Passively Self-Tuning Piezoelectric Energy Harvesting System

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Abstract. Real world systems that are candidates for vibrational energy harvesting rarely vibrate
at a single frequency, nor are these frequencies constant over time. This necessitates that
vibration harvesters operate over a wide bandwidth or tune their resonance. Most tunable devices
require additional energy or active control to achieve resonance over various frequencies. This
work presents a passively self-tuning energy harvester that autonomously adapts its resonant
frequency to the input without requiring additional energy. The system consists of a clamped-
clamped beam, a movable proof mass, and a piezoelectric patch bonded to the underside of the
beam. It demonstrated an open-circuit voltage output of 668 mVrms at 160Hz, 0.65g input
excitation. Discrepancies between displacement and voltage magnification factors upon tuning
at higher frequencies are discussed, as well as instabilities of the system and sensitivity to proof
mass characteristics.

1. Introduction
Energy harvesting is an important topic for the realization of ubiquitous wireless sensing and condition
monitoring. Vibrational energy harvesting is attractive due to the abundance of ambient vibrations from
machinery in manufacturing environments, but practical realization has been limited by the lack of
broadband solutions. Dominant frequencies of real-world machinery are rarely known in advance and
can shift with time, rendering traditional resonant harvesters impractical. Multiple approaches have been
suggested for the active adjustment of resonant tuners [1-2], but most solutions require that some of
the power generated be used for tuning. Ideal solutions should adjust their resonant frequency without
additional energy input (passively) and without user intervention (autonomously).

Various self-tuning mechanisms are discussed in literature [3-6], including a string loaded with a
moveable bead [4-6], a mass in a tube [6], and the beam with moveable mass system used in this work
[3]. Previously, [3] demonstrated the ability of a fixed-fixed beam and moveable proof mass system to
exhibit self-tuning behavior. This work represents the first time the system in [3] has been utilized to
make an operational energy harvesting device through the integration of piezoelectric materials. It also
discusses the practical challenges of the system that have inhibited detailed system characterization and
need to be overcome for real-world implementation.

2. Experimental Setup
A clamped-clamped beryllium-copper beam was fitted with a free-sliding proof mass (Figure 1-2) and
mounted to a shaker. The proof mass was a 3D printed ABS bead with a screw that was used to adjust
the size of the gap between the underside of the beam and the bead (Figure 3). A 3mm by 6mm single
layer PZT piezoelectric element was soldered onto the underside of the beam near a clamping point (Figure 4) to exploit the maximum bending point of the beam and to avoid interference with the movement of the proof mass. The capacitance of this element was measured at 2.1 nF. A shaker was used to excite the system with a given input frequency, causing the mass to move (autonomously) along the beam until the system reached resonance. The displacement of the beam center and the input acceleration were recorded with a laser displacement sensor and accelerometer respectively. The open-circuit voltage output of the piezoelectric patch was also recorded.

Investigations into the stability of the system consisted of the same clamped-clamped beryllium-copper beam with proof mass, but without the piezoelectric element.

3. Results
Figure 5 shows an example of self-tuning with an input frequency of 160 Hz and 0.65 g RMS acceleration. The proof mass was originally positioned near the center of the beam. When excitation was applied from the shaker, it moved outward (autonomously) from the center until the system achieved resonance. The self-tuning phenomenon is clearly identifiable by the simultaneous and sudden increase in output voltage.
in the level of both mid-point beam displacement and open-circuit voltage output of the piezoelectric patch once resonance was achieved. Voltage output at 160 Hz was 668 mVrms. At the same excitation, power output was 0.33 µW when connected to a 470 kΩ impedance-matched resistive load.

Figure 6 shows the relationship between open-circuit voltage and displacement magnification factors and frequency. Figure 7 shows the RMS voltage and displacement vs. frequency. All measurements were made at constant input excitation. It is hypothesized that the discrepancies between voltage and displacement magnification factors in Figure 6 at higher frequencies are due to the changing resonant positions of the proof mass along the beam at different frequencies. The different stable positions of the proof mass affect the shape of the first vibration mode and thus the beam deflection shapes and bending moments at the clamp points. Thus, it is thought that the stresses on the piezoelectric material (and output) are altered, while center beam displacement is less affected. Experimental verification of this hypothesis is necessary. At this stage, it is not fully understood why the voltage and displacement experience a drop at 164 Hz (Figure 7) and it will be cause for further investigation.

Characterization of the effects of system parameters on voltage output and beam displacement revealed inconsistencies and instabilities of the system. The system is very sensitive to the characteristics
of the proof mass, especially the size of the gap between the tip of the adjustment screw and the underside of the beam and mass. Adjustments on the order of fractions of a millimeter can change the behavior of the system. Such dependence on gap size was observed in similar self-tuning systems in literature [4]. Additionally, different gap sizes seem to be optimal only for certain combinations of mass and input acceleration.

Five distinct cases of behavior were observed: stable tuning, quasi-stable tuning, unstable tuning, damping, and inhibited motion. As shown before, Figure 5 is an example of stable tuning, where the mass moved to cause the system to enter and stay in a state of stable resonance. Figure 8 illustrates the quasi-stable tuning case, where though tuning behavior was observed, the mass would oscillate in and out of resonance about the tuned point. An example of unstable tuning is illustrated in Figure 9. If the gap size was not small enough, the mass would not remain tuned but rattle through its resonant point to the end of the beam. Alternatively, mass with a gap size that was too large could also exhibit self-damping behavior, as seen in Figure 10. Figure 11 shows the frequency dependence of the magnification factor for the same proof mass properties that yielded the case seen in Figure 10. Magnification factors below 1 confirm damping behavior and demonstrate damping over a large frequency range. Which of these behaviors, unstable tuning or self-damping, would occur when the gap was too loose is suspected to be a function of the mass, though more characterization is necessary to confirm. If the gap was too small, the motion of the mass was inhibited and no tuning behavior was observed. Further characterization would be aided by a redesign of the proof mass to include better control of gap size for better reproducibility.

**Figure 8.** Example displacement plot of a case when the system displayed self-tuning behavior, yet the tuned position of the mass was unstable, oscillating in and out of resonance.

**Figure 9.** Example displacement plot of a case when the proof mass initially achieved resonance, but continued to move through the resonant point to the end of the beam, failing to achieve stability.
Figure 10. Example displacement plot of a case when the proof mass was ‘loose’ (large gap size) and exhibited self-damping behavior. The difference between damped and un-damped displacement is less in this case due to a lighter proof mass.

Figure 11. Magnification factor vs. frequency plot demonstrating the self-damping phenomenon across multiple frequencies.

4. Conclusions
This paper presents a passively self-tuning energy harvesting system. The integration of a small piezoelectric patch on the clamped-clamped beam and mass system displayed self-tuning behavior and yielded an open-circuit voltage of 668 mVrms at 160 Hz, 0.65 g excitation. Discrepancies between the magnification factors for the voltage and displacement were observed at higher frequencies (corresponding to proof mass tuning positions further from the center). These are suspected to result from the changing of the first vibration mode shape. The moving position of the proof mass alters the bending moments at the clamp points. However, experimental verification is needed.

This paper also discusses the practical challenges and instabilities associated with the system. The system behavior was strongly dependent on the characteristics (mass, gap size) of the moveable bead. Five distinct behavior cases were observed depending on the proof mass gap size: stable tuning, quasi-stable tuning, unstable tuning, self-damping, and inhibited mass movement. Previous publications alluded to such sensitivities [4-6], but rarely specified mass gap size as a sensitive parameter. Further characterization will focus on understanding the effect of gap size and proof mass on the system.

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