Passively-Switched, Non-Contact Energy Harvester for Broad Operational Range and Enhanced Durability

William Z Zhu¹ and Carol Livermore¹

¹ Department of Mechanical and Industrial Engineering, Northeastern University, Boston, MA 02115 USA

E-mail: zhu.wi@husky.neu.edu, livermore@neu.edu

Abstract. Impact-based vibrational energy harvesters that switch passively among dynamical modes to best match the ambient conditions and perform frequency up-conversion to maximize power output can increase the operational range over which harvesters output useful power. The disadvantage of impact-based harvesting is that it can lead to premature system failure. This paper presents modelling and experimental validation of a harvester with passively-switched dynamics in which a magnetic non-contact interaction replaces the impact-based interaction of previous systems for greater robustness. A low-frequency driving beam couples to a higher-frequency generating beam via tip magnets. Simulations predict that the non-contact interaction drives a diversity of dynamical modes in which the tip of the driving beam variously is repelled from and passes the tip of generating beam. Experiments validate the predicted dynamical behaviour of the system. Output power levels are similar to predictions, with a power of 903 µW on the primary resonance at 1 g acceleration.

1. Introduction

Vibrational energy harvesting can increase the operation time of wireless sensors by converting mechanical energy from ambient accelerations into electric power [1]. One challenge of vibrational energy harvesting is the balance between resonant operation (for increased output power) and wide bandwidth (for increased operational range). Solutions to this challenge include nonlinear harvesting [2] and both active and passive tuning of harvesters’ resonance frequencies, for example as in [3, 4].

For human-powered systems, a second challenge lies in capturing the low frequency excitations that are typical of human motion while maintaining sufficient power output. It is possible to address both challenges by using separate but interacting driving and generating elements that couple into low frequencies and output power at high frequencies, respectively. Such systems may be driven by mechanical impact or non-contact means, for example as in [5, 6]. An important design consideration for such systems is robustness; large amplitude motions must not harm either the driving or the generating elements.

One example of a wide-bandwidth harvester that converts low frequency excitations into higher frequency motions of the generating element is in [7]. In [7], a driving beam and a generating beam that overlap only at their tips can interact in a few different dynamical modes, each of which has its own characteristic frequency. The harvester passively switches among modes in response to changes in ambient conditions, and impact between the beams up-converts the low ambient frequency to a
higher generating frequency. However, because the beams interact via impact, the generating beam is expected to break when the driving beam undergoes very large amplitude motions.

This paper presents modelling and experimental demonstration of a new kind of passively-switched harvester in which the inter-beam contact interaction of [7] is replaced by a magnetic non-contact interaction for greater durability. Despite the non-contact interaction, the system is still designed to switch passively among dynamical modes in response to changing ambient conditions. The low-frequency driving beam and the higher frequency piezoelectric bending actuator (the generating beam) are arranged in a facing configuration. Permanent magnets on the tips of the beams repel each other, so that deflection of the driving beam induces deflection in the generating beam.

One of the primary dynamical modes of [7] occurs when the tip of the driving beam passes from above the tip of the generating beam to below the tip of the generating beam and back. In [7], these passing dynamics are described as the driving beam ‘plucking’ the generating beam. Unlike the case of [7], here the magnetic interaction drives the generating beam to deflect away from the driving beam first before the tips pass, and again after the tips pass, potentially increasing the strength of the plucking. The second main dynamical mode of [7] occurs when the driving beam interacts with the generating beam, but the driving beam does not pass the generating beam and always remains on the same side of it (e.g. above the generating beam). These modes of motion can have different characteristic frequencies, thereby broadening the bandwidth. One goal of the present research is to characterize the role of these passing and non-passing modes of operation in the non-contact system.

2. Modelling and simulation

Figure 1(a) shows the passively switched, non-contact magnetic harvester modeled as a single degree of freedom lumped parameter system. The model includes the mass, stiffness, and damping of each beam, as well as the external vibration. The magnetic force is represented as a nonlinear stiffness. Power extraction from the generating beam is modeled as electrical damping and is included in the total damping of the generating beam. Although damping is not an exact description of piezoelectric energy conversion, it provides a rapid simulation tool for investigating the system’s dynamics.

