Resonant Frequency Tunable Vibration Energy Harvesting Device

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ABSTRACT

Vibration energy harvesting is an attractive technique for the potential powering of wireless sensors and low power devices. While the technique can be employed to harvest energy from ambient vibrations and vibrating structures, a general requirement independent of the mechanical to electrical energy transfer mechanism is that the vibration energy harvesting device operate in resonance at the excitation frequency. However, many of the energy harvesting devices developed to date are designed based on a single resonance frequency, thereby hindering their commercial emergence. To address this limitation, in this paper the design and testing of a resonance frequency tunable energy harvesting device using magnetic forces is presented. Attractive and repulsive magnetic forces are used to tune the device to resonance frequencies that are either greater or less than the untuned resonance frequency of the device. It is found that these magnetic forces can alter the resonance frequency of a cantilevered beam to ±20% of the untuned resonance frequency. In particular, the vibration energy harvesting cantilever beam with a natural frequency of 26 Hz has been successfully tuned over a frequency range of 22-32 Hz, enabling a continuous power output of 240-280 μW over the entire frequency range. The experimental results are found to agree with the appropriate theoretical models. In addition, damping in the system was found to increase with the increase in magnetic force used to tune the resonance frequency. Optimal resistance values are experimentally determined and compared with the theoretical values. These results show that using this tuning technique, a wide frequency working range vibration energy harvesting is feasible without sacrificing the output power. Even though tuning through the use of magnetic forces is demonstrated here for a cantilevered beam geometry, the technique can be generalized to tune the resonance frequency of any vibration structures.

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INTRODUCTION

While wireless sensors are becoming increasingly popular because of their wide range of applications, one major requirement of practical concern is having a self powering power source which will enable the sensors to be employed in autonomous condition monitoring and wireless data transmission. Vibration energy harvesting has the potential to power these devices, which would be an efficient way of powering because of the omnipresence of vibrations. In particular, the very little maintenance required for these devices and ability to be surreptitiously deployed in hostile and inaccessible environments makes it highly attractive powering source for a number of applications. Williams [1] developed a generic model for vibration to electrical energy power generation, and many researchers have demonstrated different techniques to scavenge this vibrational energy. For example, electrostatic-based micro power generators based on vibration energy were designed and developed by Roundy [2, 3], Miao [4], and Mitcheson [5], while Glynne-Jones [6] and Beeby [7] have developed vibration energy harvesting devices using the electromagnetic technique. Piezoelectric based energy scavenging devices were fabricated by Roundy [8], Jeon [9], and Hong [10]. A recent review of vibration energy harvesting has been done by Beeby and Tudor [11] and covers much of the work done in this area. Most of the devices built to date are designed to operate only at a single specific excitation frequency. In order for the commercial emergence of these devices, they should be working over a wide frequency range.

The most straightforward manner to alter the natural frequency of the energy harvesting structure is to change the stiffness or the mass associated with it, where the stiffness of the device is dependent on the length, width, thickness and the elastic modulus of the vibrating beam structure. In addition, recent efforts have sought to broaden the frequency range of energy harvesting devices through alternative mechanisms; for example, Leland and Wright [12] have applied axial load to tune to frequencies below the unloaded natural frequency of a simply supported beam, Nishida [13] has developed a MEMS array with a dynamically modifiable power for energy harvesting, and Malkin and Davis [14] have developed a multi-frequency piezoelectric energy harvester. In terms of power density and efficiency, however, a robust energy harvesting device methodology useful over practical range of excitation frequencies is still lacking. Further, while the frequency of the energy harvesting device can be tuned using either active tuning or passive tuning, active techniques consume continuous energy to alter the stiffness thus must be carefully considered and judiciously implemented. On the other hand, passive techniques are limited by the design constraints. A semi-active or active-only-when-invoked technique would appear to be an optimal way of tuning the resonance frequency of the device.

In this paper, an energy harvesting device is tuned to lower and higher frequencies (compared to the untuned resonance frequency of the beam) using external applied magnetic forces. Magnetic contact can be avoided by designing the distance between the magnets and magnetic stiffness required [15]. This technique allows one to tune the resonant frequency of the device with an occasional and limited input energy, with the tuning mechanism passive at other times. Even though this technique is demonstrated here for tuning a cantilevered structure, it can be generalized for use with any arbitrary vibration structures.

