Hybrid Nonlinear Vibration Energy Harvester Due to Combined Effect of Stretching and Magnetic-Induced Nonlinearity

Osor Pertin and Koushik Guha

Abstract Vibration energy harvesting (VEH) is viable solution for battery free and self-powered micro-/nano-systems. The ambient vibration available for harvesting is low, random and broad. Hybrid energy harvester provides an alternative to narrow bandwidth, high operational frequency and low-power density VEH. In this paper, nonlinear hybrid vibration energy is developed by integrating both piezoelectric and electromagnetic VEH. The piezoelectric energy harvester and electromagnetic harvester is optimized for low frequency and maximum power generation configuration. The device is designed for maximum stretching-induced nonlinearity and repulsive magnetic nonlinearity to achieve bistable-quartic (BQT) potential. The potential profile and restoring force is studied to show enhanced performance of the device. When excited at the natural frequency of 59 Hz and acceleration amplitude of 0.5 g, a total voltage generation of 2.6 V (Piezoelectric voltage = 1.8 V and induced electromagnetic voltage = 0.8 V) is reported. The hybrid design enhances the frequency bandwidth, power generation and off-resonance operation making it efficient to be used in broadband random vibration environments.

Keywords Microelectromechanical system (MEMS) · Vibration energy harvester · Nonlinear · Wideband · Bistable · Stretching

1 Introduction

Microelectromechanical system (MEMS)-based vibration energy harvester (VEH) has been very popular among the micro-energy harvesting methods for their easy miniaturization, implementation and high power density [1]. VEH devices usually harvest the ambient mechanical vibration into usable electrical by electrostatic, piezoelectric and electromagnetic transduction mechanisms. Piezoelectric harvester (PEH) and electromagnetic harvester (EMH) are popular among researchers because of their high electromechanical coupling effect and they do not require external bias

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O. Pertin (✉) · K. Guha
Department of Electronics and Communication Engineering, National Institute of Technology, Silchar 788010, India

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source like electrostatic harvester. The generated electrical output can be used to realize self-powered microelectronics circuits like wireless sensor nodes (WSN), implantable and wearable devices. Conventional linear VEHs based on resonance of the structure have the drawback of high frequency, narrow bandwidth and low output generation**.** Also, the environmental vibration is low, broad and varying with time and therefore the VEHs perform inefficiently in real-time practical use. Significant researchers have been resolute on reducing the operational frequency, widening the bandwidth and enhancing the output power density of the VEHs [2, 3].

Nonlinear vibration energy harvester has become a recent popular choice owing to its lower resonant frequency and broad bandwidth. It is proved that introduction of nonlinearity in energy harvesting will broaden the operational bandwidth and show superior power generation [4]. Marzencki M et al. introduced nonlinearity into a clamped–clamped PEH device with a central located seismic mass by redesigning the interlayer stresses of beam [5]. In 2009, Erturk et al. [6] and Cottone et al. [7] reported the bistable PEH configurations based on magnetic attraction and repulsion arrangements, respectively, that shows the potential energy profile with a potential barrier between two potential wells. Navabi S et al. proposed a MEMS PEH, whose operational bandwidth is improved taking the advantage of both the multimodal and stretching-induced nonlinearity [8]. But the three proof masses used increases the size and device complexity. In a similar design concept, Liu et al. achieved a wide band electromagnetic harvester using an array of harvester unit covering different designated frequencies [9]. Saibal R et al. reported that magnetic-induced bistable nonlinear structure reduced the frequency while restricting the bandwidth widening [10]. Therefore, Pranay P et al. of same team developed and demonstrated that magnetic-induced bistability and stretching-induced quartic potential profile in a single design enhances the performance across the vibration spectrum of an electromagnetic VEH device [11]. But usually output performance is reduced for broadband harvester.

Hybrid energy harvesters have been developed by many researchers in order to enhance the generated power. It is reported that Hybrid VEH configuration integrated with piezoelectric and electromagnetic mechanism shows improved performance compared to the single mechanism in widening the bandwidth and enhancing the output power [12, 13]. In 2019, Guangyi Z et al. proposed a hybrid energy harvester composed of a piezoelectric portion contained with a double-clamped trapezoidal beam and an electromagnetic portion featured with a plane coils and a magnet sleeve [14]. They experimentally found that output power shows 52.4% improvement generating 0.637 mW power. Haipeng L et al. reported a hybrid harvester based on fixed–fixed beam with deposited PZT layers and magnetic attraction-induced nonlinearity which reduced the stiffness and operational frequency [15]. Similar nonlinear hybrid harvester is designed by Ping L et al. which benefits from the advantages of nonlinear magnetic repulsion technique and frequency up conversion simultaneously [16].

