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Broadening the bandwidth of piezoelectric energy harvesters using liquid filled mass

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Abstract

A narrow bandwidth is one of the most challenging issues that vibrational energy harvesters have to overcome. This paper demonstrates a novel method of broadening the bandwidth without significantly reducing the peak output voltage. The method uses a liquid filled mass to create a sliding mass effect in order to broaden the bandwidth. The fluid mass increased the full-width-half-maximum (FWHM) value from 1.6 Hz to 4.45 Hz with no significant decrease in peak-to-peak voltage when compared to an empty mass. The fluid filled mass has a non-linear mass distribution during low frequency, high acceleration applications.

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Keywords: Energy Harvesting, Piezoelectrics, wide bandwidth, cantilever, sliding mass

1. Introduction

Vibrational energy harvesting devices have been highly researched over the past decade, and significant advances have been made both in design, efficiency, and material development. However, one of the major disadvantages of vibrational energy harvesters is that they require a high Q-factor or low bandwidth in order to obtain high power. The narrow bandwidth is important for obtaining high power, but makes implementing the device into a real-life application difficult as most vibrational sources have varying frequencies during operation. Typically, MEMS based piezoelectric energy harvesters have a narrow bandwidth of around 1 Hz, due to the stiffness of the substrate, which is typically Si. If the frequency of the vibrational source shifts by more than 1 Hz the power obtained is significantly decreased, and most vibration sources have varying frequencies throughout their normal operation [4]. The resonant

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frequency of vibrational energy harvesting devices can also vary from their predicted value due to manufacturing processing by 1-5% [7]. Therefore, the bandwidth needs cover at least a 5% deviation in resonant frequency in order to be functional. For MEMS devices this variation could be due to thickness of Si, etching profile of Si, and thickness of all the layers. Various methods to increase bandwidth have been investigated including: cantilever design [3, 6], use of a mechanical stopper [5], external forces like magnetic or electrostatic attraction [9], creating an array of cantilevers [4], and multiple or sliding masses [1, 2]. All of these techniques increased the bandwidth, but significantly decreased the power harvested by either reducing the Q-factor or by increasing the volume and thus decreasing the power density. This paper demonstrates a novel concept to increase the bandwidth by creating a non-linear mass distribution, which changes the centre of mass during operation. The paper describes a method using a liquid filled mass, which has the capability of shifting its centre of mass during oscillation of the cantilever, by creating a rolling wave. The concept is designed for devices that operate at low frequency and high acceleration. The high acceleration and low frequency is required in order to force the liquid into shifting its centre of mass.

2. Materials and Methods

The concept of widening the bandwidth using a liquid filled mass is demonstrated using a commercial piezoelectric energy harvester (Volture V25W, Mide). The mass however, was custom designed and manufactured using Perspex. A cavity was created in the Perspex to allow fluid to be added to the mass as shown in Fig. 1. Water was the primary fluid that was used in this paper. However, glycerol was also used to determine what effect viscosity had on widening the bandwidth. An electromagnetic shaker (Labworks Inc.) along with feedback control via an accelerometer was used to demonstrate the concept as shown in Fig. 1. The bandwidth is defined as the Full width half maximum (FWHM) value.

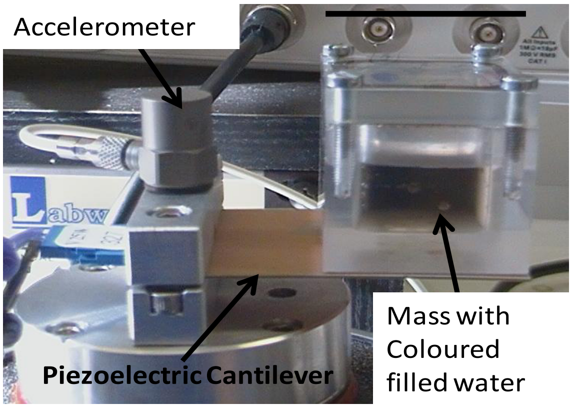

Fig. 1. Image of the device setup, which shows the piezoelectric cantilever with Perspex filled liquid mass on a vibrational shaker, colour added to water for visual representation. Scale bar 2 cm.

