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# IMPROVING THE PERFORMANCE OF A VIBRATION ENERGY HARVESTING DEVICE USING MAGNETS

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## ABSTRACT

Harvesting energy from ambient vibration source is a promising method for providing a continuous source of power especially for low power micro electro mechanical system (MEMS). Thus, multiple methods were proposed in order to overcome the linear resonant generator system. This paper presents experimental results on two modes (softening and bi-stable) the use of magnets for improving the functionality of energy harvesting device under constant input displacement. Two set of the experiments were conducted. The quasi-static measurement was conducted to investigate the system stiffness and the dynamic measurement was conducted to investigate the performance of the response across a frequency range. The results for four configurations which operate in attractive and repulsive mode with a fixed gap between the magnets are investigated. The result shows that there is a wider bandwidth for the device operating in the softening mode. By placing with the double attractive stationary magnets, the energy harvester shows the most effective softening non-linear system.

**Keywords:** energy harvesting, magnetic stiffness, softening.

## INTRODUCTION

With the advances in the technology of low power microelectromechanical system (MEMS), developments in the portable electronic devices and wireless sensor networks (WSN) have also emerged. WSN is widely used in various application including patient health monitoring, environment monitoring (e.g. coastal monitoring), wildlife tracking and surveillance in military. Usually, batteries are used as primary power source for these devices.

However, the development in battery technology is still poor compared to the development in MEMS system. Due to the limited lifetime, the battery requires replacement or recharging from time to time. In some cases such as patient health monitoring devices (implanted medical device), environment monitoring and wildlife tracking, the battery replacement becomes very difficult, increasing the maintenance cost and, most importantly, dangerous.

One of the ways to solve this is by applying an alternate power source to recharge the batteries for long duration. Harvesting energy from ambient sources has received significant attention due to ubiquity within the last decade. Power can be generated from various ambient sources including solar, wind, thermal, acoustic noise and vibration. Among these sources, vibration energy harvesting is particularly attractive because of its abundance and existence everywhere such as in human motions, ocean waves, automobiles, machines, household goods and structures (building and bridge). The vibration source is normally converted into electrical energy using electromagnetic, piezoelectric, electrostatic or magnetostrictive transduction mechanism.

Most vibration based harvesting device is typically configured as a base-excited linear resonant generator that consists of a single degree of freedom (SDOF) mass-spring-damper system. The maximum power can be generated when the natural frequency of the device matches with the frequency of the ambient (i.e. resonant frequency) (Williams and Yates, 1996).

The challenge is offered by the ambient vibration source is low frequency range. The average power of a vibration is directly proportional with the cube of the resonant frequency (Williams and Yates, 1996). The average power dramatically drops at low frequency accordingly. Thus, Najafi and Külah, (2008) suggested a magnetic force based frequency up-conversion to produce a higher output power. Sari *et al.*, (2010) employed a series of cantilevers to amplify the generated voltage and power using frequency up-convention method.

Since the unpredictable varying frequency of ambient sources, it is difficult to tune the natural frequency of the device to always match the frequency of the ambient at all times. The average power of a resonant energy drops drastically when the natural frequency of the device deviates from the frequency of the ambient sources. In order to address this issue, two approaches, frequency tuning and widening the frequency bandwidth have been suggested in the literature.

Eichhorn *et al.*, (2009) applied a pre-stress mechanism that can be passively be adjusted by rotating a screw to tune the natural frequency of the device. Several researchers have been exploited the non-linear method to widen the bandwidth either in the theoretical or experimental studies(Brennan *et al*., 2008) (Mann and Sims, 2009) (Barton *et al*., 2010) (Andò *et al*., 2010) (Vocca *et al*., 2012) (Tang *et al*., 2012). Due to potential to widen the bandwidth and amplify harvested power, Nguyen and Halvorsen, (2010) proposed using softening spring compared using linear spring or hardening spring for broadband random vibration. Bi-stable can be implemented with a specific design in the mechanical structure of the device (Qiu *et al*., 2004).

This paper presents experimental results on the use magnets to improve the functionality of energy harvesters under constant excitation level. In this study,

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single and double stationary magnets configurations are introduced to improve the performance of the energy harvesting device. Results on the quasi-static and dynamic response of the device involving both attractive and repulsive modes at the fixed gap between magnets are presented. This paper focused on the energy harvesting device in producing the non-linear behaviour, which is, involving mechanical domain only.