In this paper, a hybridization of nonlinear PEH and nonlinear EMH approach is developed for harvesting vibration energy. We have used the novel idea of nonlinear segmented trapezoidal PEH that will also introduce stretching into the hybrid system. Trapezoidal FR4 material cantilever beam with segmented piezoelectric (PZT) layers, NdFeB permanent magnet and a circular copper coil are used to make the hybrid energy harvester design. The harvester induces bistability through repulsive magnetic arrangement at tip of the FR4 spring structure and administers quartic potential profile with very low potential barrier between two wells due to stretching of thin and hollow fixed guided trapezoidal beam. It is already proved that segmented trapezoidal PEH at strain nodes shows improved performance compared to the conventional non-segmented PEH [17]. Tapered hollow structure demonstrates stretching in high order which enhances the frequency bandwidth and power density of the VEH [18]. For maximum electromagnetic-induced voltage, already reported four pole arrangement of NdFeB permanent magnets and circular wound coil are employed [10, 11]. The model of the hybrid harvester is developed and simulated across range of frequencies for performance analysis.

This paper is organized as follows: Sect. 2 describes the development of the hybrid VEH design and simulation. Section 3 discusses the simulation obtained results. The concluding comments are given in Sect. 4.

2 Structural Design and Simulation of the Nonlinear Hybrid Vibration Energy Harvester

2.1 Structural Design

The harvester design consists of FR4 material spring structure, segments of PZT layers, NdFeB magnets, and copper wound coil. Figure 1(a) shows the proposed hybrid design where the stretchable segmented trapezoidal PEH employs the piezoelectric transduction and the copper coil and NdFeB magnets arrangement employs electromagnetic transduction for harvesting electrical energy from mechanical energy. For the electromagnetic part, Fig. 1(b) shows the distribution of magnetic-field of the four magnets arrangement around the coil responsible for maximum flux distribution and a soft magnet sleeve that will bind magnetic-field lines in a narrow region to make the coil cut more induction magnetic lines which will in turn improve the electromagnetic output. Figure 1(c) shows the schematic diagram of the nonlinear PEH portion. The trapezoidal beam design produces more uniform strain distribution and therefore makes efficient use of the beam volume compared to the conventional rectangular beam. The rectangular holes at the wider end of the trapezoidal piezoelectric harvester will reduce the stiffness and increase the order of stretching. Figure 1(d) shows the piezoelectric polarization direction of the PZT beam which can be used to locate the strain node for segmentation. The magnetic repulsive pair at guided end of FR4 spring structure introduces bistable nonlinearity into the system.

The generalized Duffing potential energy equation $U(y)$ and the consequent spring reaction force which is derivative of the potential, $F(y) = -\frac{\partial \mathrm{U(y)}}{\partial y}$ is given by [11],

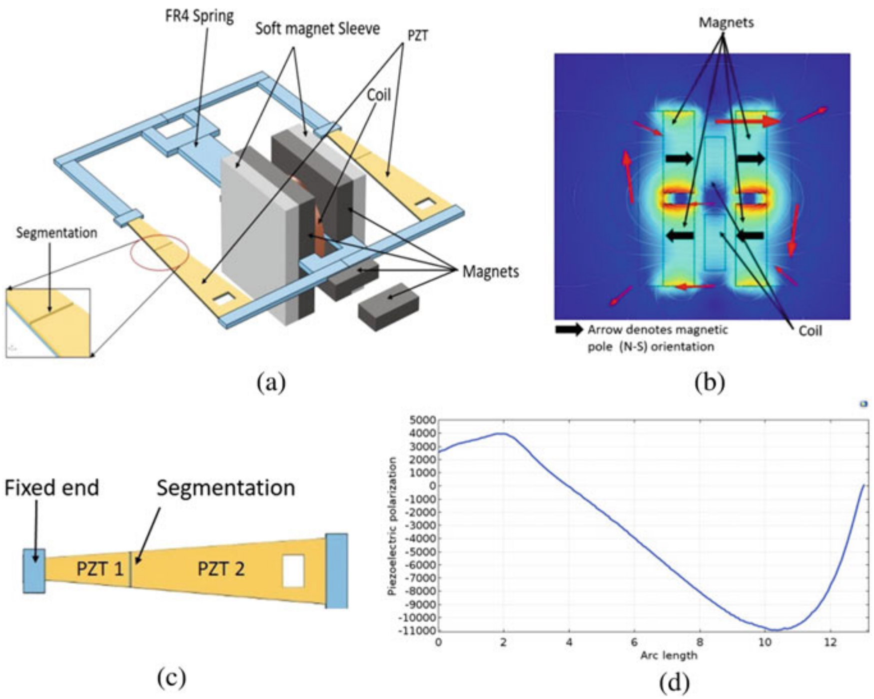

Fig. 1 **a** Proposed nonlinear hybrid piezoelectric-electromagnetic VEH. **b** Magnetic flux lines in electromagnetic assemble. **c** Schematic of segmented nonlinear trapezoidal PEH. **d** Piezoelectric polarization curve along the piezoelectric beam length

$$U(y) = \frac{1}{2}Ay^2 + \frac{1}{4}By^4 \tag{1}$$

$$F(y) = -Ay - By^3 \tag{2}$$

where y represents the deflection of the oscillator, A and B are independent nonlinear parameters.The final generated power of the designed nonlinear hybrid energy harvester is the sum of piezoelectric power output P_p and electromagnetic power output P_{em}.