3. Results

For the initial proof-of-concept the peak to peak voltage of the piezoelectric cantilever was measured versus frequency as shown in Fig. 2. For comparison two masses were investigated 1) an empty cavity mass, to act as the control and 2) a fluid filled cavity mass. The fluid filled cavity was filled with deionised water. Initially 50% of the cavity volume was filled with water. Two different accelerations were investigated 1g and 4g. The results show at 1g acceleration that there was no significant increase in bandwidth as the empty cavity had a bandwidth of 1.6 Hz, whereas the water filled cavity had a bandwidth of 1.62 Hz. There was a small change in resonant frequency due to the increased mass from the water. The peak-to-peak voltage was also not affected at 1g. However, the water filled mass demonstrated a significant increase in bandwidth at 4g with an increase to 4.45 Hz, and no significant decrease in voltage. At 4g and 1g the empty mass had a similar bandwidth with a small increase from 1.6 to 1.8 Hz.

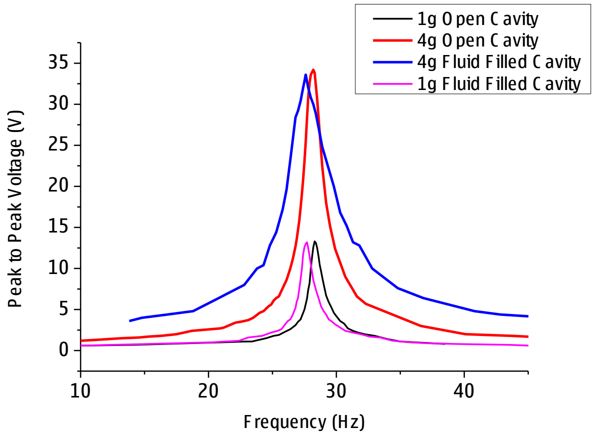

Fig. 2. Comparison graph of Voltage vs. Frequency of empty mass and fluid filled mass with varying acceleration.

A graph showing the peak-to-peak voltage versus frequency for a water filled mass with varying accelerations is shown in Fig.3. The results show a bandwidth of 3.57, 4.45, and 1.6 Hz for 6g, 4g, and 1g accelerations respectively. The 6g acceleration demonstrated a slight decrease in bandwidth when compared to the 4g acceleration. This is believed to be due to the motion of the fluid. At 4g the fluid is visually seen to behave similar to a rolling wave, where the fluid is sliding back and forth. However, at higher acceleration (6g) the water motion began to be chaotic. The fluid was displacing vertically as well as horizontal, which lead to splashing of the water on the lid, so droplets detach from the bulk fluid.

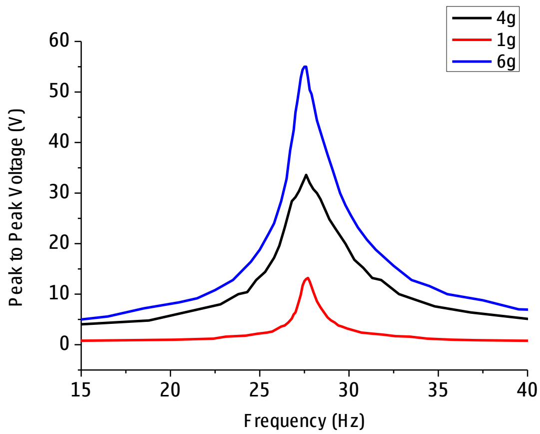

Fig. 3. Graph of Voltage vs. Frequency of 50% water filled mass at various accelerations.

The authors proceeded to investigate if the amount of fluid in the mass had any effect on the performance, by varying the amount of water in the mass, while keeping the acceleration the same. The results show that when the mass is filled with 37.5% and 75% water that there was a slight increase in bandwidth when compared to an empty cavity having values of 2.46 hz and 2.54 Hz (Fig. 4). However, the 100% filled cavity had no significant increase in bandwidth when compared to control. The 100% filled mass should have a similar bandwidth as the empty cavity as the liquid has nowhere to move. As shown in Fig. 4 there is a shift in resonant frequency due to the weight change from the amount of water added. This demonstrates that a fluid filled mass can also be used to tune the resonant frequency, and that heavier liquids could be used to increase tunability. Using liquid to tune the resonant frequency is an easier concept compared to previous attempts to tune the frequency, based on unique device design or altering the device after manufacturing [8].

