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Design study of a mechanically plucked piezoelectric energy harvester using validated finite element modelling

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ABSTRACT

This paper develops a coupled piezoelectric-circuit finite element (FE) model for a mechanically plucked piezoelectric energy harvester (Mech-PEH), which uses plastic plectra to pluck piezoelectric bimorph cantilevers. The Mech-PEH was modelled as a piezoelectric cantilever with either a displacement or a force applied at the tip, and a load resistor connected across its electrodes. The FE model was validated with a difference around 2.7% between the simulated and measured energy outputs and able to predict the vibration- and energy-related characteristics of the Mech-KEH. It was used to investigate the effects of the bimorph's geometric parameters and the plucking frequency on the energy outputs. It is concluded that (1) when the same plucking force is used, the energy output of the Mech-PEH can be increased by reducing the stiffness of the bimorph through reducing its width or thickness, or increasing its length, and (2) a high plucking frequency with a free vibration period is beneficial in improving the energy output. It is pointed out that the bending fatigue strength of the piezoelectric material limits the designed highest energy output, and that when designing bimorph parameters for the Mech-PEH, both the energy output and the expected life time should be considered.

1. Introduction

Recently there has been a surge of research in the area of energy harvesting, which extracts energy from an ambient environment and converts it to useable electrical energy to provide sustainable power supply for wireless electronic devices [1]. This has been driven by the desire to reduce or remove the need for battery replacement or recharging for those devices to increase their life time and thus reduce the maintenance burden. The ambient energy sources available include solar illumination (light), radio-frequency energy, thermal energy and kinetic energy. Since beginning, kinetic energy harvesting has attracted a great of deal attention due to the almost ubiquitous presence of mechanical vibration [2], and has been investigated by using various transduction mechanisms including electromagnetic [3,4], electrostatic [5] and piezoelectric [6,7].

One of the main challenges in kinetic energy harvesting is that the available vibration is commonly spread in a wide frequency range, with the prevalence of low frequency components. This challenge is particularly applicable to piezoelectric energy harvesters (PEHs) because they usually have a resonance frequency (typically from several tens Hz to hundreds Hz) much higher than the dominate frequencies of the ambient vibration. Moreover, the PEHs usually have a high mechanical quality factor (narrow bandwidth), which means that the transduction efficiency drops significantly if the ambient vibration frequency does not match the PEH's resonance frequency.

Frequency up-conversion has been proved to be an effective strategy to address this challenge, which converts the ambient low-frequency vibration to the resonant vibration of the PEHs to achieve high electric power output. One of the earliest studies on this topic was performed by Umeda et al. [8], who used a steel ball to strike a piezoelectric monomorphic disc to induce resonant vibrations in the disc. One of the recent popular and effective method to achieve frequency up-conversion is plucking piezoelectric cantilevers, which induces an initial deflection in the cantilever and then let it vibrate freely at its resonance frequency. The reported PEHs based on this principle can use different plucking methods to deflect the piezoelectric cantilever, including magnetic plucking [9,10], impact-driven [11,12] and mechanical plucking [13]. Luong [14] used magnets, actuated by low speed wind, to pluck piezocomposite generating elements with secondary magnets attached for small-scale windmill. Pillatsch [15] developed a generator to scavenge energy from human motion, which used magnetic forces

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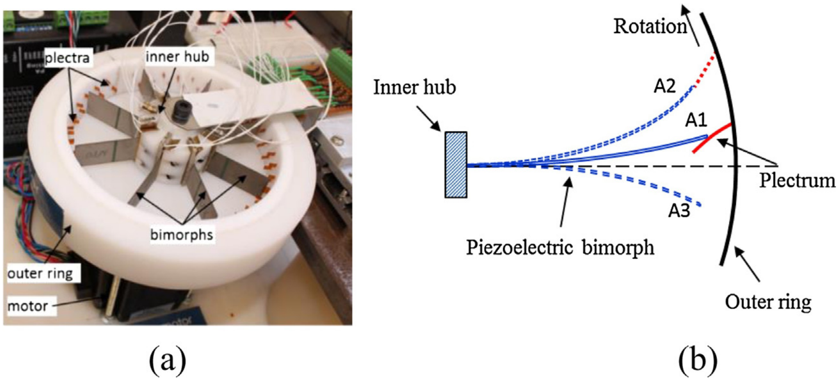

Fig. 1. (a) Prototype of the mechanically plucked piezoelectric energy harvester (Mech-PEH) (b) an illustration of the plucking process.

to convert low frequency human motion to the resonant oscillations of a piezoelectric cantilever bimorph. Renaud [16] developed an impact-driven generator, which used a steel ball sliding inside a frame to strike the piezoelectric cantilever bimorphs at the ends of the frame. Pozzi [13] developed a mechanically plucked piezoelectric energy harvester (Mech-PEH), which used plectra to pluck piezoelectric bimorph cantilevers. When used for knee-joint energy harvesting, the Mech-PEH produced an average power of 2 mW.

