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# Experimental Study on Performance Enhancement of a Piezoelectric Vibration Energy Harvester by applying Self-Resonating Behavior

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**Abstract:** This paper introduces a passive self-tuning energy harvester by applying self-resonating behavior. Under certain operating conditions, self-resonating systems have the capability to passively adjust their dynamical characteristics until the whole system becomes resonant. A clamped-clamped beam with an attached mass sliding freely with a slight gap showed self-resonating behavior. Under a harmonic input excitation and a well-defined operating regime, the mass moved along the beam thus causing a change in the natural frequency of the structure, and then stopped at the position where the natural frequency matched the excitation frequency, resulting in a significant increase in the vibration amplitude. For harvesting energy, a piezoelectric element was glued at one end of the beam. The operating regime of the self-resonating behavior was found experimentally in the two halves of the beam. In the half containing the piezoelectric element, self-resonating behavior was achieved between 126 Hz and 143 Hz. In the other half, it was achieved between 135 Hz and 165 Hz. Maximum power output of 2.5 mW was obtained under an input excitation of $4.92\,m/s^2$ and 148 Hz. It is to be concluded that applying self-resonating behavior on energy harvesting provides a promising broadband technique.

**Keywords:** Passive self-tuning, broadband technique, self-resonating behavior, mass sliding along a beam, piezoelectric energy harvesting

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## Introduction

A typical vibration energy harvester is tuned to one of its eigenfrequencies in order to maximize the harvested power. The vibration in the surrounding environment has variant frequencies, which limits the functionality of the vibration harvester to a narrow bandwidth. (Hajati and Kim 2011) introduced an ultra-wide-bandwidth energy harvester by exploiting the nonlinear stiffness of a doubly clamped resonator. A vibration energy harvester exhibiting nonlinear motion with increased frequency bandwidth, and a multi-mode motion was introduced by Yang et al. (2013) and Lin et al. (2016). Yang et al. (2014) developed a nano-generator to convert acoustic energy into electric energy via triboelectric transduction where an array of devices with varying resonance frequencies was employed.

Many techniques have been proposed to widen the bandwidth and are referred to in literature as broadband techniques for vibration energy harvesting, as reviewed by Twiefel and Westermann (2013). Each of these techniques has its own advantages, disadvantages and limitations on their applicability. One of the most widely-discussed broadband techniques is tuning the resonance frequency of the harvester to match the excitation frequency, either manually, as introduced by Mansour, Arafa, and Megahed (2010), or automatically, as introduced by Zhu et al. (2010). The manual tuning required the existence of an operator. The automatic tuning required energy for frequency sensing and for actuation. This energy was supplied by the harvester itself, as introduced by Hoffmann et al. (2016) or by an external unit as introduced by Aboulfotoh, Arafa, and Megahed (2013). The power consumed for the continuous active tuning mostly exceeded the harvested power.

Under certain operating conditions, self-resonating systems have the capability to passively adjust their dynamical characteristics until the whole system becomes resonant. Boudaoud, Couder, and Amar (1999) introduced a bead sliding freely on a magnetically forced vibrating string which exhibited specific dynamics characterized by the existence of self-adaptive behavior. Within a well-defined frequency band, the mass adjusted its position so that the whole system became resonant. Miller et al. (2013) demonstrated the experimental findings of a self-tuning clamped-clamped beam carrying a sliding mass which was the first demonstration of passive self-tuning in a beam rather than a string. Three different beams, respectively out of aluminum, steel and copper were built. The same sliding mass was used giving three different mass ratios with every beam. The band of frequencies within which the mass adapted was dependent on the ratio between the mass of the slider and the mass of the beam. Another work of experimental findings of a self-tuning resonator was presented by Pillatsch et al. (2013) where it was reported that the crucial points were found at the clamping of the beam and the size of the gap between the slider and the beam. If the gap was too tight, the mass would not move and if it was too large, the mass would start rattling and dissipating energy. Gregg, Pillatsch, and Wright (2014) introduced a passively self-tuning energy harvester through the integration of a piezoelectric patch to the clamped-clamped beam and mass system introduced by Miller et al. (2013). They observed five kinds of behavior depending on the size of the proof mass and the gap size: stable tuning, quasi-stable tuning, unstable tuning, self-damping, and inhibited mass movement. Staaf et al. (2015) introduced a self-tuning piezoelectric harvester with a free-sliding weight for wider bandwidth. As a step towards understanding self-resonating behavior, Krack et al. (2016) introduced a model of an elastic beam under harmonic excitation and an attached sliding body. Contact between the slider and the beam was modeled in terms of the Coulomb and Signorini laws, together with the Newton impact law. A key feature of the proposed model was the gap between the slider and the beam with backlash and frictional contact interactions. Furthermore, the influences of contact friction, gap size and excitation level on self-resonating behavior were investigated. Aboulfotoh et al. (2016) built a self-resonating system of a slider and a clamped-clamped beam. They provided that the operating regime was experimentally detected to be in the middle part of either of the beam's halves.

