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Nonlinear dynamics and chaos in shape memory alloy systems

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ABSTRACT

Smart material systems and structures have remarkable properties responsible for their application in different fields of human knowledge. Shape memory alloys, piezoelectric ceramics, magnetorheological fluids, and magnetostritive materials constitute the most important materials that belong to the smart materials category. Shape memory alloys (SMAs) are metallic alloys usually employed when large forces and displacements are required. Applications in aerospace structures, rotordynamics and several bioengineering devices are investigated nowadays. In terms of applied dynamics, SMAs are being used in order to exploit adaptive dissipation associated with hysteresis loop and the mechanical property changes due to phase transformations. This paper presents a general overview of nonlinear dynamics and chaos of smart material systems built with SMAs. Oscillators, vibration absorbers, impact systems and structural systems are of concern. Results show several possibilities where SMAs can be employed for dynamical applications.

1. Introduction

Nature should be the essential inspiration for researchers and engineers that try to develop systems and structures. The main inspirational point is certainly the adaptive behavior that provides the self-regulation ability. Through the history, human technology is always related to different materials and it is possible to recognize ages defined by some material invention: stone and metal, for instance. Recently, smart materials should be identified as the stimulus of a new age. Basically, smart materials have a coupling between mechanical and non-mechanical fields that confers the material a special kind of behavior. In this regard, it is possible to imagine numerous applications due to the coupling of fields that usually are not connected. The smart material age tries to exploit the idea to construct systems and structures with adaptive behavior that have the ability to change properties due to environmental changes and repairing themselves when necessary.

Among many possibilities, smart materials can be classified according to the different field couplings. Nowadays, the most used materials are the shape memory alloys, the piezoelectric materials, the magnetostrictive materials and the electro- and magneto-rheological fluids. These materials have the ability of changing their shape, stiffness, among other properties, through the imposition of temperature or stress, electrical or electromagnetic fields. Smart materials are usually employed as sensors and actuators in smart structures. The choice of proper material for each application depends on many factors and two design drivers need to be highlighted [32]: the actuation energy density; and the actuation frequency.

Shape memory alloys (SMAs) present a mechanical-temperature coupling in such a way that they have the ability to recover a shape previously defined, when subjected to an appropriate thermomechanical loading process. SMA application is usually associated with high force–displacement and low frequency. The remarkable properties of SMAs are related to phase transformations responsible for different thermomechanical behaviors of these alloys. Basically, two different phases are possible in SMAs: austenite and martensite. Austenitic phase is stable at high temperatures and stress-free state presenting a single variant. On the other hand, martensitic phase is stable at low temperature in a stress-free state, being related to numerous variants. Phase transformation may be induced either by stress or by temperature. SMA thermomechanical behavior is very complex being represented by different phenomena. Pseudoelasticity, shape memory effect, two-way shape memory effect, transformation induced plasticity are some examples of important aspects of the thermomechanical behavior of SMAs.

The macroscopic behavior of SMAs can be expressed by stress–strain curves, Fig. 1. Pseudoelasticity happens at high temperatures, where the austenitic phase is stable for a stress-free state. Fig. 1a shows a typical stress–strain curve of the pseudoelastic behavior. A mechanical loading causes an elastic response until a critical stress value is reached, point *A*, when the martensitic transformation (austenite → detwinned martensite) arises, finishing at point *B*. For higher stress values, SMA presents a linear elastic response. During unloading process, the sample presents an elastic recovery ($B \rightarrow C$). From point *C* to *D* one can note the reverse martensitic transformation (detwinned martensite → austenite).

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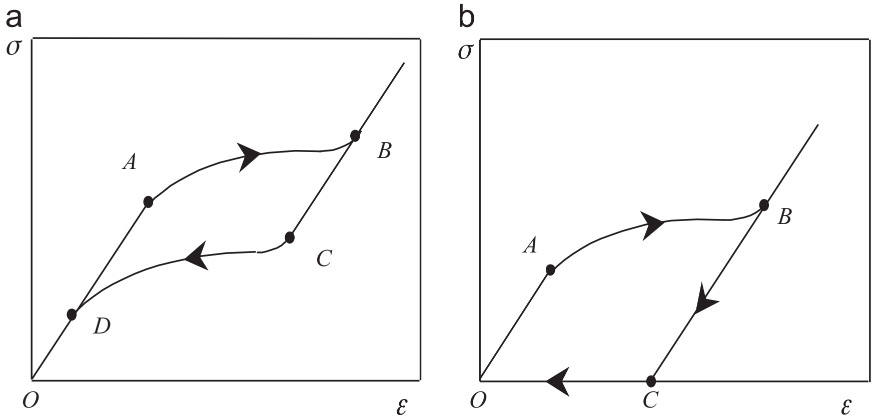

Fig. 1. SMA macroscopic behavior represented by stress–strain curves: (a) pseudoelasticity and (b) shape memory effect.