THEORETICAL WORK

Model of Tunable Energy Harvesting Device

The tunable energy harvesting device described here consists of a cantilever beam made up of piezoelectric material with a tip mass. Four magnets are used to apply attractive and repulsive forces, which are placed on the device as depicted in Figure 1. These magnets apply attractive and repulsive forces at the top and bottom of the cantilever beam and can be readily interchanged. These magnetic forces induce an additional stiffness on the beam which alters the total stiffness of the device and subsequently the resonance frequency. Here the distance between the magnets is varied in order to provide the required magnetic force to tune resonance frequency. The resonant frequency of the beam can be shifted to match both lower and higher excitation source frequencies based on the mode (attractive and repulsive) of magnetic force. The device can be represented as a lumped model, with magnetic force as a spring constant as shown in Figure 2.

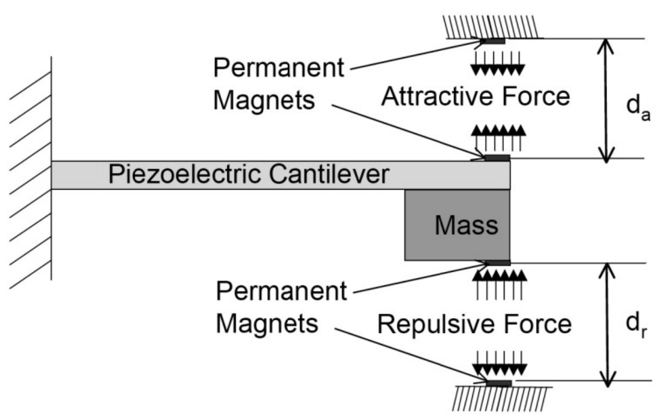
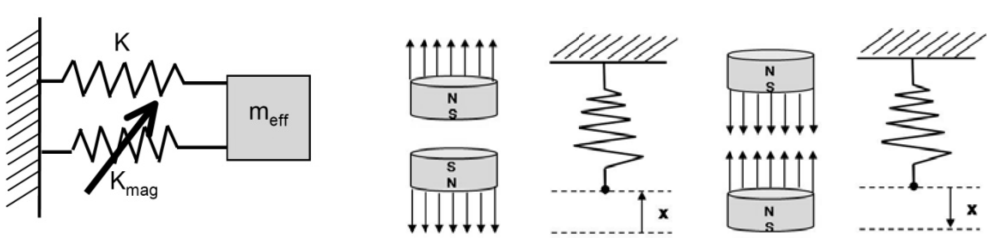


Figure 1: Schematic of resonant frequency tunable energy harvesting device.



(a) Lumped model of the device. (b) Repulsive force (Increased stiffness) (c) Attractive force (Decreased stiffness)

Figure 2: Spring equivalents for repulsive and attractive forces between magnets.

Effect of Magnetic Stiffness on Resonance and Power

For the untuned structure, the natural frequency of the beam is given as

$$\omega = \sqrt{\frac{K}{m_{eff}}} \tag{1}$$

where K is the stiffness of the beam and m_{eff} is the effective mass of the system which includes the tip mass and the mass of the beam,

$$m_{eff} = m_t + 0.23 m_{beam} \tag{2}$$

As the distance between the tip of the cantilevered beam and one of the fixed magnets is decreased, an additional magnetic stiffness is induced on the beam. (The model developed by the authors to describe the frequency tuning of the energy harvesting device using magnetic forces has been presented in more detail elsewhere [16].) The induced stiffness is dependent on the mode of magnetic force (attractive and repulsive), such that the resonance frequency of the device is now a function of beam stiffness and the stiffness associated with the magnetic force. The magnetic stiffness from the repulsive force can be written as

$$K_{mag} = \frac{\delta F}{\delta d} = \frac{\partial F}{\partial d} \tag{3}$$

whereas for the attractive magnetic force the stiffness can be written as

$$K_{mag} = \frac{-\delta F}{\delta d} = \frac{-\partial F}{\partial d} \tag{4}$$

where the negative sign for the attractive mode represents the direction of the force vector. The total stiffness would be smaller or larger than the beam stiffness based on the mode of magnetic force induced,

$$K_{eff} = K + K_{mag} \tag{5}$$

Thus for the case of the magnetically-altered device stiffness the natural frequency of the system becomes

$$\omega = \sqrt{\frac{K_{eff}}{m_{eff}}} \tag{6}$$

Further, since the cantilevered beam is made of piezoelectric material, a voltage is produced that is related to the stress of the beam as follows:

$$V = \frac{-d_{31} t_p \sigma}{\varepsilon} \tag{7}$$

where t_p is the thickness of the piezoelectric layer, σ is the stress on the surface of piezoelectric layer, $-d_{31}$ is the piezoelectric strain constant, and ε is the dielectric constant of the piezoelectric material. The output power is given as

$$P = \frac{V^2 R_L}{(R_S + R_L)^2} \tag{8}$$

where R_S is the impedance of the piezoelectric cantilever beam (also referred to as the source resistance) and R_L is the load resistance. Note that when R_S=R_L, a condition termed impedance matching, is here the device power output is optimal.