This paper introduces a self-tuning energy harvester utilizing a sliding mass along a clamped-clamped beam. The self-resonating behavior of the sliding mass is investigated as a broadband technique. The enhanced performance of the proposed self-resonating harvester and its ability to supply power to an external load will be investigated. The operating regime will be found experimentally.

## The Self-Resonating Energy Harvester

The self-resonating energy harvester introduced in this paper consists of a rigid slider attached to a clamped-clamped elastic beam. The beam is fixed on a rigid frame. There is a slight gap that permits the slider to move freely along the beam. To harvest energy, a piezoelectric element is glued at one end of the beam. The structure is mounted on a shaker that provides a harmonic excitation. A schematic diagram of the proposed self-resonating energy harvester is displayed in Figure 1.

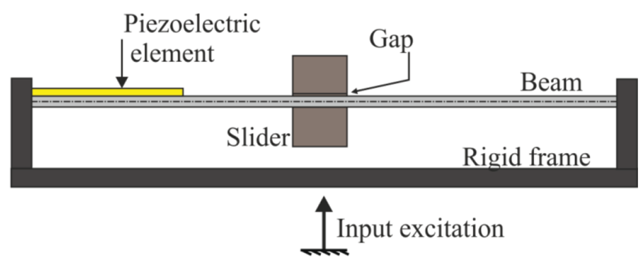


**Figure 1:** A schematic diagram of the self-resonating energy harvester.

## Experimental Setup

Figure 2 displays the experimental setup of the self-resonating energy harvester. The dimensions of the steel beam, the slider and the slot of sliding are mentioned in the order of x, y and z. The beam has a weight of 14.8 g, elasticity of 190 GPa and dimensions of $130 \times 15 \times 1$ mm. The slider has a weight of 30.8 g and dimensions of $10 \times 30 \times 20$ mm with a slot in the middle. The slot has dimensions of $10 \times 15 \times 1$ mms and a gap around 0.1 mm in both y-direction and in z-direction. The gap permits the slider to move freely along the beam. The slider has two symmetrical holes on both sides. Each hole has a diameter of 5 mm and its center line is 5.25 mm away from the center line of the slider. These two holes were used in the beginning of experiments to adjust the gap size between the slider and the beam. After finding the suitable gap size, the two parts of the slider were glued together using Pattex 2k-kleber Stabilit Express. A piezoelectric element of type Macro Fiber Composite (MFC) (Model M-2814-P2) was glued at one end of the beam using UHU PLUS Endfest 300 epoxy. A harmonic excitation is provided by a shaker of type TIRAvib 51110. The input acceleration was measured using an accelerometer of type PCB Piezotronics Model 353B17. A video of the working self-resonating

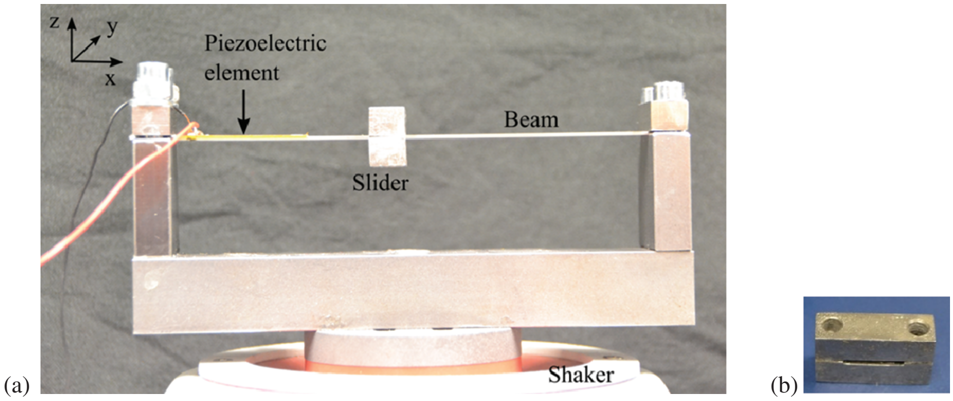


**Figure 2:** Experimental setup of the self-resonating energy harvester (a) whole system (b) slider.

energy harvester can be seen by the following link (Aboulfotoh et al., Video).