## THE PROPOSED ENERGY HARVESTING DEVICE

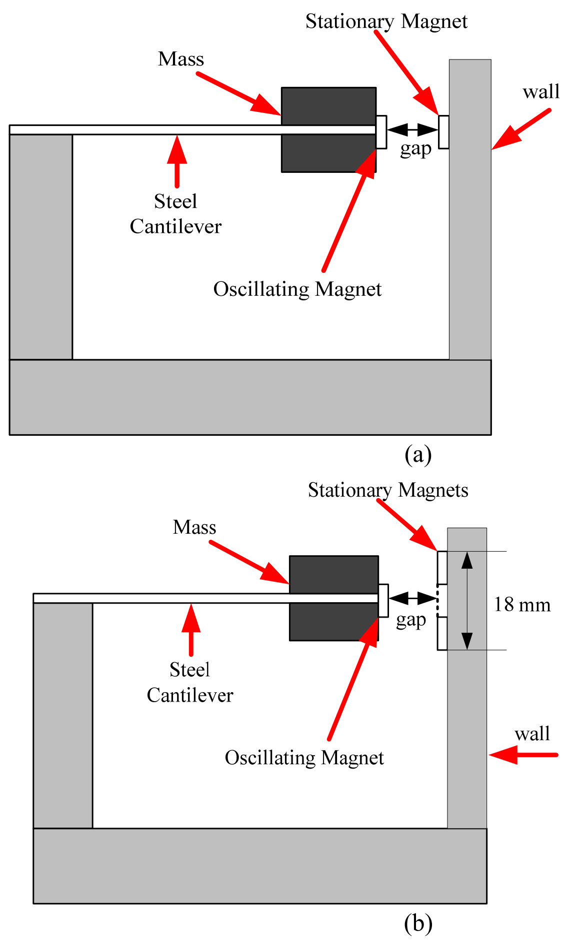


**Figure-1.** Schematic of propose energy harvester (a) Configuration with single permanent magnet and (b) Configuration with double permanent magnets.

A schematic diagram of the magnetic interaction system is shown in Figure-1. The system consists of a mass and an oscillating neodymium (NdFeB) magnet (Ø6 mm x 3 mm) mounted at the tip of a steel cantilever beam (30 mm x 0.5 mm x 56 mm) fixed at one end. In this study, two main configurations are considered. These two configurations were chosen because of the element arrangement is not difficult and can be manipulated to get various responses. Each of the configurations is divided into two basic modes (attractive and repulsive mode) as presented in Table-1. Figure-1a shows the setup for the first configuration. In this system, a single stationary magnet, either attractive or repulsive, is mounted on the wall opposite to the oscillating magnet at the fixed gap, 1.5 mm.

The second configuration, on the other hand, consists of a single oscillating magnet and double stationary magnets as shown in Figure-1b. In this configuration, both double stationary magnets are separated at constant lateral distance (1.8 mm) which is measured from upper of first magnet to lower of second magnet respectively. By setting the oscillating magnet and double stationary magnets operating in attractive mode and repulsive mode while the system is setting to operate in attractive and repulsive mode by changing the poles of the double-stationary magnets with respect to the oscillating magnet. For the results presented in this study, the gap is fixed at 1.5 mm; the device is excited at constant excitation level (0.25 mm).

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**Table-1.** The classification of the configurations used in the experiment.

| Category | Configuration |
|---|---|
| Configuration 1A | An oscillating magnet – a single attractive stationary magnet |
| Configuration 1R | An oscillating magnet – a single repulsive stationary magnet |
| Configuration 2A | An oscillating magnet – double attractive stationary magnets |
| Configuration 2R | An oscillating magnet – double repulsive stationary magnets |

## EXPERIMENTAL SETUP

In this experimental investigation, two measurements are involved; quasi-static and dynamic measurement. Quasi-static measurement is conducted to characterise the force-displacement characteristics of the system. Meanwhile, dynamic measurement is conducted to investigate the response on the system across a frequency range.

In the quasi-static measurement, the shaker was placed to operate in horizontal position to minimise the effect of gravity as shown in Figure-3. By connecting with a connecting arm, a force gauge was attached to the mass of the device to measure the restoring force of the cantilever. A linear variable differential transformer (LVDT) is attached to the base of the device to measure the tip displacement of the cantilever beam during the measurement. The experiment was implemented with a high amplitude displacement at a very low frequency (< 2.5 Hz).

In the dynamic measurement, the whole device was placed onto the shaker and excited with constant harmonic input displacement from 5 Hz to 30 Hz and then decreased from 30 Hz to 5 Hz with same increment. By applying a fixed gap (i.e. 1.5 mm), the natural frequency of the system was approximately around 16-22 Hz.Thus, this system was excited in the range of these natural frequencies.Two accelerometers were used, one was mounted on the base of the device and the other one was placed on the tip mass to measure the responses during excitation.

