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Research paper

Uncertainty analysis of an actuator for a shape memory alloy micro-pump with uncertain parameters

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ABSTRACT

In this paper, we propose a method for taking into account uncertainties of a micro-pump system using Shape Memory Alloy (SMA), based on the perturbation method. The proposed method is used to determine the thermo-mechanical response of a system. Comparisons with the mean value reference solution, illustrate the efficiency of the proposed method. The results are discussed in order to investigate the influence of the most influential parameters of the thermomechanical SMA model. The simulation results are obtained by the proposed method for static analysis with uncertainties.The perturbation method results are compared with the mean value reference solution. The results are discussed in order to investigate the influence of the Young's modulus E, the two transformations strain magnitude ε_{trac}^{T} and ε_{trac}^{TFA}, the martensite start M_s and austenite finish A_f temperatures and the stress reorientation F_ε on the static response of a micro-pump system.

1. Introduction

Micromachining technology is a miniaturization technique that can be used to manufacture various devices and systems. This technique opened up new avenues and allowed the development of various devices and small systems with high functionality, precision and performance in various fields such as automotive, aerospace, communication, medical, engineering civil. Several parametric studies have shown the high sensitivity of the behavior of these systems. However, these parameters admit strong dispersions [1–5]. Indeed, some microsystems require an effective actuator that could be suitable for very sensitive applications. Intelligent materials such as piezoelectric ceramics or shape memory alloys (SMAs) have often been taken into account for the design of micro-components and / or micro-devices [6–8]. Indeed, their coupled and multiphysical behaviors allow the conversion of electrical or thermal energy on mechanical energy for actuator applications and vice versa for sensor applications. The development of thin film production processes for these intelligent materials combined with the use of etching techniques has enabled the design of micro-components and micro-devices with complex geometry (micro-actuators, micro-valves, micro-sensors, stents, etc.) based on these thin films [9–11].

SMA actuators are among the most used micro-devices to realize such applications. Indeed, SMAs can have high forces or large deformations, which could be converted into high pressures or large strokes (deflection). For this reason, SMA actuators have been taken into account for micro-pump actuations [12–15] where the stroke of the actuator determines the volume pumped per cycle. The actuator converts input electrical or thermal energy into a mechanical movement inducing a work output. They were taken in thin SMA layers (usually NiTi) and they consider the shape memory effect property. During heating, the actuator exhibits a displacement induced by the inverse martensitic transformation. This displacement is recovered during the cooling process leading to the martensitic transformation towards the front. This cooling process is usually very weak (a fan can provide compressive convection for rapid cooling [16]). For this reason, an actuator composed of two NiTi SMA membranes engraved in a thin film and separated by a silicon spacer has been proposed [17,18]. These two membranes operate in an antagonistic manner and the actuation is always obtained by heating. The heating of a diaphragm gives an actuating displacement in one way (fluid inlet) where the heating of the other diaphragm allows the opposite actuation displacement (fluid outlet). During the heating of any membrane, the other is freely cooled. Thanks to the spacer inserted between the membranes, the direct and inverse transformations occur under the bending stress. This induces the activation and disappearance of oriented martensite variants leading to a significant transformation strain.

The current simulation is deterministic and does not integrate the uncertainties and the dispersion on the input variables and their

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consequences on the output variables [12,32]. They consider these variables to be constant. However in reality, this is not the case. To be closer to the actual effect of these parameters, they will be introduced to the model as uncertain parameters.

Several methods for taking uncertainties into account are proposed in the literature. Monte Carlo simulation (MC) is a well-known technique in this field [19]. It can give the full probability density function of any system variable, but it is often too expensive because a large number of samples is required for reasonable accuracy. Parallel simulation [20] and orthogonal decomposition [21] are some of the solutions proposed to circumvent the computational difficulties of the MC method.

The expansion of polynomial chaos (PCE) is presented in literatures as a more effective probabilistic tool for the propagation of uncertainty. It was introduced by Wiener [33] and started by Ghanem and Spanos who used orthogonal Hermite polynomials to model stochastic processes with random Gaussian variables [22].

Polynomial chaos (PC) provides a mathematical framework for separating stochastic components from a system response of deterministic responses. It is used to calculate the deterministic components called stochastic modes in an intrusive and non-intrusive way while the random components are concentrated in the polynomial base used. The method of polynomial chaos (PC) has been much more efficient than Monte Carlo in the simulation of systems with a small number of uncertain parameters [23,35].