## Fundamental Frequency of the Structure

To measure the fundamental frequency of the structure, the slider was fixed on the beam by inserting a very thin plastic sheet of negligible weight into the gap, preventing any axial or rotational motion. The structure was excited at a very low level and with a sweep of frequencies. The fundamental frequency was determined as the one that gave the maximum amplitude of vibration in the frequency range near the first bending mode. The vibrating amplitude was measured at a point in the middle of the beam using the laser vibrometer. The NI Instrument and LabVIEW were used for data acquisition. The position of the slider was considered from its center. The fundamental frequency as a function of the position of the fixed slider is shown in Figure 3. Due to the glued piezoelectric element, the two halves of the beam are no longer symmetric. Thus, the left half of the beam with the piezoelectric element is referred to as the composite half and the right half without the piezoelectric element as the simple half.

## Experimental Results and Analysis

Self-resonating behavior was investigated in both the composite half and the simple half of the beam. It was observed that the slider tended to move in the half, in which it was initially set. The investigations included different initial positions of the slider along the beam,

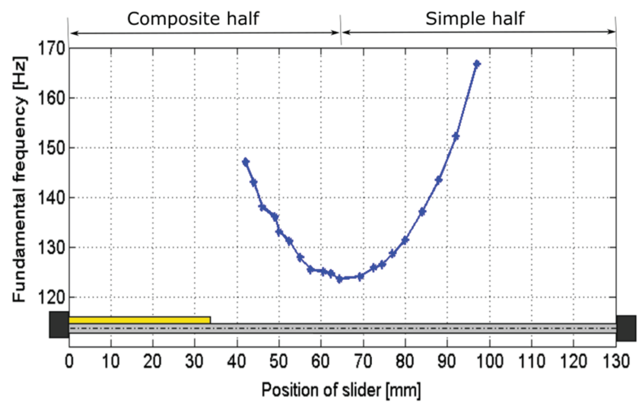


**Figure 3:** Fundamental frequency and the corresponding position of the fixed slider.

various frequency steps and a range of excitation levels. The output voltage was measured using the Digital Phosphor Oscilloscope type DPO4054 Tektronix. A video of the slider motion along the beam was recorded. Then, the position of the slider was traced utilizing the Tracker Video Analysis and Modeling Tool (free software).

### The Composite Half

All distances were measured from the left end of the beam to the center of the slider. The piezoelectric element had a length of 35 mm. Hence, the available distance for the movement of the slider in the composite half was approximately from 41 mm to 60 mm. Through this part, the slider adapted its position from 54.8 mm to 41 mm and successfully achieved and maintained the self-resonating condition for frequencies from 126 Hz to 143 Hz, respectively. Figure 4 shows the self-resonating behavior for range of frequencies between 126 Hz to 136 Hz. The slider position

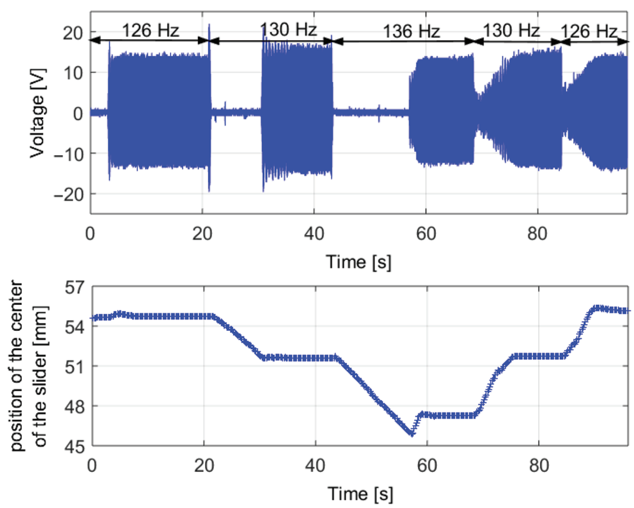


Figure 4: Self-resonating behavior in the composite half.