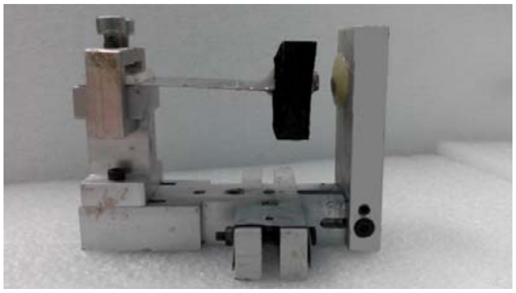

**Figure-2.** Fabricated energy harvesting device.

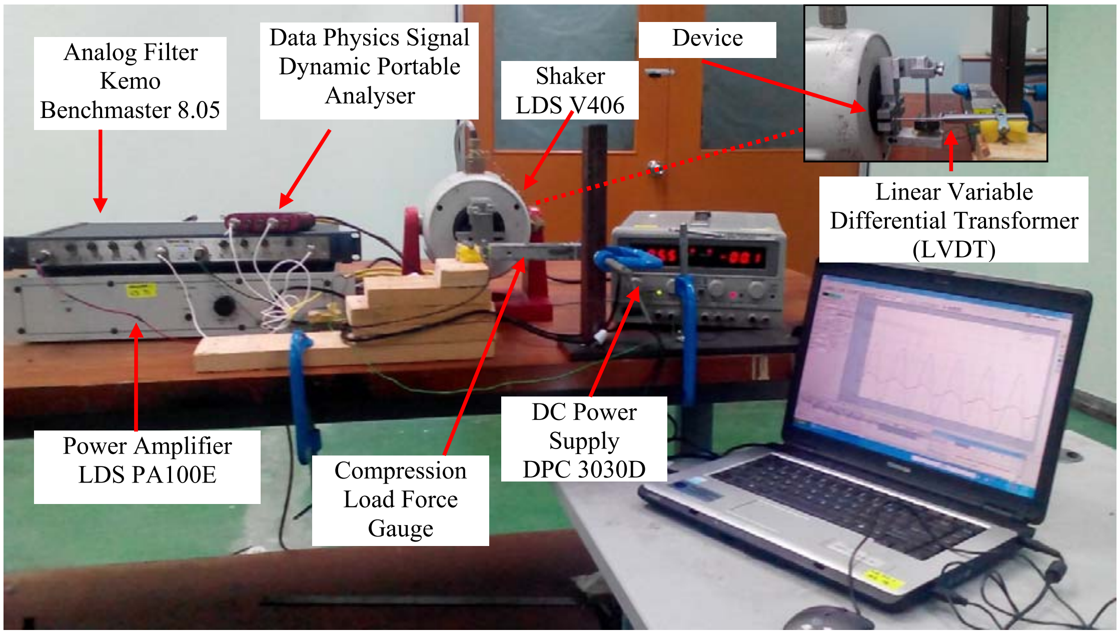


**Figure-3.** Quasi-static measurement setup.

## RESULTS AND DISCUSSIONS

Figure-4 shows the fitted curve of the measured force-displacement for four configurations while the gap for each case is maintained at 1.5 mm. It can be seen that all configurations behave as the non-linear softening restoring force except the one a single repulsive permanent

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magnet (Configuration 1R) (dashed-black). For the Configuration 1A shown in Figure-1a, the stiffness decreases as the displacement approaches its maximum value in both positive and negative displacement, thus resulting in a softening mode.

On the other hand, the configuration between the oscillating magnet and double stationary magnets is shown in Figure-1b. Notice that, the magnets are placed at a distant away from the equilibrium position of the oscillating magnet. As the mass moves upward from the equilibrium position; the stiffness of the cantilever beam dominates the motion up to the point where the attractive or repulsive magnet is placed. When the mass moves to the maximum distances, the restoring force of the system increases at a slower rate per unit displacement, which represents the non-linear softening behaviour. Among the three configurations, Configuration 1A shows the largest restoring force when the mass is approaching its maximum displacement whereas the smallest restoring force at maximum displacement is recorded from Configuration 2A.

On the other hand, the response for force-displacement of the Configuration 1R is entirely different from the other three configurations. As the mass moves from zero in the upward direction, the restoring force starts with a negative value and changes to positive at maximum motion. However, the behaviour of the system is better explained as the motion goes from maximum displacement to the zero deflection position. As the mass moves from maximum displacement, the ‘stiffness’ is positive, as shown by the positive gradient of the force against the displacement curve. When the displacement decreases further, the stiffness changes from positive to negative. In the negative stiffness region, the restoring force aids the motion rather than oppose to it. The same occurs in the negative displacement region. The system is said to operate in the bi-stable mode.

