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Power density ratio optimization of bimorph piezocomposite energy harvesters using a Multidisciplinary Design Feasible method

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ABSTRACT

A design optimization involving mechanical and electrical considerations is proposed with the aim of improving the performance of bimorph piezocomposite energy harvesters for micro-electromechanical systems. Maximization of the power density ratio of the transducer was achieved using a Multidisciplinary Design Feasible method accounting for several design variables and subjected to operational and physical constraints. The present numerical approach shows that superior performance can be obtained via multidisciplinary design in comparison to designing the mechanical and electrical parts separately. A composite cantilever beam type of harvester formed by a brass shim covered by PZT-5A piezoelectric layers was considered. Predictions of tip displacement, voltage and power output were carried out using an analytical model of the harvester, based on Euler-Bernoulli theory and an energy approach. Finite element analysis of the harvester was also performed for the purpose of model verification and analysis of fidelity issues. The results of the implemented optimization procedure provided valuable design relations concerning the dependence of the aspect ratio of the transducer on the operating frequency, as well as regarding the optimal thickness ratio to be selected for the active and substrate layers.

1. Introduction

Owing to rapid advances in micro-electromechanical systems (MEMS), harvesting energy from environmental sources has received increased attention in recent years. The need to eliminate external power sources due to device miniaturisation has been the primary motivation behind the development of this type of energy scavengers. Vibration energy is commonly available in most environments and, contrary to other ambient (renewable) energy sources, such as solar and wind power, it does not rely on favorable atmospheric conditions. Hence, many studies on how to harness its potential efficiently have been performed. Although several transduction mechanisms have been proposed for that purpose, namely electrostatic [1] and electromagnetic [2,3], piezoelectric energy harvesters (PEH) have drawn most of the attention in the field. This is mainly a consequence of the versatility of piezoelectric transducers, which are able of converting mechanical vibrations into electricity for long and uninterrupted periods of time [4]. Moreover, when compared to other transducers, PEH generally exhibit a simpler configuration, higher conversion efficiency, as well as a larger compatibility with micro-fabrication techniques [5,6].

Although the piezoelectric materials used in PEH have the capability of converting mechanical energy into electrical energy and vice versa, the present study is focused on the former capacity only. To that aim, PEH are often incorporated into structures so that available mechanical vibrations may be converted into a usable form of energy [7]. As a consequence, significant efforts have been put into the optimal design of PEH for maximum efficiency. Piezoelectric composite elements have been proposed in several shapes, sizes and materials with the goal of maximizing the power output of the transducer. Historically, the cantilever beam configuration has been the preferred choice since it is a relatively compliant structure, in addition to its compatibility with MEMS manufacturing processes. Furthermore, its low structural stiffness can allow for large strains, thus providing greater power generation [8–10]. Despite the fact that a trapezoidal-shaped cantilever beam can deliver extra energy [11,12], the rectangular-shaped geometry has been used in the majority of MEMS-based harvesters. This simpler geometry is easier to implement, and it has shown to be successful in harvesting energy from ambient vibrations, generating suitable amounts of power [5,13]. Nevertheless, the piezoelectric thickness, substrate thickness, residual

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stress, side-length and electrode coverage are known to affect the electromechanical coupling coefficient, and consequently, these characteristics have a relevant effect on the power output of the transducer also [14,15]. Hence, the ratio of the piezoelectric layer thickness to the total thickness of beam has been considered as a fundamental design variable when purporting to maximize the power output of PEH [16]. In an earlier study, the cantilever beam's length, width and thickness have been optimized using a Modified Particle Swarm Optimization algorithm [17]. Moreover, Topology Optimization Methods have been successfully applied to either maximize power generation [18] and the electromechanical coupling coefficient [19,20].

Another important consideration required for improving the efficiency of PEH is that its natural frequency must conform to the dominant frequency of the ambient vibrations. Minor frequency mismatches generally yield dramatic reductions in power output [21]. Jiang et al. [22] have studied a bimorph cantilever beam device with an added mass. These authors have shown that, by reducing the bimorph thickness and increasing the attached mass, the harvester's resonance frequency decreases, thus allowing to maximize the harvested power. However, one should point out that although the resonance frequency of PEH may be adjusted (or tuned by the use of added mass), weight restrictions are imposed in many applications, such as those concerning micro aerial vehicles [23]. Besides the resonance frequency, the damping ratio also plays a significant role in the optimization of the power output of this type of PEH [24].

From the electrical point of view, the dynamic behavior of the electrical circuit coupled to the device, as well as impedance matching, are other important aspects determining the performance of PEH. Earlier studies have demonstrated the nontrivial role of the electric circuit in the optimization of the material distribution and electric power generation [18,25]. Additionally, the optimal resistor value has been the subject of several investigations also [26–29].

