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Research paper

A two-way shape memory alloy-piezoelectric bimorph for thermal energy harvesting

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ABSTRACT

We present an analytical model to analyze the bending of a bimorph beam comprising of piezoelectric material (PM) and shape memory alloy (SMA) thin layers. The model starts from the governing equations of the bending beam based on the Euler-Bernoulli beam theory. The PM and SMA layers are supposed to be perfectly bonded. The linear constitutive equations of PMs are used. Using this approach, we investigate thermal energy conversion into electricity by mean of the SMA-PM bimorph. Particularly, the model takes into account cyclic thermal energy harvesting by coupling the direct piezoelectric effect and the two-way shape memory effect. In this case, the SMA is assumed to be trained prior to assembling the bimorph so that it can deform in a cyclic way upon cyclic thermal loading without applying any external stress. The thermal-to-electrical conversion is achieved from the induced strain within the SMA layer upon heating which induces stress into the PM layer so that it produces an electrical potential.

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1. Introduction

Currently, low power devices such as micro-sensors and MEMS are mostly supplied with energy by mean of batteries. However, batteries present many drawbacks since they are cumbersome, need to be charged and have short lifespan, not to mention the environmental pollution. For instance, a chirurgical procedure is necessary to change the peacemaker battery. To counter these issues, we witness increasing efforts to come up with alternative technologies for microsystems' energy supply. A promising idea is to take advantage of the abundant thermal energy around us and convert it into sufficient electrical power to supply a device. This is known as thermal energy harvesting (TEH). In the beginning of the 21st century, combining shape memory alloys (SMA) and piezoelectric materials (PM) became a good candidate for TEH by taking advantage of the SMAs and the PMs thermo-mechanical and electro-mechanical couplings. Under special conditions, an SMA can recover a large remanent strain while heated. This behavior is known as the shape memory effect (SME) and it is governed by a reversible martensitic phase transformation. At high temperatures, an SMA is in the austenite phase while at low temperatures it is in the martensite phase. The strain recovered within an SMA during the phase transformation can be used to induce stress within a PM so as to generate an electrical potential.

One of the pioneer works that combines SMAs and PMs was conducted by Lagoudas and Bo (1994). They held an analytical study using the classical composite plate theory of a laminated plate made of an SMA layer sandwiched between 2 PM layers. These layers are subjected to an electrical field and the mechanical response of the SMA is investigated. Later on, some studies of hybrids SMA-PM for thermal-to-electrical energy conversion emerged. (Garcia and Lobontiu, 2004) investigated the thermal actuating and sensing performance of a strain-induced multimorph using an analytical study based on Timoshenko's bimaterial thermostat (Timoshenko, 1925). The model is applied to an SMA-PM bimorph where both thermal expansion and the SMA's phase transformation are considered. Starting from the SMA in the martensitic state, Garcia and Lobontiu investigated the electrical response of the PM while the bimorph is heated. Namli and Taya (2011) first proposed a one-dimensional model of a laminated SMA-PM where all the displacement boundary conditions are clamped so that the SME induces stress in the PM upon heating. Then, they proposed a three-dimensional model based on the Eshelby theory for an SMA-PM system made of SMA inclusions inside a PM matrix. Both models enable to predict the produced power according to the material properties and thermal fluctuations. (Chang and Huang, 2010) conducted analytical studies on an SMA-PM device for TEH application using the pyroelectric effect. SMA and steel springs were used to pull the PM from a heating source to a cooling source and vice-versa. Recently, few experimental studies on different SMA-PM hybrids

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configurations were conducted for TEH purpose. (Lebedev et al., 2011) and (Zakharov et al., 2012) conceived a hybrid device composed of a pre-strained martensitic SMA ribbon glued to a macro fiber composite made of PM fibers and electrodes arranged within a polymer insulating matrix. They first investigated the electrical response with only direct piezoelectric effect then with combined direct piezoelectric and pyroelectric effects (Zakharov et al., 2013). Besides, Zakharov et al. (2012) and Avirovik et al. (2013) conducted experimental studies on a device composed of a pre-strained SMA wire in the martensitic phase attached to a PM cantilever. In all the mentioned studies carried out about SMA-PM systems for TEH applications, only one-way shape memory effect (OW-SME) is considered. In fact, the used SMA is pre-strained in the martensitic phase prior to heating so as to introduce a remanent strain, called the transformation strain, which is recovered upon heating. If we cool back the SMA in a free stress state, no macroscopic strain occurs after reverse transformation. This penalizes the use of the OW-SME for cyclic thermal actuation.

In order to use SMAs for cyclic thermal actuation by taking advantage of the SME, a first solution is to use a mechanical system that enables to generate the transformation strain within the martensitic phase prior to heating as a return spring for instance (Zakharov et al., 2012). A second solution is to "train" the SMA so that it changes its shape under a cyclic thermal loading in a free stress state. Training an SMA is a process that consists on applying a cyclic thermo-mechanical load to the material until its response stabilizes (Lagoudas and Hartl, 2008). The SMA is then called trained. During the training process, internal defects are introduced into the microstructure which generates internal permanent stresses that lead to the orientation of the crystal lattices. Therefore, while cooling a trained SMA in the austenitic phase under no applied stress, martensite is formed detwinned which leads to the material shape change. While heating back, the SMA transforms into austenite and recovers its initial shape. This behavior is known as the two-way shape memory effect (TW-SME).

