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Model refinements and experimental testing of highly flexible piezoelectric energy harvesters

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A B S T R A C T

This paper addresses limitations to existing analytical models for piezoelectric energy harvesters. The presented model is targeted at predicting behaviours of highly flexible piezoelectric devices (FPEDs) and includes high orders of substrate and piezoelectric material nonlinearity, geometric nonlinearity, and additionally the effects of both self-weight and pre-stress. Validation through experimental testing is provided.

The influence of self-weight on vibratory dynamics becomes important in FPEDs due to both material composition and dimension. The developed model facilitates the simulation of FPED performance mounted at specified angles to the horizontal. In one study, for a FPED of 120 mm in length, the resonant frequency changed by over 30 percent with mounting angle. Consideration of mounting orientation is advised as self-weight increases damping and significantly lowers FPED performance – over a 50 percent reduction in one presented case.

1. Introduction

Energy harvesting is a topic of global appeal and is receiving growing interest in terms of both research and practical application possibilities. In essence, the term refers to the conversion of wasted ambient energy into useful energy, often electrical. The focus here is on wasted kinetic energy, where transduction methods such as piezoelectricity and electromagnetism are utilised for energy capture. Among researchers the consensus is that piezoelectric transduction offers superior conversion efficiencies [1] and this mechanism is adopted in this work. The prime utilisation of energy generated by such means is to power miniature wireless sensors, e.g. tyre pressure monitoring sensors or temperature/humidity sensors. However, an investigation of using such technology to extract power on a significantly larger scale, i.e. kWs from environments such as oceans or wind fields, is currently under way. To this end, Mutsuda et al. [2] and Tanaka et al. [3] have been developing the concept of employing highly flexible piezoelectric devices (FPEDs), cantilever in form, comprised of silicone rubber (Si) and polyvinylidene fluoride (PVDF) thin films. The overarching vision is to create 'offshore renewable energy generation farms' by combining several concepts (e.g. wave motion FPEDs and wind turbines). This proposition is

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one solution to the inexorable rise in global energy demand while reducing reliance on fossil fuels and slowing global warming. The nature of FPEDs makes them ideal for the aforementioned target application environments due to their inherently low fundamental frequencies.

Early analytical modelling of cantilever piezoelectric harvesters predominantly assumed linear behaviour. Sodano et al. [4] used the Rayleigh–Ritz procedure for estimating the power output from a cantilever mounted piezoelectric generator. Ertuk and Inman [5] followed this by developing a distributed-parameter electromechanical model for energy harvesters. Patel et al. [6] extended the model by accurately incorporating effects of non-uniform beams created by altering coverage of the piezoelectric layer. Utilisation of the model showed improvements in performance is achievable by optimising piezoelectric length, with experimental data providing model validity. More recently the importance of using nonlinear models for theoretical performance predictions has come to light [7–10]. Nonlinearity in piezoelectric materials [11], in addition to geometric nonlinearity created in structures undergoing large deformations, necessitates the use of nonlinear models. Stanton's early work [7] saw the development of a nonlinear model which considered piezoelectric material nonlinearity in the form of higher order terms in constitutive equations. This was later extended in [9], where tip mass effects and further higher order terms were included to increase model robustness. For the common cantilever harvester design it is recognised and documented that performance drops off significantly as a result of mismatch between resonant and excitation frequency. It is therefore important to be able to predict how nonlinear behaviour affects the frequency response of devices to ensure that harvesters are designed to maximise performance.

The devices considered by Mutsuda et al. [2] and Tanaka et al. [3] are made from Si and PVDF layers and are highly flexible. As such they are likely to experience geometric nonlinearity and exhibit high levels of material nonlinearity. Modelling performed by Patel et al. in [10] is well suited to analyse this case as it incorporates the effects of substrate, piezoelectric and geometric nonlinearity. Serving as a basis, alterations will be made in line with Stanton et al. [9] to include higher orders of odd power nonlinearity in material constitutive equations; recognised as essential for increasing the model validity range. Differentiating from previous work, several additional key effects are also important when considering FPEDs. Firstly, self-weight influences vibratory dynamics and can be observed in the behaviour of long slender beams whether mounted horizontally or vertically. Vertical cantilevers oriented downwards stiffen due to gravitational forces with opposing effects present in beam oriented upwards against the acting direction of gravity [12]. Self-weight has previously been overlooked in work related to energy harvesters, for example in Hobeck and Inman [13] and Xie et al. [14], who both considered vertically oriented devices. In contrast, Friswell et al. [15] performed work on vertically oriented devices and integrated self-weight effects however modelling excluded material nonlinearity. The model developed in this paper will incorporate the influence of self-weight on FPEDs mounted at angles ranging from -90° to $+90^{\circ}$ to the horizontal. Pre-stress is the second key issue to influence dynamical behaviour of FPEDs. Residual stresses arise in PVDF thin films during manufacture as published by Oh et al. [16], in addition to those created during adhesive curing via chemical shrinkage [17]. Modelling and predicting residual stress effects is essential to accurately simulate the dynamics and electrical performance of FPEDs.

This paper details theoretical model refinements to an existing nonlinear model for piezoelectric energy harvesters, in terms of (i) higher order odd power material nonlinearity, (ii) sample self-weight and (iii) inherent pre-stress in samples. Through experimental testing of devices manufactured ‘in-house’ the verification of these extensions and model validation is provided. The paper is laid out as follows. Firstly, a recap of previous nonlinear modelling is detailed with modifications made to accommodate higher order odd power material nonlinearity. Secondly, data from experimental testing is provided to demonstrate the necessity of including self-weight and pre-stress and the effects they have on energy harvesting. In this section theoretical model derivations of the effects will also be presented. In the second part of the paper, attention is turned to validation. Firstly, unknown material properties, including coefficients of material nonlinearity, will be obtained through static and dynamic testing. Subsequently, model extensions relating to self-weight and pre-stress are validated individually. Additionally, the analytical model is used to highlight the importance of these effects in the prediction of FPED behaviour.

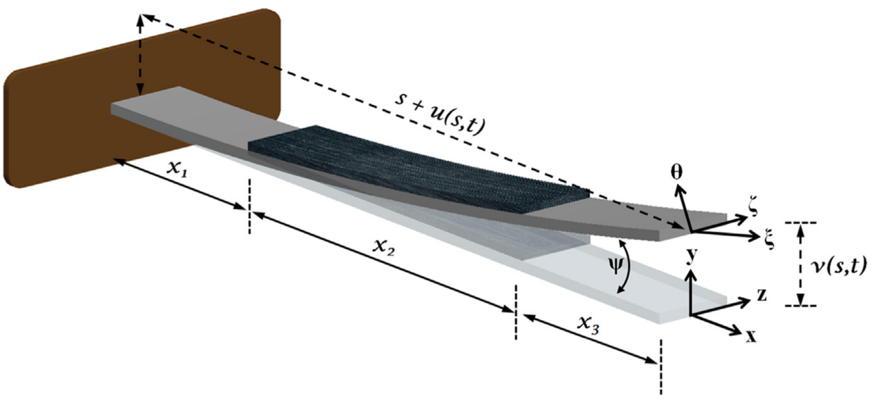

Fig. 1. Dimensional and directional notation used through this paper.