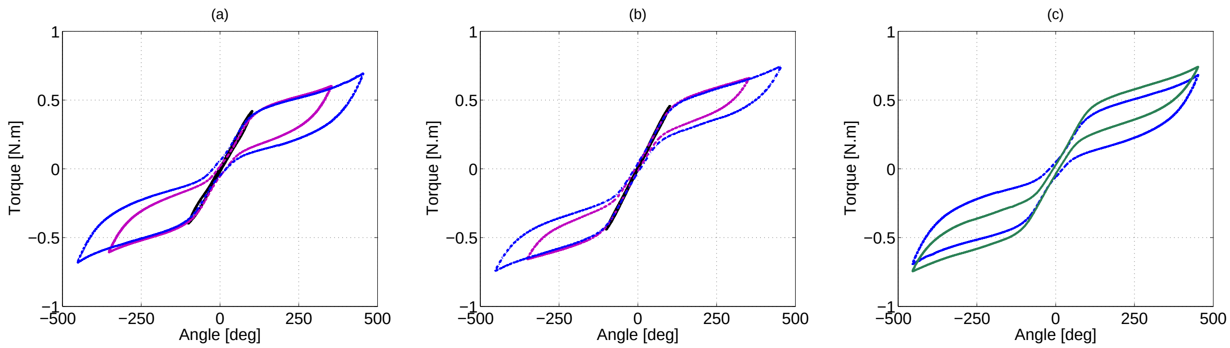


Figure 2: Quasi-static measurements at 0.01 Hz. Torque as function of the rotation angle, for three different imposed angle amplitudes (100, black, 350, purple and 450 degrees, blue). (a) specimen 1 ; (b) specimen 2; (c) comparison of the two specimens 1(blue) and 2(green) at 450 degrees.

The measurements reported in Fig. 2 have been realized for a frequency of 0.01 Hz. The effect of the speed in quasi-static tests is known as increasing the slope of the two plateaus where forward and reverse transformation occurs. This has been measured for excitation frequencies in the range from 10^{-4} to 10^{-2} Hz. However, for the frequency range of interest for the dynamical responses (0.01 to 1 Hz), quasi-static measurements do not show significant modification of the loop shape: they all collapse on those shown in Fig. 2.
Finally, Fig. 2c shows that there is an important variability of the characteristics of the wires under tests. As experiments have been conducted at room temperature, very slightly above the measured temperature $T = M_s$, slight differences between the specimen can induce large differences in the measured behavior.

Dynamic experiments

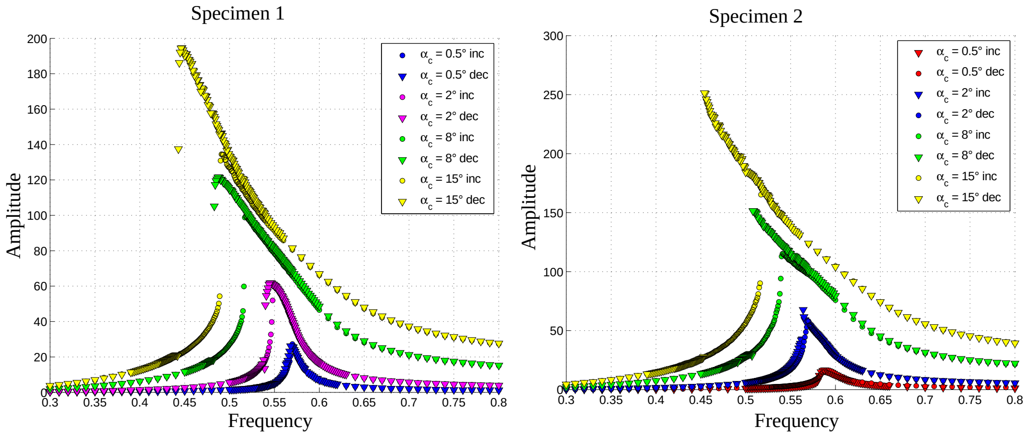


Figure 3: Frequency response curves of the two specimen. Inc. and Dec. refer to increasing and decreasing frequencies respectively.

In order to perform dynamic measurements, the inertial load is freed. A small ball bearing is fixed below the inertial mass and fixed within a heavy head lathe. Using the ball bearing allows canceling transversal vibration modes due to small imperfections of the system. A black plate is inserted between the bottom grip and the mass. A white point and a grid are drawn over the plane. A digital camera, with an appropriate image processing, allows recording the point position during the tests, from which the angular rotation of the bottom end of the wire is deduced. The heavy load have been selected so that the eigenfrequency of the first torsional mode is at 0.58 Hz. Frequency response curves are obtained from increasing and decreasing stepped sine measurements in the range [0.3, 0.8] Hz, and for an imposed angle α_c at the top end ranging from 0.5 to 15 degrees. The resulting curves are displayed in Fig.3.
The softening type non-linear behaviour is clearly evidenced by the experiment. The resonance frequency begin to shift to smaller values, then, from α_c= 8°, jump phenomena are measured for the two tested wires. As compared to specimen1, wire 2 shows a response of larger amplitudes for the same imposed rotation angles. This is the consequence of the area of the hysteresis loops measured in the quasi-static tests, which were larger for specimen 1, resulting in a larger dissipation of energy.

References

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