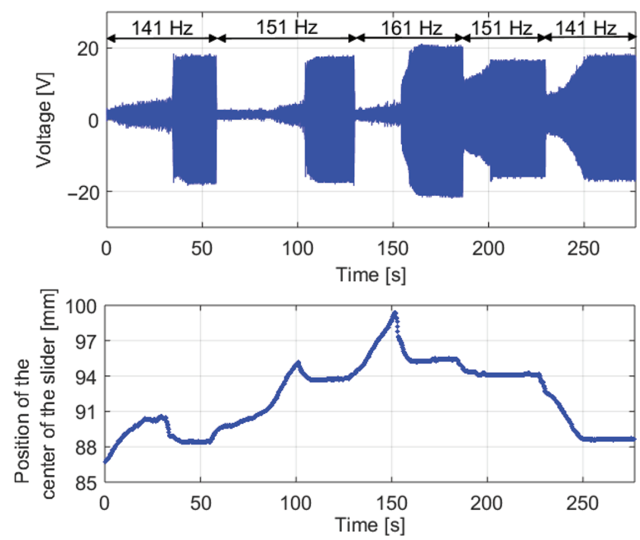


Figure 5: Self-resonating behavior in the simple half.

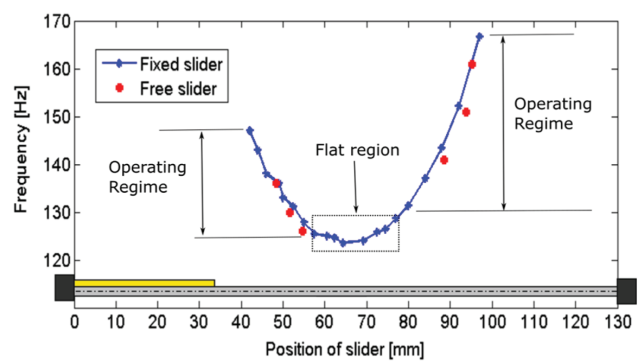


Figure 6: Operating regime along the beam.

was initially set at 54.8 mm. The system was excited by an acceleration of 3.3 $m/s^2$ and a frequency of 126 Hz. The mass remained at approximately the same position and the whole system entered a state of resonance, resulting in a significant magnification in the output voltage. Then, the excitation frequency increased by 4 Hz to be 130 Hz. The slider moved and adapted its position to 51.6 mm, where the resonance condition was reached and maintained. With another increase of 6 Hz, the mass successfully adapted its position to 47.3 mm and achieved the state of resonance of 136 Hz. The excitation frequency decreased to 130 Hz and then to 126 Hz where the mass successfully returned to 47.3 mm and 51.6 mm, respectively.

## The Simple Half

The available distance for the movement of the slider in this half was approximately from 70 mm to 125 mm. Through this part, the slider adapted its position from 82 mm to 96 mm and successfully achieved and maintained a state of resonance for frequencies between 135 and 165 Hz, respectively. Figure 5 shows self-resonating behavior in the simple part for frequencies between 141 Hz and 161 Hz and excitation acceleration of 6.7 $m/s^2$. The sliding mass moved forth and back and consequently achieved and maintained a state of resonance.

Figure 6 shows different excitation frequencies and the corresponding positions of where the free slider moved and achieved a state of resonance, in comparison with Figure 3 which shows the fundamental frequencies and their corresponding positions of the fixed slider. It is to be concluded that the free slider moves to the position whose fundamental frequency equals the excitation frequency. The middle region between the two halves has the lowest fundamental frequencies and the rate of change of fundamental frequency is small with respect to change of position. This region will be referred to as the flat region. If the slider is initially set in the flat region or close to the end of the beam, it does not show self-resonating behavior. This result is compatible with the operating regime detected analytically by Krack et al. (2016).

The ability of the self-resonating harvester to supply power to external loads is investigated here. The slider was initially set in the simple half. A harmonic excitation of 4.92 $m/s^2$ was provided. At 148 Hz and 155 Hz, the slider achieved and maintained the state of resonance at various applied load resistances. The corresponding output voltage was measured. The load resistances were applied using Resistance Box Chauvin Arnoux BR07. The voltage and power are displayed in Figure 7(a) and 7(b), respectively.

