A Bistable Vibration Energy Harvester with Synchronized Extraction and Improved Broadband Operation through Self-Propelled Feedback

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ABSTRACT

We have earlier presented a piezoelectric cantlever-based vibration energy harvester, which uses bistability from magnetic repulsion, and synchronized extraction circuits, to increase the harvested energy and the frequency range of operation. However, small amplitude excitations may not be able to overcome the magnetic repulsion, causing the cantilever to vibrate around one of the bistable positions with reduced amplitude. In this work, we present a mechanical method to increase the excitation amplitude range over which the harvester operation remains bistable, by spring-loading one of the previously fixed-position magnet creating the repulsive force, such that it can only move linearly, towards and away from the cantilever. As a result, as the magnet on the cantilever tip moves towards the spring-loaded magnet, the latter is pushed away, increasing the distance, hence reducing repulsion, and vice-versa. Thus, a sort of negative feedback is introduced, favoring bistable operation over larger excitation ranges.

Keywords: Energy harvesting, nonlinear systems, piezoelectric transducer, switched circuits.

1 INTRODUCTION

Harvesting vibration energy requires a transduction mechanism to convert mechanical energy into electrical form [1]. The three most common transducers for vibration energy harvesting are electromagnetic, electrostatic and piezoelectric. Electromagnetic transducers utilize relative velocity between a coil and a magnet for transduction [2], while electrostatic ones utilize relative displacement between conduction plates [3]. Piezoelectric transducers make use of active materials [4], which develop electric charges in response to applied mechanical stress. For our research, we concentrate on piezoelectric transducers, which lend themselves to simple implementations, microengineering, and a variety of material choices.

Piezoelectric-based harvesters may be either linear or nonlinear. Linear harvesters are efficient only at their resonant frequencies. In order to maximize the energy transduced from broadband ambient vibrations, we have considered nonlinear harvesters. In [5, 6], we had presented an accurate model for a nonlinear bistable harvester based on the standard Butterworth van Dyke piezoelectric model, combined nonlinear harvesting with synchronized energy extraction circuits, and developed a prototype with extensive simulated/experimental results. The present work extends our earlier work by presenting a completely mechanical way of increasing the bistable range of operation of the harvester, thus increasing efficiency, with close to zero energy cost.

2 BROADBAND BISTABLE HARVESTER

For harvesting applications where energy might be distributed over a spectrum of frequencies, such as ambient vibrations, for example those from thunder or structural vibrations, broadband harvesting is needed in contrast to linear resonant harvesting, which is efficient only at a single frequency. Nonlinear systems have been used as broadband harvesters [7, 8]; a bistable system with two equilibrium positions is one such implementation.

In [5, 6], based on [9], we realized the bistable system with a cantilever and two permanent magnets (PMs) with the same polarities facing each other, one at the cantilever tip, and the other fixed in the same plane as the cantilever (see Fig. 1 for an implementation and Fig. 2 for its illustration).

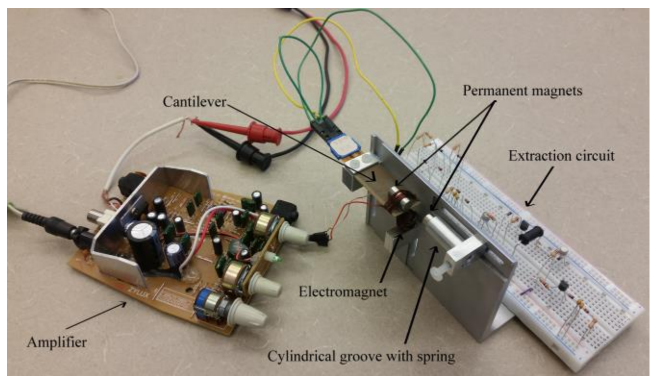

Fig. 1: Bistable harvester and self-propelled tuner.

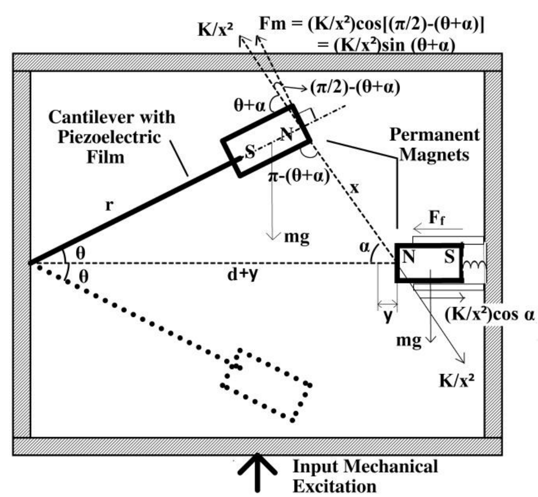

Fig. 2: Bistable harvester with spring-loaded magnet.