In this paper we propose an analytical model that enables to study thermal-to-electrical energy conversion by mean of a bimorph made of a trained SMA and a PM thin layers. We chose particularly the TW-SME instead of the OW-SME for two main reasons. First, as the bimorph bends upon heating, the induced stress in the untrained SMA layer may not be high enough to induce a transformation strain in the martensite formed after cooling, in which case the bimorph will not recover its initial shape. Secondly, if we apply a cyclic thermal loading to an untrained SMA subjected to a stress, its shape is not completely recovered after each cycle due to the accumulation of small strains from a cycle to another (Lagoudas and Hartl, 2008), whereas these remanent small strains are not generated anymore within a trained SMA which makes it recover completely its initial shape after each cycle. In Section 2 of this paper, we write the equations describing the bending of the bimorph following (Garcia and Lobontiu, 2004) and (Timoshenko, 1925) works and we derive the expressions of the tip deflection of the bimorph and the electrical potential induced by the transformation strain. In Section 3, we present the equations describing the TW-SME behavior of a trained SMA and we take into account only partial phase transformation to consider small strains so that the induced displacements within the bimorph remain small enough to avoid nonlinear geometry effects, with which the study in Section 2 would not be valid. In the 4th section of this paper, we first present an example of a study where we investigate both the order of magnitude of the applied thermal loading and the thickness of the SMA layer to keep the displacements small and secondly, we investigate the bimorph's tip deflection and the induced electrical potential for a fixed SMA thickness and for a specific thermal load.

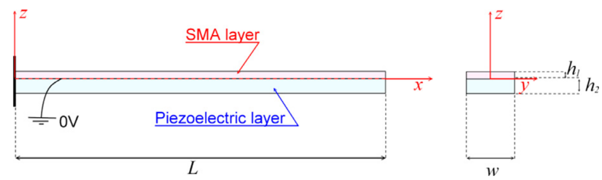

Fig. 1. Schematic view of the SMA-PM bimorph.

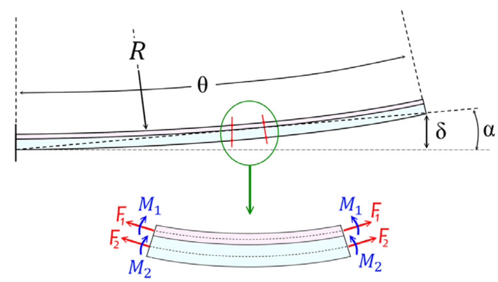

Fig. 2. Schematic view of the bended bimorph along with the applied forces and bending moments.

2. The SMA – PM bimorph model

The considered bimorph is made of an SMA layer and a PM layer with thicknesses h_1 and h_2 respectively (Fig. 1). Both layers have the same length L and the same width w. We assume that the bimorph's dimensions fulfill the following hypotheses:

- The layers are perfectly bonded and the length L is very long compared to the width w, to the overall thickness $h = h_1 + h_2$ and to the displacements of the bimorph's tip;
- The thickness h is very small compared to the width w.

These hypotheses enable to adopt the Euler Bernoulli assumptions for beams which are:

- The cross-sections of the bimorph remain plane and normal to the mean axis;
- The deflections of all the points in a cross-section are small and equal to the deflection of the mean axis of the bimorph;
- No lateral displacement occurs (according to y-direction).

These hypotheses enable to assume that both layers bend with the same radius of curvature R. Besides, we suppose that the SMA has been trained to exhibit SME according to the x-direction, and we assume that the SMA layer is thin enough to be uniformly heated and cooled. Furthermore, the thermal expansions of both materials are neglected in this study and the PM layer is assumed to be polarized according to the z-direction (Fig. 1).

When the bimorph is subjected to a thermal load, the SMA layer undergoes phase transformation that induces transformation strain ε^{tr} according to the x-direction, and since the SMA layer is bonded with the PM layer, the bimorph bends and consequently the PM deforms and generates electrical potential. If we consider a cut among the bimorph as depicted in Fig. 2, the SMA layer is subjected to an axial force F_1 and a bending moment M_1, and the PM layer is subjected to an axial force F_2 and a bending moment M_2. Let us note that the values of the forces and those of the bending moments can be either positive or negative depending if the SMA tends to stretch or shrink.

The SMA layer is subjected to three types of strains: the strain caused by the axial force $F_1/(E_1A_1)$, the bending strain $h_1/2R$ and the transformation strain ε^{tr}. On another hand, the PM layer is subjected to the strain caused by the axial force $F_2/(E_2A_2)$ and to the bending strain $h_2/2R$ where: $A_1 = h_1w$ is the section of the SMA

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