$$P_{\text{output}} = P_p + P_{\text{em}} \tag{3}$$

Table 1 Geometric dimension and material properties

Description (Geometry)	Value	Description (Material)	Value
Total length of device	35 mm	Density of PZT	7500 (kg/m^3)
Piezoelectric stretching beam length	12 mm	Density of FR4	1900 (kg/m^3)
Beam Width at clamped end ($x = 0$)	1 mm	Density of NdFeB	7500 (kg/m^3)
Beam width at guided end ($x = l$)	3 mm	Young modulus, PZT	64(GPa)
Thickness of PZT	0.1 mm	Young modulus, FR4	22(GPa)
Thickness of FR4 substrate	(0.1–0.4) mm	Young modulus, NdFeB	160(GPa)
Distance between two PZTs	0.1 mm	Piezoelectric constant	-16.6(C/m^2)
Distance between two repulsive magnets Magnet size Mass of magnets	3.5 mm $8 \times 4 \times 1.5$ mm 3.6 kg$\times 10^{-3}$	Permittivity constant	25.55 (nF/m)

2.2 *Finite Element Analysis*

The hybrid VEH design model is created using FEM software COMSOL MULTIPHYSICS 5. Body load of 0.5 g acceleration is applied as mechanical input on the device. The FR4 spring is fixed at the one end and the other end is guided by the applied excitation. The structure is meshed before performing any simulations analysis. Complete mesh consists of 21,610 domain elements, 12,347 boundary elements, and 2292 edge elements.Geometry and material properties of the structure is given in Table 1.

3 Result and Discussion

The force vs. displacement curve shows nonlinear behavior of the system (Fig. 2(b)) while the potential energy profile shows a bistable-quartic curve with two wells having a very shallow potential barrier between the potential wells (Fig. 2(c)) as compared to single well profile of a mono-stable quartic configuration without repulsive magnetic pair. The obtained nonlinear stiffness constant of the BQT is 4.83 $\mathrm{N}\times 10^7/m^3$ while mono-stable configuration shows a stiffness value of 6.26 $\mathrm{N}\times 10^6/m^3$.

Figure 3 compares the generated voltage of hybrid harvester to single-energy harvesters. The combined effects of stretching nonlinearity and repulsive magnetic bistable nonlinearity improve the frequency bandwidth of both the generated piezoelectric voltage and induced electromagnetic voltage in the coil. The generated