 TechConnect Briefs 2017, TechConnect.org, ISBN 978-0-9975117-9-6

Due to the repulsive force between the magnets, the cantilever bends away from the horizontal axis, in essence shifting its equilibrium position from horizontal. The shift can occur either above or below the horizontal axis, presenting two equilibrium states, symmetric to the horizontal axis. Configured this way, for large excitations, the cantilever is able to snap back and forth between the two equilibrium positions. This effectively increases the vibration amplitude and velocity for the same input excitation, hence the voltage and power outputs, as compared to the linear operation [9]. We demonstrated a gain of up to 30% in the vibration amplitude and open circuit piezoelectric voltage compared to the linear (monostable) operation [5, 6, 21]. A mathematical model that we derived is also reported in [5, 6, 21] and predict the same behaviors.

3 EXTENSION OF BROADBAND RANGE

The bistable harvester presented above gives improved performance over a linear harvester whenever it operates in the bistable mode, regardless of the excitation frequency. This requires the external vibration applied to be large enough so as to overcome the repulsive magnetic force. Otherwise, when the input excitation is below the magnetic repulsive force, the harvester vibrates in the monostable mode at one of its stable equilibrium positions, in which case the efficiency can be worse than a linear harvester due to the interference from the magnetic force to the excitation force. In order to ensure that the harvester remains in the bistable mode over a wider range of input amplitudes, we envision that the magnetic force be changed adaptively: it be decreased with decreasing input vibration, thus lowering the magnetic force to be overcome, and be increased with increase in input vibration, thus improving efficiency through increased vibration amplitude and velocity.

Here we propose a completely mechanical way of adaptively tuning the distance between the PMs, with close to zero energy cost, by spring-loading the previously fixed PM and restricting its motion in linear horizontal domain by placing it inside a cylindrical sleeve, as shown in Fig. 2. As the cantilever moves towards the horizontal position, the PM on spring is pushed inwards due to the compression of the spring caused by the repulsive force, increasing the distance between the magnets, and thereby reducing the magnetic force. As the cantilever moves away, the repulsive force decreases, and the spring relaxes, pushing the PM closer to the cantilever thereby increasing the magnetic force. Thus the spring-loading provides for a type of negative feedback, altering the distance between the PMs in a way that increases in the range of bistable operation.

The Butterworth van Dyke (BVD) model for piezoelectric materials [10, 11], shown in Fig. 3, was used in [5, 6] to model the bistable harvester, with the primary side modeling the mechanical behavior and the secondary side the electrical one. The mechanical side acts as a second-order mass-spring-damper system, with an electrical analog of a inductor-capacitor-resistor system, where inductance M_m equals the mass, capacitance $C_m=1/k$ is the mechanical compliance (the inverse of the lumped stiffness constant k), and resistor R_m equals the mechanical damping. On the other hand, the electrical side is a capacitive load C_e (where charge is developed) with resistive load R_e (where dielectric losses occur). Forces are represented by voltages and velocities by currents. Energy is transferred from one domain to another through a transformer with transduction ratio $\rho = d_{eff}.k$, where d_{eff} is the piezoelectric strain constant.

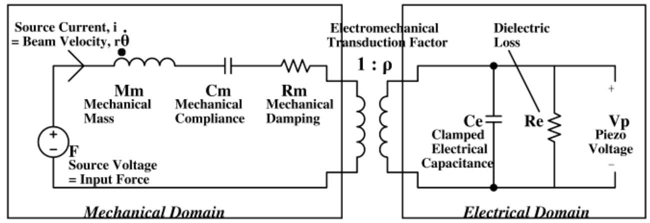

Fig. 3: Butterworth van Dyke model.

We use the BVD model to represent the spring-loaded magnet structure as well, where the input force F is a sum of the externally applied vibration, the adaptively changing nonlinear magnetic force, and the force due to gravity. The velocity $i=rd\theta/dt$ is the product of the cantilever length r and the angular velocity.

4 POWER EXTRACTION

The introduction of bistability and the spring-loaded magnet makes the electric energy source nonlinear, and thus requires nonlinear extraction schemes for efficient harvesting [12-15]. The extraction circuits used in our work have been detailed in [5, 6], and briefly discussed here. Since the extracted energy is required to charge a battery, all circuits analyzed have a battery as the load. Also, since the ambient vibrations are alternating in nature, the transducer output is also alternating, necessitating the use of a rectification step to be able to charge a dc battery load.

4.1 Standard Extraction Circuit

The standard extraction circuit of Fig. 4 uses simply a rectifier [12, 14]. As the cantilever vibrates, the charge on C_e builds up to a voltage V_p. As V_p rises above V_b by two diode drops V_D, the diodes conduct, charging the battery.