EXPERIMENT

A piezoelectric ceramic stripe actuator is used as the energy harvesting cantilever, with a tungsten tip mass at the free end to lower the natural frequency of the beam. NdFeB magnets are attached to the beam at the top and bottom of the tip, and the other two magnets required for the applied magnetic force are fixed to the enclosure of the device aligned in the vertical direction to the cantilever magnets as shown in Figure 3. The beam is fixed to a vertically hanging screw and spring system, which can be used as a control displacement actuator, whose pitch and the number of rotations would provide the distance between the magnets. An accelerometer mounted on the device and the lead wires from the energy harvesting piezoelectric cantilever are connected to a DAQ card for real-time data monitoring using LabView software to record the power from energy harvesting cantilever for various resonance frequencies. Mechanical vibrations needed to provide the excitation source to drive the cantilever are provided by an electrodynamic mini shaker, which is connected to a function generator and a power amplifier. The distance between the magnets is varied such that the resonance frequency is tuned to different excitation frequencies. The complete setup of the device is shown in Figure 4.

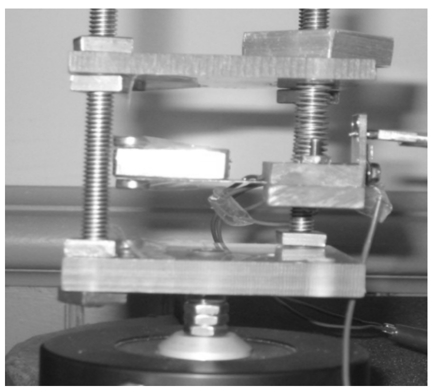


Figure 3: Tunable energy harvesting device.

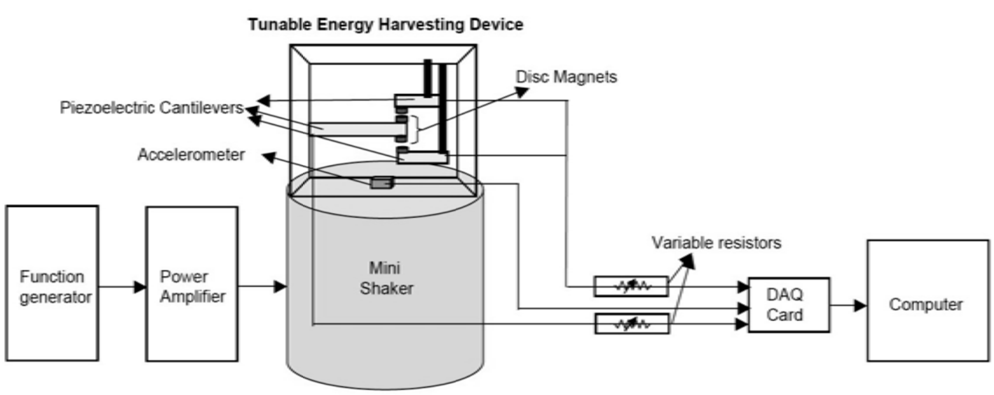
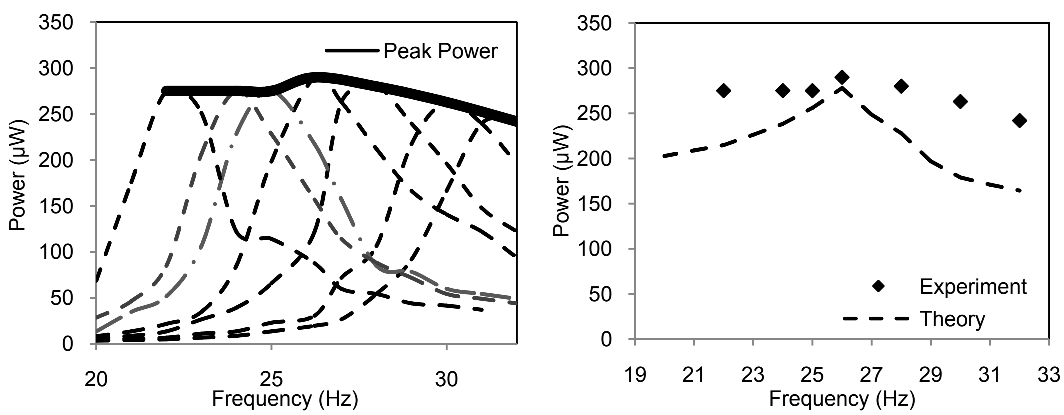


Figure 4: Layout of the experimental setup.