Although the plucking strategy has been implemented in many piezoelectric energy harvesting devices, little effort has been made to improve the energy output through design study of geometric parameters of the piezoelectric cantilever and the plucking frequency. This paper develops a coupled piezoelectric-circuit finite element model for the Mech-PEH proposed in [13]. The experimentally validated FE mode is able to simulate the energy-related and vibration-related characteristics of a plucked piezoelectric bimorph and thus provides a powerful tool for the optimisation of structures and systems of such energy harvesters. Parametric study is performed to investigate the effects of the bimorph's geometrical parameters and the plucking frequency on the energy output, aiming to gain an understanding on the behaviors of the Mech-PEH with varied design parameters and thus provide design guidance for improving the energy output.

It should be noted that the FE [17,18] and analytical [19] modelling of PEH have been well documented in the literature. However, most of the work are based on piezoelectric cantilevers with an added mass on the tip and subject to seismic excitation. Little work has been performed to model piezoelectric cantilevers subject to sporadic plucking action. Pillatsch [20] developed an analytic model to predict the performance of a magnetically plucked bimorph. However, the ability of the model to perform design optimisation has not been provided. Pozzi [21] developed a FE model for mechanically plucked piezoelectric cantilevers, but the model each time can only simulate either the deflection phase or the free vibration phase in a plucking cycle. The FE model developed in this work is able to predict the performances of the mechanically plucked piezoelectric cantilevers during the whole plucking cycle. In addition, the model is able to simulate the dynamic responses of the cantilever subject to consecutive plucking actions, and thus can be used to investigate the effects of the plucking frequency on the performance of the cantilever.

2. Mechanically plucked piezoelectric energy harvester

2.1. Description of the Mech-PEH

A prototyped Mech-PEH is shown in Fig. 1. The plucking mechanism is the same as was presented in Ref. [13]. A 31.8 mm long piezoelectric bimorph was fixed on the inner hub to form a cantilever with a free length of 26 mm sixty rectangular plectra were embedded in the outer ring. They are made of 125 μm-thick Kapton® polyimide film (IM8031, Advent Research Materials Ltd., Oxford, UK) and have a much lower stiffness than the piezoelectric bimorphs studied in this paper. The reason to choose flexible plectra is because stiff plectra will lead to high impact between the plectra and the bimorph and consequently significantly reduce the life time of the bimorph because piezoelectric materials are very brittle. A stepping motor was used to actuate the outer ring to rotate to simulate the ambient motion, whereas the inner hub was held static by a bracket. A schematic of the plucking action is shown in Fig. 1(b). As the outer ring rotates, the bimorph is first deflected by a plectrum because of the overlap between the bimorph and the plectrum (A1). As the rotation progresses, the bimorph loses contact with the plectrum and is released (A2). Following that, the bimorph vibrates freely around its original position at the resonance frequency (A3). As the bimorph is plucked consecutively by the plectra, the low speed rotation from the outer ring is converted to the resonant vibration of the bimorph, thus achieving frequency up-conversion and high electrical energy output. The Mech-PEH can be used for energy harvesting in many ambient environments, for example, wind flow energy harvesting, but it was specifically designed to harvest the kinetic energy from knee-joint motion in [13]. This paper will take the knee-joint energy harvesting as a case for design study of the Mech-PEH.

3. FE modelling approach

The FE model of the Mech-PEH was developed using commercial package ANSYS 14.5 (ANSYS Inc., Canonsburg, PA, USA). The Mech-PEH was modelled as a piezoelectric bimorph with an external load force/displacement applied at the tip and a load resistor connected across its electrodes, as schematically shown in Fig. 2(a). Displacement constraints were applied to the top and bottom surfaces in the clamped portion of the bimorph to form a cantilever.

3.1. Coupled piezoelectric-circuit FE model

The bimorph comprises an internal brass substrate and two PZT layers on either side, covering the entire surfaces. It is polarised for series connection, i.e. the two PZT layers are oppositely polarised. Therefore, in the FE model, opposite polarisation directions were specified to the two PZT layers, as shown in Fig. 2(b). This was achieved by specifying opposite piezoelectric constants to one of the two PZT layers. Alternatively, the opposite polarisations directions can be specified by assigning different local coordinate systems to the two PZT layers. The bimorph can also be polarised for parallel connection, i.e. the two PZT layers are polarised in the same