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Widening the bandwidth of vibration energy harvesters using a liquid-based non-uniform load distribution

Nathan Jackson*, Frank Stam, Oskar Z. Olszewski, Hugh Doyle, Aidan Quinn, Alan Mathewson

Tyndall National Institute, University College Cork, Cork, Ireland

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ABSTRACT

Vibration energy harvesters typically have a narrow bandwidth, which allows them to generate high amounts of power, but only at a specific frequency. This paper presents a novel method of increasing the bandwidth of a cantilever beam by creating a non-uniform load. The concept uses a liquid filled mass, which causes the structures overall centre of gravity to shift as the beam bends. The overall centre of gravity shifts due to the mass change caused by the dynamic behaviour of the fluid. This paper validates the concept both numerically and experimentally by using a custom manufactured fluid filled mass on a piezoelectric cantilever. A water filled mass demonstrated a 2.8x increase in bandwidth for low acceleration (<1 g) and low frequency cantilever (27 Hz) devices. The effects due to liquid density and liquid viscosity are also experimentally measured. The numerical estimations match well with the experimental results for low accelerations (<0.5 g). Above 0.5 g acceleration the liquid water used in the cavity became chaotic, which caused liquid droplets to separate from the bulk liquid, thus reducing the overall mass for given point in time. This non-linear liquid dynamic behaviour further increases the bandwidth by creating a larger variation in the resonant frequency. In addition, as the fluid viscosity increases, the acceleration from the vibration source required to cause movement in the fluid also increases. The measured open circuit peak to peak voltage demonstrated an increase in bandwidth without significant loss in voltage.

1. Introduction

Vibration energy harvesting devices have been highly researched over the past decade, and will continue to grow, especially in the microelectromechanical systems (MEMS) area due to the high demand for powering the internet of things. Sensor applications and demand continue to increase, but powering them is still a challenge [1,2]. The most common application for energy harvesting devices is powering a wireless sensor node, which could be located in a remote area where replacing a battery is expensive or undesired [3,4]. A cantilever based structure is the most common type of vibrational energy harvester for both piezoelectric and electromagnetic based devices. The amount of power a device is capable of harvesting depends on numerous factors including: the power management circuit, quality of the active material used, and design of the cantilever structure. However, one of the most important features when optimizing the amount of power harvested is to match the resonant frequency of the cantilever with the frequency of the vibration source.

Cantilever structures, especially silicon-based MEMS cantilevers, typically have high Q-factors [5–7]. A high Q-factor cantilever structure results in lower energy loss, which is good for optimizing power or increasing sensitivity of a sensor. However, any frequency deviation from either the source or from the cantilever over time will induce significant reduction in output power. The amount of deviation that is allowable depends on the bandwidth of the cantilever. Low frequency (<250 Hz) linear vibration energy harvesters typically have high Q-factors or narrow bandwidths of <2 Hz [6,8,9]. Based on the high Q-factor, the bandwidth of the cantilever devices can be less than 0.25% of the resonant frequency [10]. However, resonant frequency deviations of MEMS cantilevers across a 6-inch wafer are usually greater than 1.5%, which are due to deviations in the uniformity of the different layers [10]. Finite element modelling (FEM) is commonly used to predict the resonant frequency and design the structures prior to fabrication. However, the predicted resonant frequencies can differ by at least 5% due to manufacturing issues such as layer thickness and stiffness of materials [11], as well as damping properties. Therefore

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* Corresponding author.
E-mail addresses: Nathan.Jackson@tyndall.ie, njack@asu.edu (N. Jackson).

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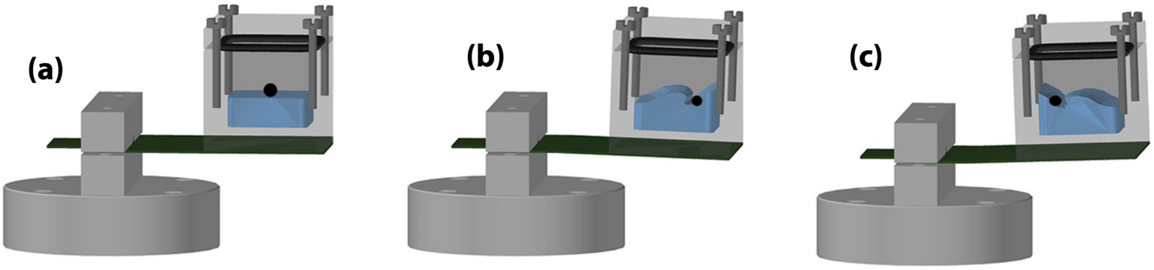

Fig. 1. Schematic of the vibration energy harvester device with custom mass filled with liquid. (a) Demonstrates the fluid motion while the cantilever is at rest, (b and c) demonstrates the concept of generating a moving mass by creating rolling waves in the fluid, which changes the centre of gravity. (b) Demonstrates effect as cantilever bends down while (c) demonstrates effects when cantilever bends up. The black dot represents the centre of gravity shift in (b and c).

the bandwidth of the energy harvester should cover at least a 5% deviation in frequency to overcome prediction and manufacturing deviations, unlike current devices which only cover 0.25%.