The equation for the harvester’s equivalent 1D lumped parameter system is

$$[m\ddot{x} + c\dot{x} + kx]_{D,G} = F(t) + F_m(x_D, x_G),$$  \hspace{1cm} (1)

where $m$, $c$, and $k$ are the mass, damping, and stiffness of the beam, and the subscripts $D$ and $G$ denote either the driving or generating beam. The total damping term for the generating beam, $c_G$, accounts for both viscous damping and electrical extraction from the PZT to a load. Modelling electrical extraction as damping is described in [8]. The function $F_m(x_D, x_G)$ denotes the magnetic force between the driving and generating beams as a function of the deflection of the beams in the x direction. A full analytic equation of magnetic force between two non-identical permanent magnets would require
resource-intensive calculations. Instead, the magnetic force is approximated using a least squares method as in [9]. The least squares approximation is

\[ F_m(x_D, x_G) = \alpha_{DG} \frac{d_{DG}^2 (x_D - x_G + y_{DG})}{\sqrt{d_{DG}^2 (x_D - x_G + y_{DG})^2}} \]  

(2)

where \( d_{DG} \) and \( y_{DG} \) are the horizontal and vertical separations between the tip magnets at rest and \( \alpha_{DG} \) is the magnetic force at that horizontal separation. The values used for \( \alpha_{DG} \) are found in [10].

The harvester’s dynamics are integrated using the Runge-Kutta method in MATLAB (ode45). The simulation calculates parameters for failure detection due to over deflection of the PZT beam as well as voltage, power, and converted energy over time. Table 1 lists the parameters used in the simulation.

| Table 1: List of parameters for model |
|--------------------------------------|
| **Driving Beam** | **Generating Beam** |
| Material | ABS plastic | PZT-5A |
| Mass m (g) | 9.6 | 0.217 |
| Total Damping Coefficient (c) | 0.0300 | 0.0235 |
| Stiffness k (Nm\(^{-1}\)) | 14.1 | 445 |
| Capacitance C (nF) | N/A | 3.5 |

**Figure 2.** Predicted dynamic map of the system  
**Figure 3.** Predicted average power map

Figure 2 shows the predicted dynamics map of the harvester. Two types of passing dynamics are observed, referred to here as switched and plucked dynamics. In plucked dynamics, the driving beam passes the generating beam, leaving the generating beam free to ring down and generate power. In switched dynamics, the driving beam passes the generating beam but remains so close to the generating beam after passing that its magnetic force impedes the free ring-down of the generating beam, limiting the output power. Two types of non-passing dynamics are observed, referred to here as following and coupled dynamics. In coupled dynamics, the driving beam is repelled by the magnetic force so that it appears to “bounce off” of the generating beam without actually touching it. After the driving beam moves away, the generating beam undergoes free ring-down. In following dynamics, the driving beam is again repelled by the magnetic force, but it never moves away far enough for the generating beam to undergo a free ring-down. In some regions, passing (typically plucked) and non-passing (typically coupled) dynamics are interleaved in a beat pattern (also shown in figure 2). Passing dynamics occur around the primary and secondary resonances and/or at high accelerations, whereas non-passing dynamics occur around the secondary resonance, off resonance, and/or at low
accelerations. Figure 3 shows the predicted power vs driving acceleration and driving frequency, with substantial power contributions at the secondary resonance. Powers of greater than 100 µW are typically produced in regions where passing dynamics are exhibited. The peak power shifts from 6 Hz to 7 Hz as the driving acceleration is increased. Figure 4 plots the predicted average power vs driving frequency for driving accelerations of 0.5g, 1.0g, 1.5g, and 2.0g. A single power peak is observed at 0.5g but broadens at higher accelerations to a pronounced two-peak structure with significant power output at both the primary and secondary resonances.