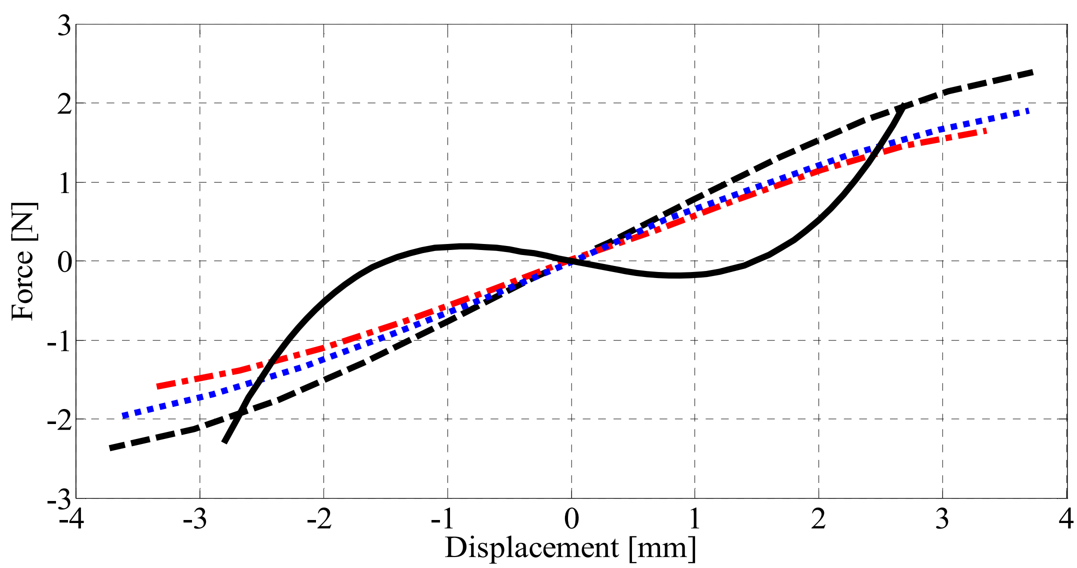


**Figure-4.** Force-displacement curves under different configurations; a) Configuration 1A (dashed), b) Configuration 1R (solid), c) Configuration 2R (dotted) and d) Configuration 2A (dashed-dotted).

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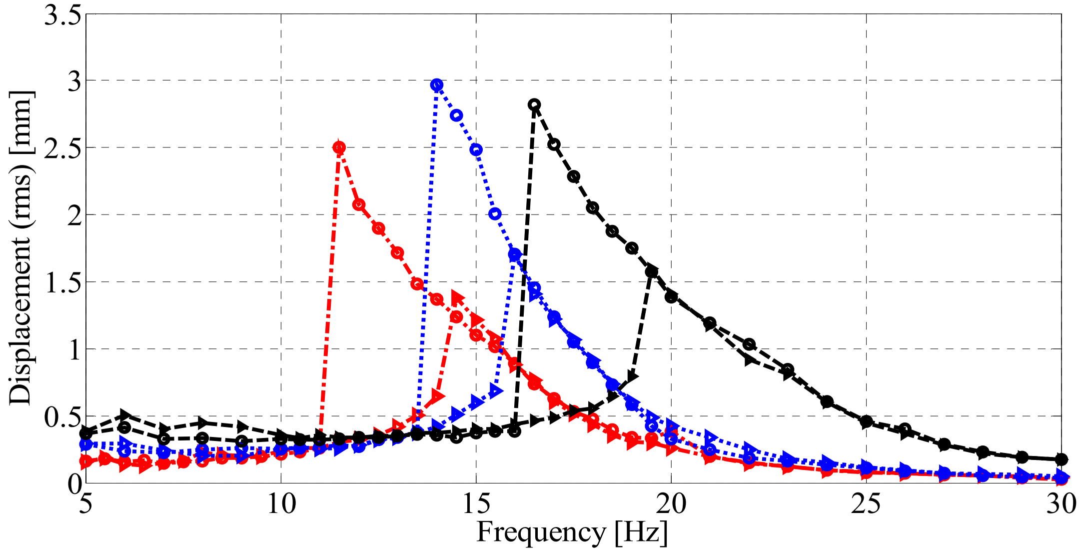


**Figure-5.** Measured frequency response curves with different configurations while the gap is 1.5 mm a) Configuration 1A [sweep-up (dashed-circle) and sweep-down (dashed-triangle)], b) Configuration 2R [sweep-up (dotted-circle) and sweep-down (dotted-triangle)] and c) Configuration 2A [sweep-up (dashed-dotted-circle) and sweep-down (dashed-dotted-triangle)].