RESULTS AND DISCUSSION

The power output from the energy harvesting device as a function of magnetic tuning of the device resonant frequency is plotted over a range of excitation source frequencies as shown in Figure 5(a). An initial frequency of 26.2 Hz (at an acceleration of 0.8 m/s^2) matches the resonance frequency of the untuned cantilever beam. As the excitation source frequency is altered between 20 Hz to 32 Hz, the magnetic force applied to the cantilever beam is adjusted to tune the device to maintain a resonance condition and enable a continuous power output of 240 µW-280 µW to be obtained. The experimental results comparatively agree with the theoretical model as shown in Figure 5(b).

In addition, it has been possible to measure the magnetic force required to shift the resonance frequency of the untuned cantilevered beam (no magnetic force applied) to tune the device to the source excitation frequencies. As expected, the magnetic force required to tune the device increases as the difference between the untuned and excitation frequencies increases. Figure 6 shows the measured magnetic force from the experiment at each tuned frequency.



(a) Power from the tunable energy harvesting device at different resonance frequencies

(b) Power from experimental and theoretical model (damping compensated)

Figure 5: Power output versus frequency

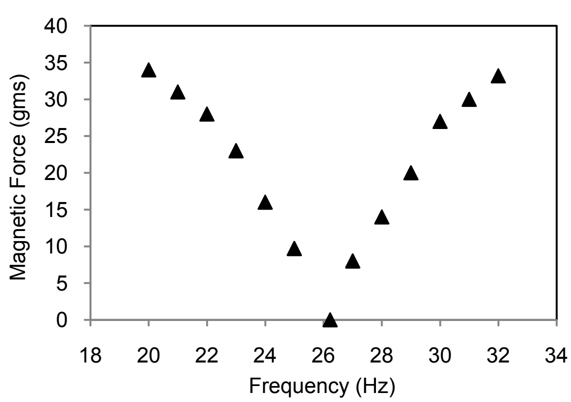


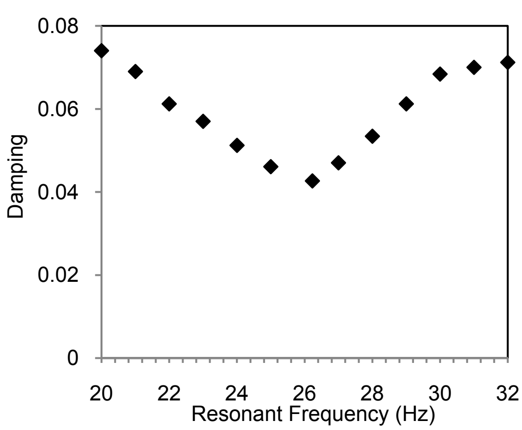
Figure 6: Force necessary to tune the device as a function of source excitation frequency

Changes in the level of damping within the system were also found with respect to the resonance frequency. It is experimentally found that the damping in the system increases as the cantilevered beam is tuned to frequencies far from the untuned resonance frequency, which is depicted in the above Figure 7(a). In addition, the optimal resistance required to maximize the power output is determined by changing the resistance and monitoring the power output. Theoretical values of lead resistance were determined by performing impedance matching to optimize power. A plot of experimental power versus resistance for the untuned cantilever beam at 26.2 Hz is shown in the above Figure 7 (b).

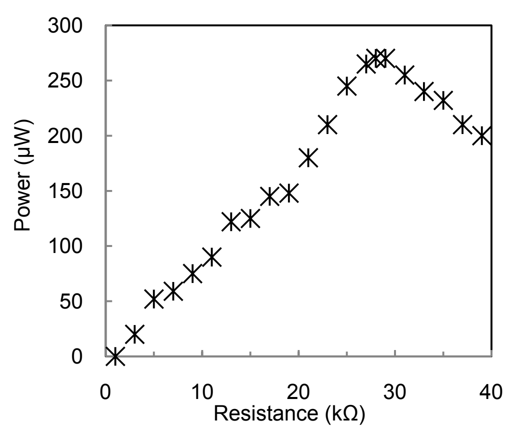
CONCLUSIONS

A frequency tunable energy harvesting device using magnetically induced stiffness has been demonstrated. Attractive and repulsive forces are used to adjust the effective stiffness of the device, which allows the resonance frequency to be tuned to lower and higher source frequencies. A piezoelectric cantilever based energy harvesting device, with an untuned resonance frequency of 26 Hz, has been successfully tuned in the frequency range of 20-32 Hz, producing a continuous power output 240-280 µW. Here the distance between the magnets is used as the variable to control the magnetic force applied at the tip of the cantilever beam. In addition, it was found that damping in the device increases as the resonance frequency is shifted from the untuned resonance frequency with the application of magnetic force. The frequency range of the energy harvesting device is dependent on the yield strength of the beam, volume of the device (to avoid magnetic contact), and the minimum power output requirement.