![Figure 4. Predicted average power vs driving acceleration for driving accelerations of 0.5g, 1.0g, 1.5g, and 2.0g.](image)

3. Experiments

Figure 5 shows the experimental setup of the system. The harvester base is made from 3D printed plastic (fused deposited polylactide resin). Attached to the base is an accelerometer (Analog Devices model ADXL 203EB). The harvester is driven by a closed loop feedback shaker table (Labworks Inc., model ET-139). A 10 g proof mass and a 4.76 mm diameter, 0.79 mm thick N52 grade neodymium magnet are mounted at the tip of an acrylonitrile butadiene styrene plastic driving beam so that the magnetization direction is parallel to the neutral axis of the driving beam. The generating beam is a 31.75 mm long, 3.175 mm wide, 0.51 mm thick, two layer, brass reinforced, series poled PSI-5A4E bending actuator (Piezo Systems, INC. T220-A4-103X) with a tip-mounted 3.175 mm square, 1.59
mm thick N42 grade neodymium magnet. The generating beam is connected to an impedance matched load resistor, and the acceleration and the voltage across the load are recorded. The average power is calculated by numerically integrating instantaneous power over time and normalizing by time.

Figure 6 maps the observed dynamics. Driving frequencies of 5 Hz and below and high accelerations at 6 Hz and 7 Hz were omitted due to technical limitations of the test platform. However, the system itself is successfully operated at all other frequencies and accelerations, including at high accelerations on resonance. This is in contrast to the system of [7], in which the potential for damage upon impact limited the harvester’s safe operational range. The experiments show similar dynamics to the predictions of figure 2. The robust two-peak structure observed of figure 3 is shifted to slightly lower frequencies than in the simulations, reflecting the effects of fabrication variations. Plucked and beat pattern dynamics are observed over a greater frequency range, and switched dynamics are not observed. These results indicate that the real system undergoes energetic plucking and beat pattern dynamics more readily than the simulated system. The discrepancy reflects the limitations of the approximations used in the simulation, in particular the simulation’s approximation of the dynamics as one-dimensional rather than two-dimensional.

Figure 7 plots the measured and predicted average power vs driving frequency for a driving acceleration of 1.0 g. The measured amplitude of the peak output power (903 µW) is similar to but somewhat exceeds the predicted amplitude (486 µW). The measured and simulated half-power bandwidths cannot be directly compared because the driving beam impacts the harvester base on resonance, reducing the output power. The measured range at 1.0 g does not encompass the secondary resonance at which following dynamics give way to higher power output dynamics, so the anticipated secondary power peaks are not visible.

4. Conclusion
The present simulations and experiments demonstrate that a magnetically-interacting, non-contact harvester can switch passively among dynamical modes to adapt to changing ambient vibrational conditions. Unlike the case of [7], in which the highest amplitude regions of the operational range had to be avoided to prevent breakage, the present harvester is able to operate at large accelerations on resonance without damage. Measured and predicted powers are similar, with a measured power of 903 µW on the primary resonance at 1 g acceleration.

References
[1] Harne R L and Wang K W 2013 Smart Mat. and Struct. 22(2) 023001
[2] Cammarano A, Neild S A, Burrow S G and Inman D J 2014 Smart Mat. and Struct. 23(5) 055019
  Zhu D, Tudor M J and Beeby S P 2010 Meas. Sci. and Tech. 21(2) 022001
[3] Eichhorn C, Goldschmidtboeing F and Woias P 2009 J. of Micromech. and Microeng. 19(9) 094006
[4] Liu T and Livemore C 2012 Proc. of PowerMEMS 2012 pp. 492-495
[5] Gu L and Livermore C 2011 Smart Mat. and Struct. 20(4) 045004
[6] Kulah H and Najafi K 2008 Sens. J. IEEE 8(3) 261-268
[7] Liu T, St Pierre R and Livermore C 2014 Smart Mat. and Struct. 23(9) 095045.
[8] Inman D J and Erturk A. 2011 Piezoelectric Energy Harvesting Modelling and Application (NJ, USA: John Wiley & Sons) pp 68-73
  Wang Q-M, Xiao hong D, Xu B and Cross L E 1999 J. of App. Phys. 85(3) 1702-1712
[9] Al-Ashtari W, Hunstig M, Hemsel T and Sextro W 2012 Smart Mat. and Struct. 21(3) 035019
[10] Zhu W Z 2015 M.Sc. thesis (Northeastern University)