Afterward, the sample presents an elastic discharge. When the loading–unloading process is finished, SMA has no residual strain, however, there is an energy dissipation represented by the hysteresis loop.

The position of this hysteresis loop is temperature dependent and, since the temperature goes down, the hysteresis loop moves down as well. For low temperature behavior, the hysteresis position can be such that there is a residual strain after the loading–unloading process. Fig. 1b shows the stress–strain curve related to the shape memory effect. Basically, the martensitic phase is the only stable phase under this condition. When the sample is subjected to a mechanical loading, the stress reaches a critical value, point *A*, beginning the reorientation from the twinned into the detwinned martensite, ending at point *B*. During the unloading process, the SMA sample presents a linear elastic response, resulting in a residual strain (Point *C*). This residual strain can be recovered through a sample's heating, which induces the martensite–austenite phase transformation.

The description of SMA thermomechanical behavior is the objective of several research efforts. The constitutive modeling is related to phenomenological features to take into account the changes in the microstructure due to phase transformation [46,45]. Paiva and Savi [45] and Lagoudas [32] presented a general overview of the SMA modeling, with the emphasis on the phenomenological constitutive models.

The remarkable properties of SMAs are attracting technological interest in several fields of sciences and engineering. Machado and Savi [35] presented an overview of the most relevant SMA applications within biomedical field. The success of SMA biomedical applications is due to the non-invasive characteristic of SMA devices and also due to their excellent biocompatibility. SMAs are usually employed in surgical instruments, cardio-vascular, orthopedic and orthodontic devices, among other applications. Self-expansive structures constitute one of the main applications of SMAs, as the Simon filters and stents.

Besides biomedical applications, SMAs have been investigated to applications in engineering fields. Paiva and Savi [45] and Lagoudas [32] discussed some of the most important engineering applications. Self-expanded structures are employed to promote deployments and to establish connections. Another interesting application is related to multi-actuated flexible structures that can be applied in hydrofoils or wings. Robotic applications are also exploiting SMA characteristics, trying to mimic the continuous movement of muscles that is important for the construction of members as hands, arms and legs. Besides, automotive applications are also considering the use of SMAs for different purposes [17].

Dynamical systems with SMA elements constitute another important field of potential application being associated with both the adaptive dissipation of energy related to their hysteretic behavior and large changes in their mechanical properties caused by phase transformations. These aspects can be exploited both in the adaptive–passive and the active control, and a limiting factor is the slow rate of response. SMA is also being used in impact systems where it is expected that the high dissipation capacity due to hysteresis loop results in less complex behaviors. This can dramatically changes the system response when compared to those obtained with an equivalent linear elastic impact [48,62,61].

The dynamical response of SMA systems has complex dynamical responses including chaos and hyperchaos. The investigation of SMA oscillators is treated in different studies showing the general complexity of the nonlinear dynamics of SMA systems [49,50,36,37,38,30,31,10,11,12,9,54]. Aguiar et al. [3] presented an experimental investigation of SMA oscillators showing some of these complex behaviors. Doaré et al. [23] discussed torsional behavior of SMA systems. Besides, it is important to mention some efforts related to the characterization of chaos using either Lyapunov exponents [38] or 0–1 test [34].

SMA structures have been investigated by different approaches. The finite element method is an important tool to this aim. Concerning dynamical applications, Gholampour et al. [25] discussed some aspects of smart structures with SMA members. Collet et al. [16] analyzed the dynamical response of SMA beams, as well as Auricchio and Sacco [5]. De Paula et al. [19] treated an SMA grid employed for aerospace applications. Savi and Nogueira [57] and Savi et al. [51] discussed two-bar trusses with SMA elements.

Hybrid composites with SMA actuators are another application for shape and buckling control and also to change natural frequencies. Hajianmaleki and Qatu [26] presented a general review about vibration of composite beams, including the ones with SMA members. Nonlinear dynamic response of sandwich beams with SMAs is treated in Khalili et al. [29] using the finite element method. Shariyat et al. [58] presented the nonlinear dynamics analysis of rectangular composite plates with SMA wires.

The use of SMAs for control purposes is vast. The tuned vibration absorber (TVA) is a passive vibration control device for achieving reduction in the vibration of a primary system subject to external excitation. The TVA consists of a secondary oscillatory system that once attached to the primary system is capable of absorbing vibration energy from the primary system. An alternative for systems where the forcing frequency varies or has a kind of uncertainty is the concept of an adaptive tuned vibration absorber. This device is similar to a TVA but with adaptive elements that can be used to change the tuned condition [1,63,27,14]. Savi et al. [56] discussed the use of SMAs in tuned vibration absorber and Williams et al. [65] investigated a