In a nutshell, and despite the multitude of interdisciplinary variables affecting the performance of PEH, published design optimization studies of composite beams are usually carried out by considering only very limited, and separate, design variables. Recently, a few researchers have obtained significant enhancements by using simultaneous design optimization rather than optimizing separately the host structure and the electrode profile of the piezoelectric material [30,31]. However, in simultaneous design optimization, the relevant disciplines are not coupled with each other, regardless of the physical significance of their interactions. In markedly contrast to this approach, with the use of Multidisciplinary Design Optimization (MDO), interdisciplinary coupling is not ignored in the problem.

Aiming at contributing to the improvement of the performance of PEH for MEMS-based applications, this paper proposes a multidisciplinary design methodology to optimize small piezocomposite transducers in which the piezoelectric layer is coupled to an external electrical resistor. By employing a monolithic technique, namely a Multidisciplinary Design Feasible (MDF) method, the electrical power output and the weight of the device are set as objective functions and several design variables and constraints are accounted for based on each intervening discipline. In Section 2, the electromechanical formulations for a piezocomposite cantilever beam operating as an energy harvester are given. In Section 3, the implemented MDO formulation, including the design variables, objective functions, constraint formulations and the coupling analysis, is described in detail. In Section 4, a reference configuration is simulated to illustrate the proposed modeling as well as for verification purposes. In Section 5, the optimization results are presented and discussed. Finally, the main findings of this investigation are summarized in Section 6.

2. Electromechanical formulations for a piezocomposite cantilever beam

In a bimorph harvester configuration two active layers of piezoceramics cover a substrate, which operates as a passive layer between the active ones. Electrodes are also installed on upper and lower surfaces of each piezoelectric layer, and those may be connected to each other in series or parallel, depending on the intended application. Fig. 1 shows a schematic of the piezocomposite cantilever beam with a series connection between the active layers. It must be noted that both the series and parallel wiring options produce the same peak power. However, the voltage output is doubled in a series connection (two piezoelectric elements poled in opposite directions), whereas the obtained current is doubled in a parallel connection (same polarization directions) [32]. The minute thickness of the electrodes will be neglected in the present analysis, thus the beam thickness h is assumed to be given by the sum of the thickness of the substrate layer and twice the thickness of the piezoelectric layers. In addition, an excitation consisting of a harmonic transverse base acceleration will be considered as input.

The coupled electromechanical behavior of the beam is governed by the linear-elastic constitutive relations connecting four field variables, namely the mechanical stress T, strain S, electric field E, and developed electric displacement D. In matrix form [33], the aforementioned quantities are related through the piezoelectric permittivity ε, the piezoelectric constant linking the strain and charge density e, and the stiffness matrix c^E, as follows:

$$\begin{aligned} \{T\} &= [c^E]\{S\} - [e]\{E\}, \\ \{D\} &= [e]^t\{S\} + [\varepsilon^S]\{E\}. \end{aligned} \tag{1}$$

In Eq. (1) the superscripts E and S denote parameters applied at constant electric field and constant strain, respectively, and the superscript t indicates the transpose.

2.1. Analytical model

An analytical model for the PEH may be obtained based on Euler-Bernoulli theory and an energy approach. The concept explored here is similar to that described by DuToit et al. [34] and Kim et al. [35], where Hamilton's Principle for deformable bodies has been applied to an electromechanical system. Considering two specified time instants t_1 and t_2, the variational problem determining the dynamics of this system can be written in a generalized form, where magnetic terms have been neglected and δ denotes the first variation of a function, as follows:

$$\int_{t1}^{t2} [\delta(T_k - U + W_e) + \delta W]dt = 0. \tag{2}$$

Individual energy terms in Eq. (2) are the kinetic energy T_k, the internal potential energy U, and the electrical energy W_e, as given by:

$$T_k = \frac{1}{2}\int_{V_s} \rho_s\{\dot{u}\}^t\{\dot{u}\}dV_s + \frac{1}{2}\int_{V_p} \rho_p\{\dot{u}\}^t\{\dot{u}\}dV_p, \tag{3}$$

$$U = \frac{1}{2}\int_{V_s} \{S\}^t\{T\}dV_s + \frac{1}{2}\int_{V_p} \{S\}^t\{T\}dV_p, \tag{4}$$

$$W_e = \frac{1}{2}\int_{V_p} \{E\}^t\{D\}dV_p, \tag{5}$$

where the integrals in Eqs. (3) and (4) involve contributions due to both the substrate layer (subscript s) and the piezoelectric layers (subscript p). However, only the latter contribute to the integral