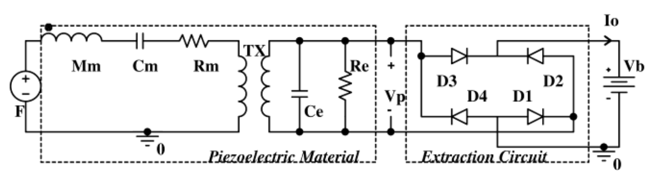

Fig. 4: Standard energy extraction circuit.

4.2 Synchronous Charge Extraction

For the Synchronous Charge Extraction (SCE) circuit of Fig. 5 [12, 14], we make use of the electronic breaker circuit [13, 16] to implement a self-propelled, low-power switch that triggers at displacement extrema [5, 6]. The switch remains open normally while electrostatic energy builds up on C_e as the piezo-cantilever moves from zero displacement to one of the extrema. At the displacement extrema, the switch is automatically closed, transferring the energy stored in C_e to the coupled inductor as magnetic energy, and consequently, through the diode to the battery.

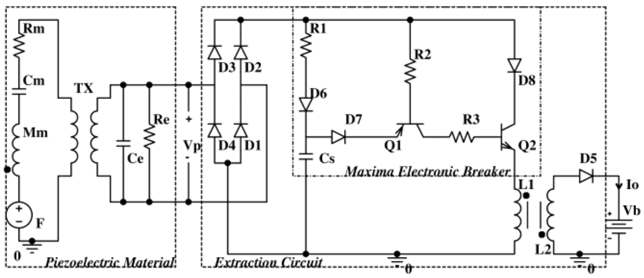

Fig. 5: SCE circuit with electronic breaker circuit.

4.3 Parallel Synchronized Switch Harvesting on Inductor

In the parallel Synchronized Switch Harvesting on Inductor (SSHI) circuit of Fig. 6 [12, 14], we use the electronic breaker again to implement the switch [5, 6]. It remains open normally, and the battery charges while V_p is greater than V_b. At a displacement extremum, the switch is closed to form an L-C_e oscillator, for half the L-C_e time-period to let the voltage on C_e, clamped at V_b due to the battery, invert in polarity through the inductor L, during which the battery is not charged. The polarity reversal allows for greater charging period in one vibration cycle.

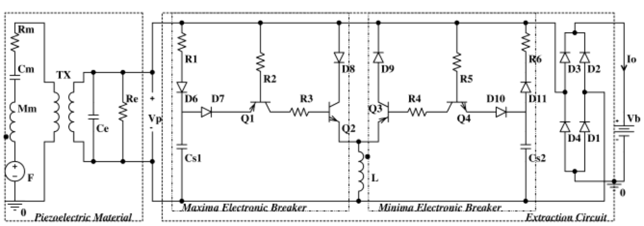

Fig. 6: SSHI with maxima/minima electronic breakers.

5 RESULTS

To validate our design ideas and models, we prototyped our harvester, shown in Fig. 1. It uses the piezoelectric cantilever Volture V21B by Midé [17], of dimensions 69.1 mm x 16.8 mm x 0.64 mm (piezoelectric dimensions 35.56 mm x 14.48 mm x 0.2 mm).The spring-loaded magnet systems with different spring constants k_{sp} were tested with the extraction circuits of Section 4 with a battery load. For each circuit, for the range of excitations considered, the spring-loaded magnet systems not only led to increased bistable range of operation, but comparable or higher power outputs. For example, at 90Hz excitation, considering the spring with spring constant $k_{sp}=1e4$ N/m in Fig. 7 showing harvester outputs with SCE circuit, we get a lower cutoff for bistable activation by about 40 mV (a 33% reduction), and almost a 100 times increase in power output at 250 mV excitation than that for the fixed magnet system, thus establishing a proof-of-concept for our design. Similar plots for standard and SSHI circuits are shown in Figs. 8 and 9.

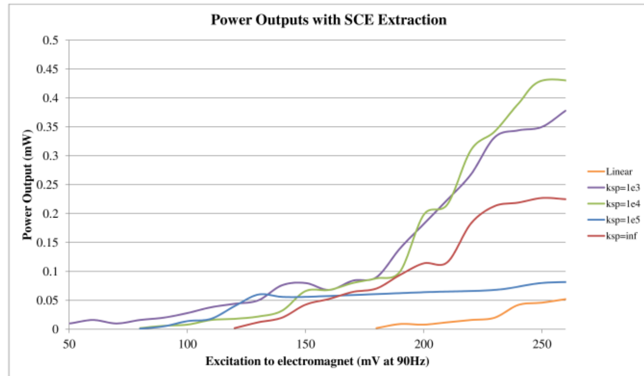

Fig. 7: Spring-loaded SCE system outputs at 90Hz.

