Optimised piezoelectric energy scavengers for elder care

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Abstract

Low power wireless electronics requires portable and autonomous power sources. This motivates the interest in energy harvesting. Among the proposed solutions, vibration-based piezoelectric bimorphs are characterised by marked advantages. This work investigates the possibility to increase the specific power generation of piezoelectric scavengers by structurally optimising their shape. Analytical and FE simulations are performed allowing the proposed layouts to be compared. The advantages of optimised layouts are proven and discussed.

1 Introduction

The rapid development of low power wireless electronics opened up perspectives of pervasive wireless sensor networks to be used in a broad range of technical fields. Pervasive wireless networks require portable power sources to increase their autonomy, thus motivating the current interest in energy harvesting. Among the proposed solutions, vibration-based scavengers made of metallic cantilevers coated with piezoelectric material seem especially promising. Piezoelastic cantilevers vibrating at resonance frequencies provide good electromechanical coupling, a marked energy storage capacity and are suitable for miniaturisation [1-3].

A piezoelectric energy scavenger is practically a leaf spring. Piezoelectric materials are characterised by a linear electromechanical coupling between strain and voltage; as the stress-strain behaviour in the elastic domain is also linear, a condition of uniform stress can thus be regarded as a valid structural optimisation criterion. This

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principle, widely studied in the case of mechanical springs [4], has already been proposed for energy scavenging, but it was not further investigated. For elder care applications the scavenger has to comply also with the need to minimise the used volume, as well as with constrains on dynamic resonance conditions.

The aim of this work is the design of optimised cantilever piezoelectric energy scavengers which allow the highest specific power per unit volume to be harvested at their resonance frequency. The electromechanical performance of the considered structures is evaluated by means of analytical [3] and FEM coupled field analyses. The results show that in structurally optimised configurations the output power is significantly larger than that obtainable in a reference rectangular layout.

2 Optimised cantilever configurations

A rectangular cantilever piezoelectric scavenger (Fig. 1) is taken as reference. The cantilever is loaded at the free end with a proof mass. The bending of the cantilever induces loading on the upper and lower piezoelectric layers of thickness t_c, which are bounded to the metallic beam of thickness t_s. All the considered configurations are dimensioned so as to attain a constant 50 Hz resonance frequency, matching hence that of excitation sources often found in human surroundings.

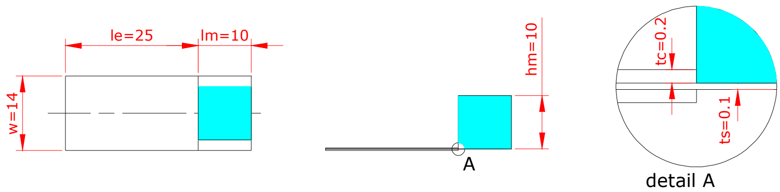
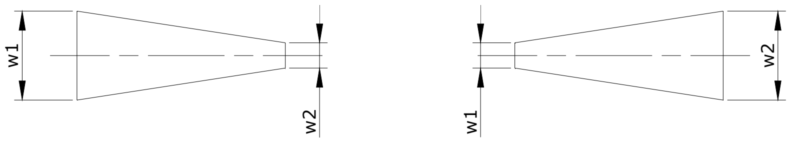


Figure 1: Reference rectangular piezoelectric energy scavenger.

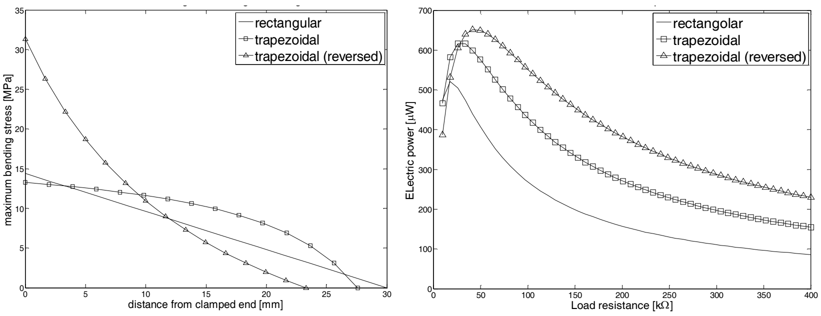
To attain the highest possible strain (and hence voltage) in the piezoelectric layer, optimised trapezoidal profiles characterised by uniform stress distribution along the entire length of the device are then considered. Two trapezoidal layouts, indicated respectively, based on the clamping condition, as 'trapezoidal' and 'reversed trapezoidal' are studied (Fig. 2). A first comparison with the reference structure is performed by imposing equal maximum widths; this is called "Design 1". On the other hand, "Design 2" is characterised by equal volumes of the piezoelectric layers for all the considered geometries. In this case the upper surface of the piezoelectric layer and its electric capacity are equal to those of the rectangular shape. However, since the piezoelectric layer behaves as a capacitive transducer, the distribution of electrical charge along the layer is also important. Both optimised designs of Fig. 2 maximise the portion of the cantilever loaded at maximal bending stresses and strains (Fig. 3a). With respect to the rectangular structure, the average stress is thus bigger by 53.3% for the reversed trapezoidal configuration in the case of Design 1, and by 6.6% for the trapezoidal configuration in the case of Design 2.