Such a technique shows promise as a way to maximize the power output for energy harvesting applications over a wide range of frequencies. The technique is suitable to an autonomous energy harvesting device methodology with self tuning capability provided by a feedback loop control that would dictate the distance and mode (attractive and repulsive) of the force between magnets.



(a) Damping versus resonance frequency



(b) Power output versus load resistance at 26.2 Hz

Figure 7: Damping versus frequency and harvested power versus resonance resistance

REFERENCES

[1] Williams, C.B., Yates, R.B., "Analysis of a micro-electric generator for Microsystems", Sensors and Actuators A, 52: P. 8-11, 1996.
[2] Roundy, S., Wright, P.K., Pister, K.S.J., "Micro-electrostatic vibration-to-electricity converters", Proceedings of IMECE02, P. 1-10, 2002.
[3] Roundy, S., Wright, P.K., Rabaey, J., "A study of low level vibrations as a power source for wireless sensor nodes", Computer Communications, 23: P. 1131-1144, 2002.
[4] Miao, P., Holmes, A.S., Yeatman, E.M., Green, T.C., "Micro-machined variable capacitors for power generation", Electrostatics conference of the institute of physics, Edinburg, 2003.
[5] Mitcheson, P.D., Miao, P., Stark, B.H., Yeatman, E.M., Holmes, A.S., Green, T.C., "MEMS electrostatic micropower generator for low frequency operation", Sensors and Actuators, 115: P. 523-529, 2004.
[6] Glynne-Jones, P., Tudor, M.J., Beeby, S.P., White, N.M., "An electromagnetic vibration-powered generator for intelligent sensor systems", Sensors and Actuators A, 110: P. 344-349, 2004.
[7] Beeby, S.P., Tudor, M.J., Koukharenko, E., White, N.M., O'Donnell, T., Saha, C., Kulkarni, S., Roy, S., "Design, fabrication and simulations of microelectromagnetic vibration-powered generator for low power MEMS", DTIP of MEMS and MOEMS", Montreux, Switzerland, 2005.
[8] Roundy, S., Leland, E.S., Baker, J., Carleton, E., Reilly, E., Lai, E., Otis, B., Rabaey, J.M., Wright, P.K., Sundarajan, V., "Improving power output for vibration-based energy scavengers", Pervasive Computing, 2005.
[9] Jeon, Y.B., Sood, R., Jeong, J.H., Kim, S.G., "MEMS power generator with transverse mode thin film PZT", Sensors and Actuators A, 122: P. 16-22, 2005.
[10] Hong, Y.K., Moon, K.S., Levy, M., "Single crystal piezoelectric transducers to harvest vibration energy", Proceedings of SPIE, 6048: P. 1-7, 2005.
[11] Beeby, S.,P., Tudor, M.,J., White, N.,M., " Energy harvesting vibration sources for microsystems applications", Measurement Science and Technology, 17: P. R175-R195, 2006.
[12] Leland, E.S., Wright, P.K., "Resonance tuning of piezoelectric vibration energy scavenging generators using compressive axial preload", Smart Materials and Structures, 15: P. 1413-1420, 2006.
[13] Nishida, T., Resonant energy MEMS array and system including dynamically modifiable power processor", The Journal of the Acoustical Society of America, 119(4): P. 1908, 2006.
[14] Malkin, M.C., Davis, C.L., "Multi-frequency piezoelectric energy harvester", The Journal of the Acoustical Society of America, 118(1): P. 24, 2005.
[15] Kulah, H., Najafi, K., "An electromagnetic micro power generator for low-frequency environmental vibrations", 17th IEEE international conference on MEMS, 8265: P. 237-240, 2004.
[16] Challa, V.,R., Prasad, M.,G., Shi, Y., Fisher, F.,T., " A wide frequency range tunable vibration energy harvesting device using magnetically induced stiffness", Proceedings of IMECE07, 41985: P. 1-9, 2007.