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Achieving increased bandwidth for 4 degree of freedom self-tuning energy harvester

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ABSTRACT

The frequency response of a self-tuning energy harvester composed of two piezoelectric cantilevers connected by a middle beam with a sliding mass is investigated. Measurements show that incorporation of a free-sliding mass increases the bandwidth. Using an analytical model, the system is explained through close investigation of the resonance modes. Resonance mode behavior further suggests that, by breaking the symmetry of the system, even broader bandwidths are achievable.

1. Introduction

Over the last decade, the topic of self-powered systems has received increasing attention, especially with the appearance of wearable devices [2]. Instead of pure battery dependency, self-powering systems incorporate an energy storage component as well as an energy harvester. Energy harvesters can power devices by converting ambient energy sources (such as heat, light and vibrations) into electrical energy. Sources of vibrations for energy harvesting can be transportation vehicles, construction equipment and the human body.

A kinetic (vibration-based) energy harvester needs to have an operating frequency that matches the frequency of prevalent ambient vibrations in order to achieve a desirable power output [3]. Single piezoelectric cantilevers typically operate over a narrow bandwidth and, therefore, an appropriate design must be employed for the targeted vibrational source. However, in real-life applications, vibrational sources are intrinsically frequency-variant – sometimes over a broad bandwidth. To overcome the narrow bandwidth of conventional single piezoelectric cantilevers, various approaches have been reported as summarized below.

Ferrari et al. used multiple harvesters, each working at different resonance frequencies, forming a multi frequency energy converter [4]. Zhou et al. and Aldraihem et al. developed a double-beam configuration where a wide beam enhances the power and bandwidth of a connected shorter and thinner beam that contains the piezoelectric material [5,6]. Ou et al. placed two tip masses on a beam as a simple solution to enhance the bandwidth and derived a generalized model for a beam with any number of tip masses [7]. Additionally, Wu et al. (2012, 2014) proposed a two Degrees of freedom (DOF) design that is composed of a

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main beam and an inner secondary beam [8,9] and Erturk et al. proposed an L-shaped beam structure [10]. They were able to tune the first two natural frequencies of the structures to be relatively close to each other, achieving broadening of the bandwidth. Tang et al. included magnets in their energy harvesters where non-linearities were utilized in order to enable the harvesters to adapt to the variable input frequency by tuning the harvesters resonance frequency [11]. As a bonus, the magnets can act as tip masses that also create a Faraday's effect with auxiliary inductive coils [12] for broader bandwidth.

Another concept that enables a broader bandwidth for an energy harvester is to use a self-tuning resonator. This type of device adapts its resonance frequency to the source of vibration over a wide range of frequencies. Boudaoud et al. demonstrated a free to slide mass on a vibrating metal string, actuated by an oscillating magnetic field, which can self-adjust the system to certain input frequencies [13]. The free sliding mass adds one degree of freedom to the system. A different approach uses a bead inside a hollow cylindrical cantilever [14]. A more recent study from Miller et al. also achieved a self-tuning harvester behavior through a fixed-fixed beam and a sliding mass configuration [15,16].

Our self-tuning harvester consists of two piezoelectric cantilevers; both fixed and static in one end and free to move in the other end. For each cantilever, a tip mass is attached to utilize the concept of extended stress distribution [17]. A middle beam of aluminum, containing the sliding mass for self-tuning, connects both tip masses and acts as a mechanical coupling.

By using a middle beam to host the sliding proof mass, the design space for the self-tuning is less restricted by the specific properties of the piezoelectric cantilevers. In previous modelling efforts for simpler systems of a moving mass on a cantilever [18] or a moving mass on a double clamped beam [15], the mathematical expressions for the motion of the beam and of the proof mass become challenging to interpret directly – even with simplifying assumptions. The general argument to explain the self-tuning mechanism, as given by Miller et al. [15], is that (for a given excitation at a certain frequency) the proof mass will move on the beam until it reaches a position where the mode of vibration has a resonance with the driving frequency. As has been shown experimentally for the double clamped beam [15], the proof mass can alter its position, as the driving frequency changes, in order to maintain resonance. The numerical modelling of Khalily et al. [18] results in a continuously lower resonance frequency as the proof mass approaches the non-clamped end of the cantilever. In contrast, the lowest resonance in the double clamped system is given by having the mass near the beam center [18]. It is, however, not obvious from previous results how proof mass motion is expected to influence the resonance frequency in our more complex structure.

In this paper, we derive a tailored analytical model that adequately describes the observed measured frequency response of our self-tuning device. Our model can explain both the observed movement of the sliding mass and the impact on system performance through altering the length of the middle beam.

2. Method

The self-tuning harvester is intended to provide power for an intelligent wireless sensor (IWS). The IWS will collect temperature data and transmit the data via Wi-Fi. The data will be collected from a gas turbine where the self-tuning harvester will convert vibrations into power.

The self-tuning harvester is measured with two different lengths of the middle beam, called Short Beam (SB) and Long Beam (LB) [19]. From a harvesting perspective, the LB had the most interesting result. Therefore, the analytical investigations were focused on the LB configuration. The output difference between SB and LB are explained by the results of the analytical calculations.

3. Experimental setup

The harvester consists of two mechanically coupled piezoelectric cantilevers connected via a middle beam (Fig. 1). The piezoelectric cantilever MIDE v21b [20] is an industrial standard cantilever composed of two layers of lead zirconate titanate

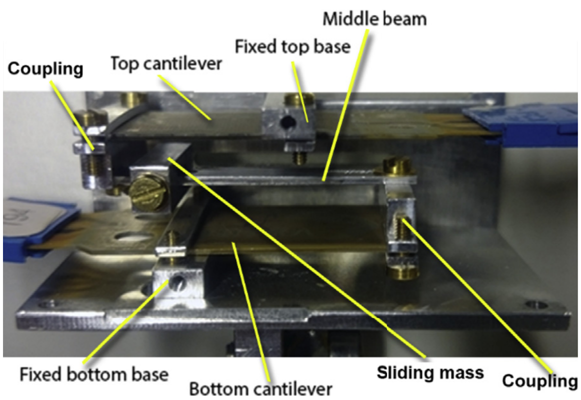

Fig. 1. The 4DOF self-tuning energy harvester seen from the side (side wall is missing).