(a) trapezoidal (b) reversed trapezoidal

Figure 2: Optimised trapezoidal profiles with equal maximum widths.

The coupled electromechanical performance of the proposed configurations in resonance conditions is analytically evaluated according to the model proposed in [3]. The generated electrical power for a given resistive load is compared in Fig. 3b. The proposed optimised configurations result in an electric power higher than that of the rectangular scavenger (Table 1). Performance is better in the case of Design 1, since the smaller volume assures larger electrical power densities.



(a) (b)

Figure 3: Comparison between the reference rectangular scavenger and optimised trapezoidal profiles with equal maximum widths. Maximum bending stress along beam length (a) and electric power generated via a resistive load (b).

3 Finite element analyses

Numerical FE analyses were performed to investigate in detail the stress and voltage distributions. Modal analyses were carried out to check the reliability of the lumped-parameters analytical model in predicting the natural frequency of all the considered configurations [5]. Very small deviations (< 4%) confirmed the assumptions included in the analytical model. This was further confirmed by preliminary experimental tests performed on a rectangular scavenger excited via a shaker that allowed power levels of few hundred μW across tens of kΩ of load to be achieved.

Table 1: Performance parameters of the reference rectangular (R) and of optimised trapezoidal (T) and reversed trapezoidal (RT) energy scavenger geometries.

		Design 1		Design 2	
	R	T	RT	T	RT
Maximum electric power [μW]	520.7	618.8 (+18.8%)	649.4 (+25.1%)	575.6 (+10.5%)	601.5 (+15.5%)
Average voltage [V]	20.49	28.10 (+37.2%)	24.97 (+21.9%)	22.47 (+9.7%)	15.25 (-25.6%)

The voltage distribution is computed by performing a harmonic dynamic analysis that, for an imposed excitation of the clamped end, allows the displacement of the cantilever free end to be calculated at resonance frequency. The obtained displacement is used as input to the static coupled-field analysis, resulting in the bending stress, strain and voltage distributions on the piezoelectric layer. A good correspondence between voltage and bending stress distributions along the beam length with that calculated analytically was found (Fig. 4). Computed average values of the voltage obtained in the piezoelectric layers (Table 1) confirm the better performance of Design 1. In the case of the reversed trapezoidal layout of Design 2, the local stress concentration at the clamped end limits the possible increase of the average voltage value.

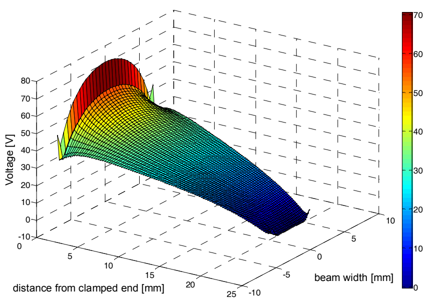


Figure 4: Voltage distribution on the upper electrode of the trapezoidal scavenger of Design 1 obtained via FEM simulations.

4 Conclusions and outlook

The structural optimization of cantilever energy scavengers based on a uniform stress distribution criterion was performed. A computational procedure aimed at encompassing constrains on volume, dynamic response and electromechanical coupling is thus proposed. Trapezoidal configurations are shown to allow higher electric power densities to be obtained if compared to a rectangular layout proposed in literature.

A thorough experimental validation of the obtained optimised geometries is being set-up. The experiments will allow evaluating also the sensitivity of the device to effects such as the compliance of the constrains, the positioning, shape and fixture of the proof mass, stress concentration effects, the brittleness of the piezoelectric layers as well as proper integration with the electronics. Experiments will also be carried out on a configuration of the scavenger where the proof mass is replaced with a permanent magnet, allowing an additional electromagnetic energy source [6]. The latter could allow achieving the tuning of the frequency of the resulting device by influencing its axial stiffness. Configurations based on an assembly of several scavengers, which increase the frequency bandwidth of the system [7], will also be evaluated. The study will further proceed by including the scaling effects involved in miniaturised scavenging solutions aimed at elder care.

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