Increasing the bandwidth to allow energy harvesting devices to operate in real-life applications is one of the major challenges associated with vibration energy harvesters. Numerous methods to increase the bandwidth have been investigated including: non-linear cantilever design [12–14], mechanical stoppers [15], external forces such as magnetic or electrostatic [16], creating an array of devices [6], and sliding masses [17]. All of these methods demonstrated a significant increase in bandwidth, but they accomplished this by lowering the Q-factor or increasing the volume. The reduced Q-factors result in a significantly lower power density, which is below the required amount to power a wireless sensor node (~100 μW cm^{-3}). Tuneable energy harvesting is another method to overcome a narrow bandwidth, by tuning the resonant frequency of the cantilever to the frequency of the vibration source. The method involves altering the structure or stiffness of the material to change the resonant frequency of the cantilever [18–20]. Most of these methods require complex manufacturing techniques, which are not possible in large scale production as each device would need to be individually assessed. In addition active tuning during operation due to frequency change at the source would require an active mechanism, which typically requires more power than the energy harvester can produce, and is thus counterproductive.

This paper demonstrates a novel concept of increasing the bandwidth without significantly reducing the power output. The aim of the paper is to develop a novel method to widen the bandwidth enough to cover the error due to manufacturing and small deviations in frequency of the vibration source. The concept investigated uses a sliding mass mechanism, where the resonant frequency of the cantilever structure changes due to a change in the centre of gravity of the mass. This work builds on previously reported methods that demonstrated that a sliding mass could be used to tune the resonant frequency, by changing the location of the centre of gravity [21]. The method described in this paper uses a mass that changes its centre of gravity as the cantilever bends, thus making the resonant frequency a function of time that is continuously changing, which widens the bandwidth instead of tuning the frequency as previously described. As the centre of gravity changes due the dynamic movement of the mass during operation the cantilevers resonant frequency will be constantly changing its resonant frequency, which will result in a broadening effect. A sliding mass can be integrated into macro-scale devices using various methods. However, integrating a sliding mass into a MEMS microfabrication process is challenging. The authors aimed to develop a method for generating a sliding mass effect that has the potential to be scaled down to the MEMS level. This paper focuses on the validation of the novel mechanism of a macro-scale piezoelectric device.

The mechanism of broadening the bandwidth using a sliding mass is based on a non-uniform load distribution using a liquid filled mass. As the cantilever bends the liquid moves from one side of the mass to the other by changing the inclination angle of the cantilever. This dynamic movement of the cantilever causes the fluid to move, which changes the location of the systems centre of gravity causing changes in the structure's resonant frequency during actuation. Therefore, the resonant frequency of the cantilever changes as a function of time. The multiple frequencies during actuation combine to form a widened bandwidth. Liquid filled devices have been previously used to dampen electrostatic devices by operating in a liquid environment [22], but this is the first time that a liquid filled mass has been used to increase the bandwidth. The amount of broadening is expected to be affected by the density and viscosity of the liquid. The effects associated with varying the liquid properties are demonstrated in this paper along with validation of the concept. An initial proof of concept was previously demonstrated by the authors [23]. Numerical models and FEM were used to further validate the concept and to develop methods for predicting the outcome for future applications.

2. Materials and methods

2.1. Concept

The concept of using a liquid filled cavity mass to widen the bandwidth is based on a sliding mass concept. The resonant frequency of a rectangular cantilever is affected by the location of the centre of gravity of the mass as previously demonstrated [21]. Therefore if the centre of gravity of the mass is constantly changing, the resonant frequency of the cantilever will be changing during oscillation, which will result in widening the bandwidth. The concept in this paper includes using a liquid filled mass to create a non-uniform load distribution, as shown in Fig. 1. At rest the centre of gravity of a uniformly distributed mass is in the centre, assuming the mass of the cantilever is negligible compared to the load. However, as the cantilever starts to bend the fluid creates a rolling wave or sloshing effect, which shifts the centre of gravity towards the distal end of the cantilever when bent downwards (Fig. 1b), and towards the proximal or tethered end when bent upwards (Fig. 1c). The location change in the centre of gravity is dependent on the density and viscosity of fluid, as well as the amount of deflection or acceleration applied.

2.2. Numerical analysis

The 1st mode of the resonant frequency of a linear rectangular cantilever with proof mass can be numerically calculated using a 1-D spring mass system. Assuming the proof mass is much larger

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