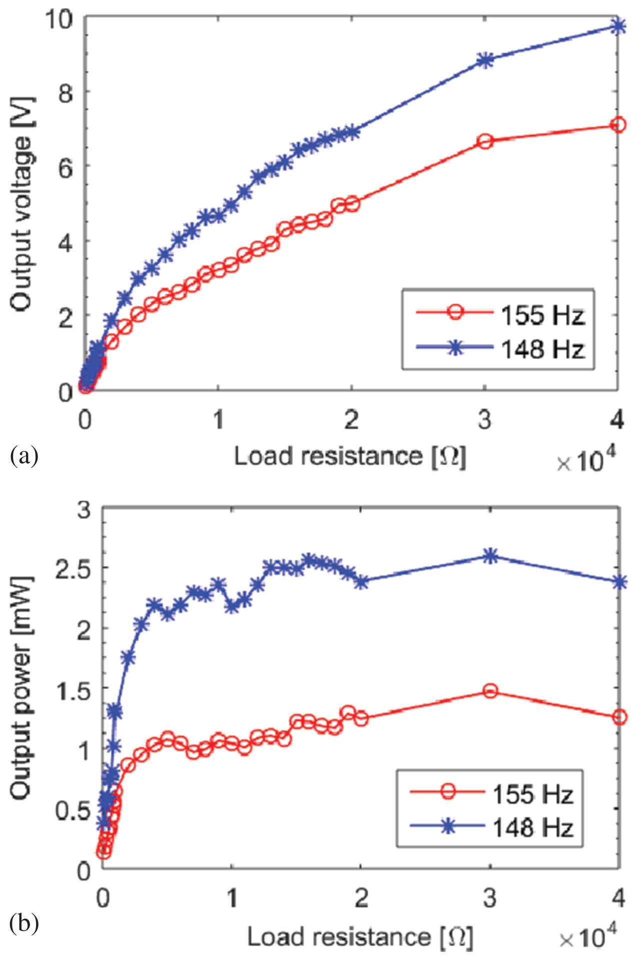


Figure 7: (a) Voltage (b) Power of the self-resonating energy harvester.

## Relatively Small Changes in Excitation Frequency

The change in excitation frequency has a strong influence on self-resonating behavior. If the system is in the resonating condition and the change in the excitation frequency is low, the slider does not move, but the vibrating amplitude increases, as shown in Figure 8. Excitation frequency began at 130 Hz. The slider adapted its position successfully and entered a state of resonance. A small change of 1 Hz in the excitation frequency resulted in an increase in the vibrating amplitude, but the slider stayed at the same position. When excitation frequency reached 134 Hz, the vibrating amplitude dropped and then the slider began moving to achieve a state of resonance of 134 Hz. After the slider achieved the state of resonance at 134 Hz, an increase of 1 Hz in the excitation frequency again caused an increase in the vibrating amplitude while the slider did not move axially.

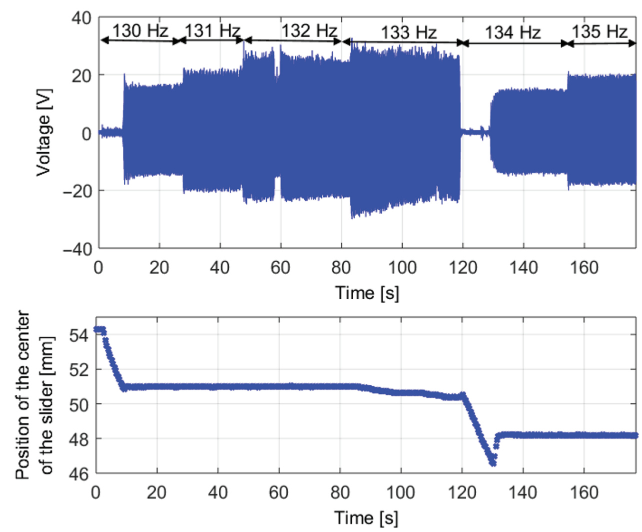


Figure 8: Low change in excitation frequency (1 Hz).

The experiments have shown the high sensitivity of self-resonating behavior to the gap and the friction between the slider and the beam. The excitation level also has a strong influence on the available distance that the slider has the capability to cross and then achieve a state of resonance. If the excitation frequency varies greatly in comparison to the fundamental frequency of the slider's current position, the slider fails to achieve self-resonating behavior. Thus, further investigations are still required.

# Conclusion and Future Work

The self-resonating behavior of a free sliding mass along a clamped-clamped beam is successfully applied to energy harvesting. Within a large bandwidth of excitation frequencies, ranging from 135 Hz to 165 Hz, the slider moves to the position whose fundamental frequency equals the excitation frequency. The slider achieves and maintains the self-resonating behavior, resulting in a significant increase in the vibrating amplitude and hence the output voltage. This provides a promising technique for broadband energy harvesting. The operating regime was experimentally detected for both halves of the beam. The experiments showed the high sensitivity of self-resonating behavior to the size of the gap, friction, excitation level and change in excitation frequency. Thus, our future work will concentrate on studying the dependence of the self-resonating behavior on various operating conditions.

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