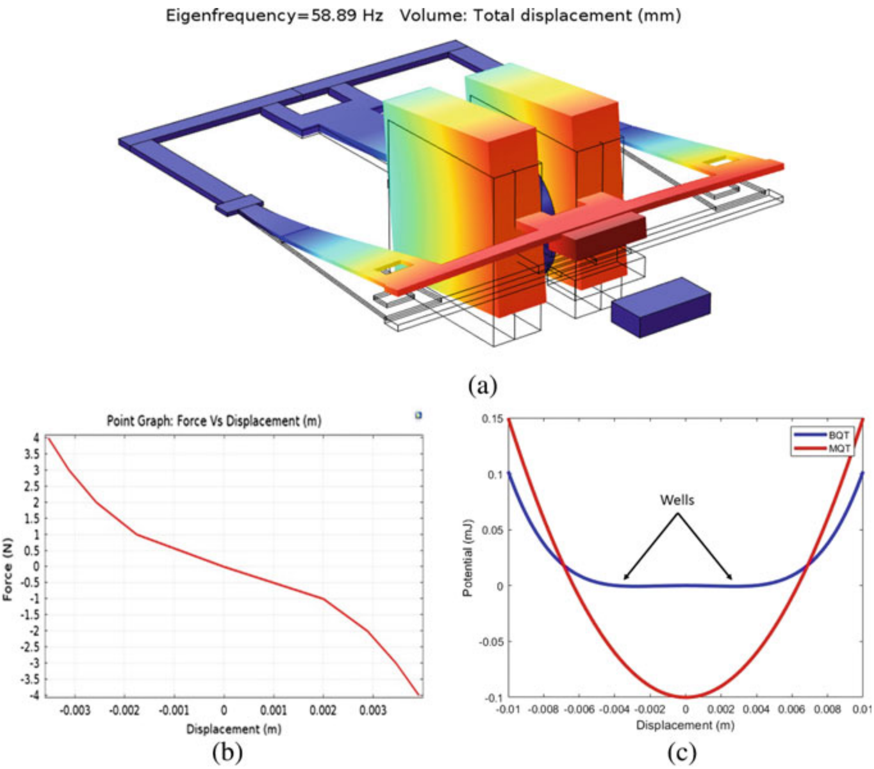

Fig. 2 **a** Proposed design in the fudamental mode of vibration with 58.89 Hz eigen frequency. **b** Nonlinear restoring force. **c** Comparison of potential energy profile of bistable-quartic (BQT) configuration having a distance of 3.5 mm between the two repulsive magnet pair and mono-stable qartic (MQT) configuration without the magnetic pair

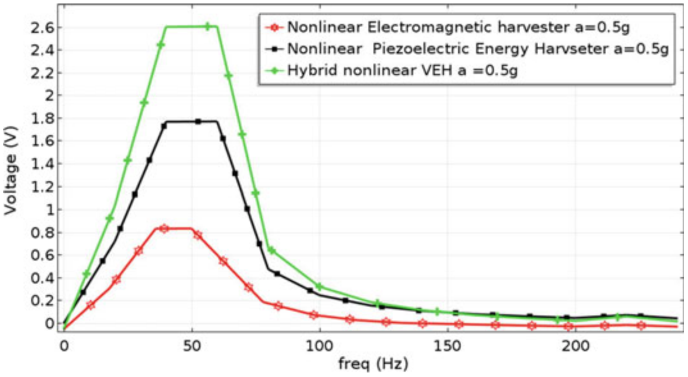

Fig. 3 Output voltage comparison of nonlinear piezoelectric energy harvester, nonlinear electromagnetic energy harvester and hybrid nonlinear energy harvester across a frequency sweep of (10–250 Hz)

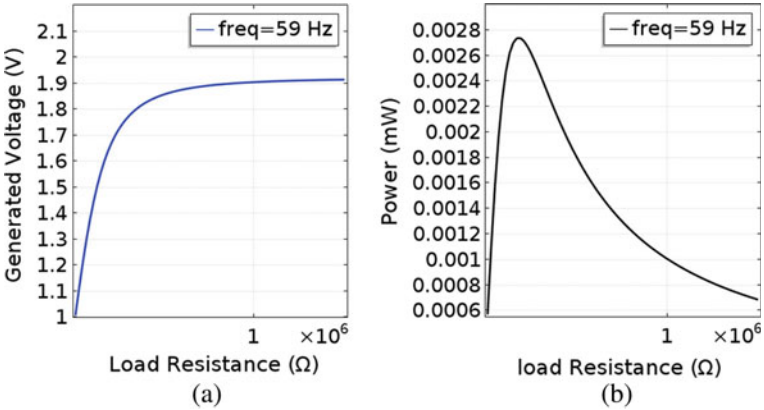

Fig. 4 **a** The varying output voltage for varying piezoelectric load resistance, **b** varying output power for varying load at mechanical excitation of 59 Hz and 0.5 g

voltage of PEH portion is 1.8 V and of EMH portion is 0.8 V for 0.5 g input acceleration and optimal load value of 200kΩ. The generated piezoelectric voltage depends on the size of piezoelectric PZT layers and therefore the generated voltage is lesser compared to state-of-art piezoelectric harvesters because the proposed model also include the concept of nonlinearity due to stretching reducing the size of PZTs. The output of the hybrid nonlinear VEH is the sum of piezoelectric voltage and electromagnetic voltage, and hence, hybrid design shows increase in power generation capability compared to single harvesters.

The peak operating frequency of the proposed harvester will change with different mechanical acceleration input; therefore, the optimal load of the harvester too changes. The load resistance of the electromagnetic harvester does not vary greatly and is kept constant at 1000 Ω. The change in piezoelectric voltage at the peak resonant frequency of 58.88 Hz and mechanical excitation of 0.5 g for varying load resistance is as seen in Fig. 4. The optimal piezoelectric load resistance is reported to be 200kΩ.

4 Conclusion

A low-frequency hybrid nonlinear VEH using both piezoelectric and electromagnetic transduction mechanism is proposed and studied. The choice of FR4 material and optimized shape of the spring structure for maximum stretching results in lower oscillating frequency. The introduction of nonlinearity using stretching and bistable repulsive magnet shows improvement in frequency bandwidth, output generation capability and off-resonance performance making it efficient to be used in broadband random vibration environments. The reported generated voltage is quite enough to operate the WSNs and nano-/microsystems.

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