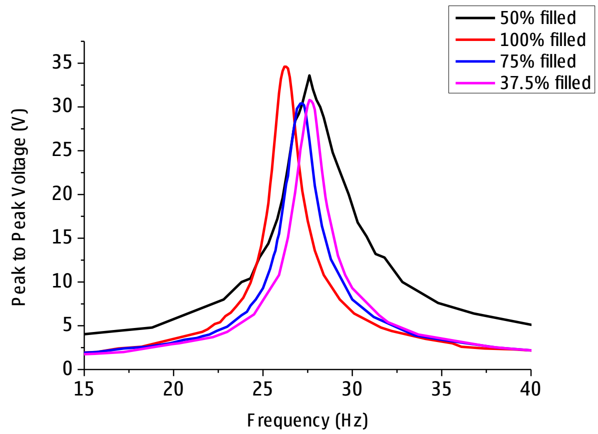

Fig. 4. Graph of Voltage vs. Frequency of different amounts of water filled mass operating at 4g acceleration

The viscosity of the fluid used will make a difference in the performance of the device, so the authors investigated using a high viscosity fluid (glycerol). Glycerol was used because viscosity is approximately 1000x greater than water, 1.4138 Ns/m^2 compared to 0.001 Ns/m^2 for water. However, glycerol only has a slightly higher density than water 1.26 g/cm^3 compared to water 1.0 g/cm^3. Given the amount of fluid used this equates to only a 2% change in mass by using glycerol compared to water. The results shown in Fig. 5 demonstrate that a higher acceleration is required to get the same bandwidth increase when using a higher viscosity fluid. The bandwidth for the glycerol study are 1.73, 2.46, and 3.13 Hz for 1, 4, and 6g acceleration respectively The results were also visually witnessed as higher accelerations were required in order to get the higher viscous solution to create a wave based movement. The results show that viscosity of the fluid has a significant impact on the amount of acceleration that is needed to cause an increase in bandwidth. However, increasing the mass of the fluid should increase the bandwidth because the sliding mass component would contribute more to the overall mass, therefore the centre of mass would have a greater displacement which will increase the bandwidth.

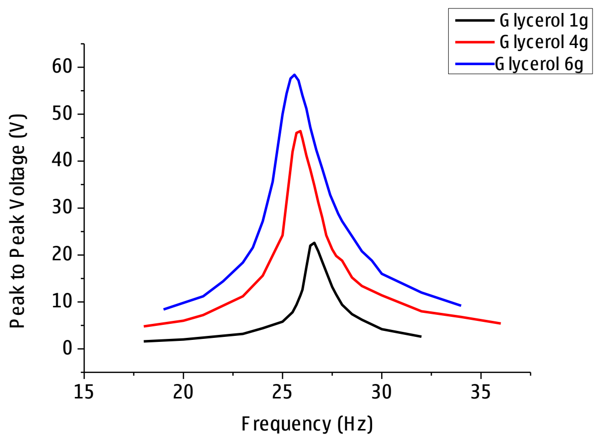

Fig. 5. Graph of Voltage vs. Frequency of varying acceleration for cavity filled with glycerol to 50%.

4. Conclusions

The results from this work demonstrate the potential for using a liquid filled mass to increase the bandwidth of a cantilever based vibrational energy harvester without significantly decreasing power. The concept is based on the use of a sliding mass, where the centre of mass is constantly changing depending on the cantilevers oscillations. It is known that moving the centre of mass of a cantilever structure will alter its resonant frequency; therefore a sliding mass should broaden the bandwidth. This non-linear mass distribution concept for fluid only applies when a certain acceleration threshold is met. If the acceleration is below the threshold then the mass acts similar to a single point mass, but as the fluid splashes around the centre of mass changes its location. The initial results demonstrate that viscosity and density of the liquid are critical properties that will affect the bandwidth. In conclusion the authors found that a 50% filled mass gave the widest bandwidth, and a low viscosity fluid is idea for lower acceleration. However, higher viscosity fluids could be used for applications that have high accelerations. This novel concept allows for small increases in bandwidth which can be used to cover the 5% manufacturing error, and any small changes of the vibration source. The concept has been validated using water and high viscosity glycerol at low frequency, high acceleration applications. Future work will involve investigating other types of fluids and enhancing the bandwidth by optimizing the mass shape and properties.

Acknowledgements

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