Figure-5 shows the measured frequency response curves for three configurations (Configuration 1A, Configuration 2A and Configuration 2R), operating under constant of input displacement (0.25 mm). It can be seen that, the frequency response curve skew to the left. When the device was excited from 5 Hz to 19 Hz, the response increases monotonically until it suddenly jumps up to higher amplitude. When the frequency is further increased, the response gradually decreases until 30 Hz. On the other hand, when the frequency is swept from 30 Hz to5 Hz, the response increases gradually to a maximum point where it suddenly drops to lower amplitude and continues to decrease monotonically until 5Hz. The more soften the stiffness of the systems, the more shift to the left the frequency response curve is. It can be seen that the jump-up (jump-down) frequency for both Configuration 2R and Configuration 2A occurred at 15.5 Hz (14 Hz) and 14 Hz (11.5 Hz), respectively.

This figure shows that Configuration 2A manages to operate in a much lower frequency region compared to Configuration 1A and Configuration 2R.However, the amplitude of the response is less compared to other configurations. In terms of softening system, the more skew to the left of the frequency response curve, the more effective the configuration is. This is because the system is able to operate at low frequency by amplifying the amplitude. Thus, it can be concluded that the effective configuration can be made by having the double stationary attractive magnets (Configuration 2A) which have to be placed such in Figure-1b.

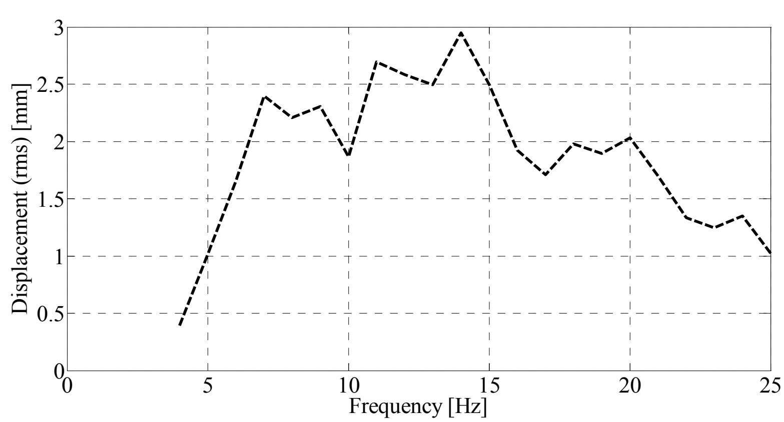


**Figure-6.** Measured frequency response curves for Configuration 1R while the input displacement is 4.5 mm.

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The measured frequency response for bi-stable mode (Configuration 1R) is shown in Figure-6. In this configuration, the device is excited at a higher excitation level (0.45 mm) to ensure the mass jumps from one stable state to another stable state and vice versa. In this mode, the frequency is swept from 4 Hz to 25 Hz. At low frequency, the amplitude of the response is low, which means the mass oscillates in one of the stable states only. When the frequency is further increased, the amplitude of the response increases suddenly. In this case, the mass has sufficient energy to oscillate between the two stable states (cross well-motion). The cross well motion can be seen for a range of frequency until the response drop to the smaller value again due to the increase in the mechanical impedance of the mass.

## CONCLUSIONS

This paper presented experimental results for the non-linear energy harvesting device. The nonlinearity in the system was realized by having magnetic stiffness in addition to linear stiffness of the cantilever beam. The arrangement of magnet is made-up of an oscillating magnet and stationary magnet. For the first configuration, a stationary magnet was attached opposite to an oscillating magnet. For the second configuration, double stationary magnets which were separated at 1.8 mm (measured from upper magnet to lower of second magnet), were mounted opposite to an oscillating magnet. Both configurations were operated in attractive mode and repulsive mode, respectively.

By having a fixed gap between the magnets, it was found that Configuration 1A, Configuration 2A and Configuration 2R operate in the softening mode. Configuration 1R, on the other hand, operates in the bi-stable mode. The effect of the arrangement magnets configuration influenced the effectiveness stiffness of the softening system.

This dynamic response of the device operating in the softening mode showed the more soften the stiffness of the system is, the lower the jump frequencies are. The bi-stable mode requires a higher excitation level for the mass to travel between two stable states. This response is less sensitive to a range excitation frequency thus makes it beneficial for a wider bandwidth application.

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