Disturbance methods are very widely used in the field of stochastic finite elements. They are based on a development in the Taylor series of the frequency response function (FRF) (eigenfrequencies or time response) in relation to basic random physical variables, mechanical properties, geometric characteristics or applied loads. Disturbance methods calculate the mean and standard deviation of F.R.F. of a mechanical structure that has uncertain variables. This method is used in many fields to solve linear and non-linear problems, be they static or dynamic modes [24]. The computation of the first two statistical moments by Taylor's development of the frequency response is shown in [25]. Unlike the system response, the modal parameters (frequencies and eigenmodes) vary slowly depending on the properties of the system. The disruption of approaches to these values has been developed [26]. In [27], a nifty first-order perturbation method has been developed.

According to M. Shinozuka, the perturbation methods of two orders need more computing that variability study by Monte Carlo method [28]. Indeed, the calculation of derivatives of order two of the response function compared to basic random variables is particularly heavy to realize. Furthermore, the second order terms affect only the mean values of the response and are negligible compared with the terms of a zero-order and first order [29,30].

In this study, the uncertain analysis of the thermomechanical response of a micro-pump system with an SMA actuator is carried out utilizing the perturbation method combined with the finite element method. The results are discussed in order to investigate the influence of the Young's modulus E, the two transformations strain magnitude ε_{trac}^{T} and ε_{trac}^{TFA}, the martensite start $M_s$and austenite finish A_f temperatures and the stress reorientation F_ε of variants on the static response of this system. The description of the studied micro-pump with SMA actuator is presented in Section 2. In the next section, the SMA thermomechanical behavior model is presented. In Section 4, the theoretical basis of the perturbation method is presented. Numerical results are presented in Section 5. Finally in Section 6, to conclude, some comments are made based on the study carried out in this paper.

2. Description of the studied micro-pump with SMA actuator

The design adopted by the micro-pump actuator was originally proposed by Benard et al. [17,18], and its thermomechanical response was analyzed by the finite element method in [12]. He considers two NiTi membranes in the martensitic state with martensite variants that are self-adaptable at room temperature, as shown in Fig. 1a. They have an initial flat shape and are glued together with a crown in the outer contour, and with an intermediate spacer made of silicon material. This

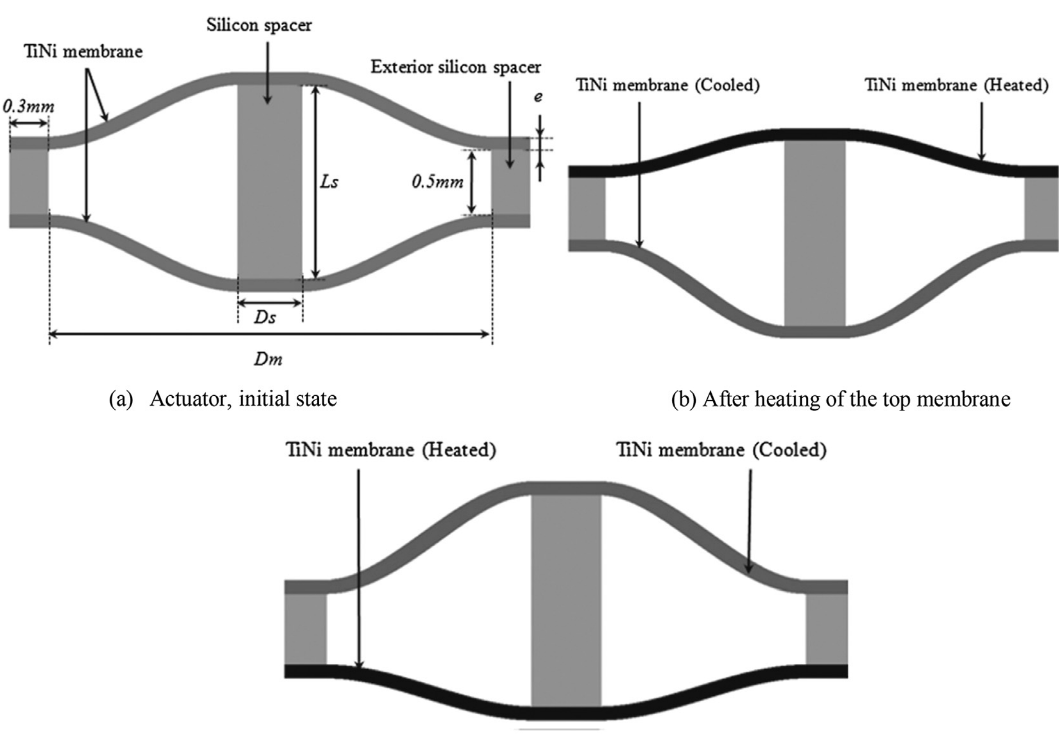

Fig. 1. Sketch of the NiTi actuator cross-section. Heating or cooling membrane causes the motion along the horizontal direction, e is the membrane thickness, Dm is the membrane diameter, Ds is the spacer diameter, Ls is the spacer length [24].