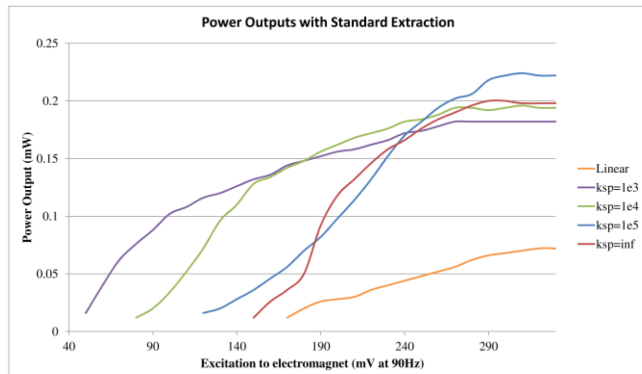

Fig. 8: Spring-loaded standard system outputs at 90Hz.

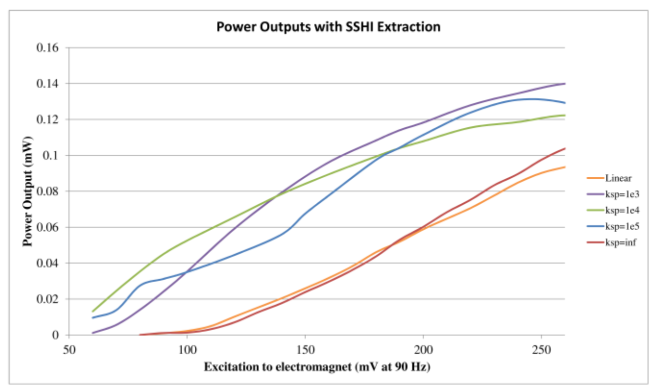

Fig. 9: Spring-loaded SSHI system outputs at 90Hz.

Similarly, for a broadband excitation using a multitone signal with frequencies varying from 1 to 95 Hz at 1 Hz intervals, for $k_{sp}=1e5$ *N/m* in Fig. 10 with an SSHI circuit, we get over 20% increase in power output at higher excitation levels over the fixed magnet system, and lowering the cutoff for excitation by about 60 mV (a 60% percent reduction in the lower cutoff).

6 CONCLUSION AND APPLICATIONS

This paper presented a completely mechanical way of adjusting the distance between the magnets of a bistable piezoelectric vibration energy harvester, thus adjusting the magnetic force of repulsion between them, in response to the applied excitation, so as to increase the bistable range of operation of the harvester. Spring-loading the previously fixed magnet introduces implicitly a negative feedback: as the magnet at the tip of cantilever approaches the spring-loaded magnet, the spring compresses, increasing the distance between the magnets, and conversely. This modification leads to increased input amplitude range of bistable operation as well as increased power output levels.

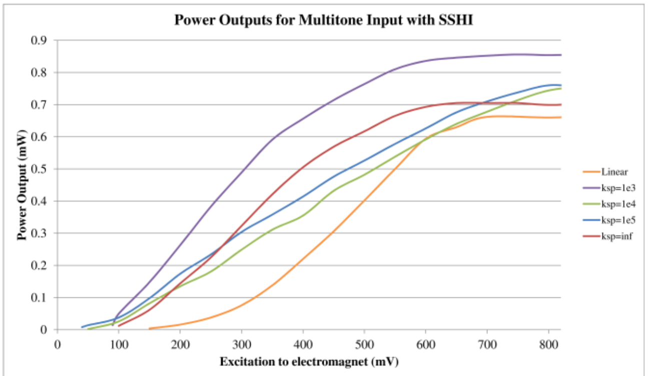

Fig. 10: Spring-loaded SSHI system outputs for multitone.

It is to be noted that depending on the range of input amplitudes of the application, a spring-loaded system with an appropriate value of spring constant may be chosen so that the activation of the bistable mode can occur at the lowest excitation. Also, we note that this work has been presented as a proof of concept, and the various parameters could be adjusted to customize the energy harvester according to the specifications of a desired application.

6.1 Practical Applications

The energy harvester could be customized for various applications, including structural health monitoring sensors like bridge sensors [18, 19], condition monitoring for equipment like electromechanical machines and vechicles, human motion such as body-wearable devices [20], and so on. For example, as discussed in our work in [21], a typical bridge sensor presented in [18] operating for an hour a day would consume on average about 3.68 mW. Typical bridge vibrations have low accelerations (0.1-1 m/s^2) over low frequencies (1-40 Hz) [19]. The harvester presented here can be customized for this application to power such bridge sensors; in [21], we report extracting 30% of the required power from our harvester using similar excitations. For more details of the invention, please visit:
http://isurftech.technologypublisher.com/technology/19689

ACKNOWLEDGEMENTS

This work was supported in part by the National Science Foundation under the grants CCF-1331390 and IIP-1602089, and a Regents Innovation Fund at the Iowa State University.

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