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Performance of a modified magnetostrictive energy harvester in mechanical vibration

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Abstract

The field of harvesting electrical energy from ambient vibration has grown with rapid interest. Perpetual source of electrical energy can be extracted from structural vibrations. The paper deals with a technology for scavenging electricity from vibration using iron-gallium alloy. This alloy offers high ductile property and the effect of inverse magnetostriction is also quite high. In this paper, a bending type magnetostrictive prototype energy harvester has been considered. Volume of the used material is $7 \times 2 \times 42 \text{ mm}^3$. Forced & free vibration characteristics have been examined on this prototype. Maximum conversion efficiency of 49% has been achieved at input frequency of 30 Hz.

Keywords: Electrical engineering, Energy, Mechanical engineering, Electromagnetism

1. Introduction

There has been much recent interest among researchers of scavenging electrical energy from natural vibration. Since the demands of various control transducers is increasing, the design of novel material including magnetostrictive material in

combination with such transducers have driven towards the development of low power consuming ferromagnetic sensors. There is a large number of structural and automobile vibration sources in the world [1] & hence, various kind of vibrational energy harvesters have been manifested. Energy can be harvested from vibration using various passive elements such as electromagnetic, electrostatic type. The electromagnetic energy harvesters are mainly made of permanent magnets and copper coils. At the time of mechanical vibration, a change in magnetic flux occurs due to the relative movement between permanent magnets and coil inside the electromagnetic harvesters. As a result, an alternating emf generates across the coil as per the law of electro-magnetic induction [2]. But poor coupling & low resonant frequency are the main disadvantages for power generation in electro-magnet type energy harvesters. Electrostatic harvesters are capacitive in nature. The relative motion between the electrodes under mechanical vibration creates variable capacitances with a dielectric material in between the plates.

Vibration energy harvesting using active materials is more advantageous in comparison with passive materials because active materials offer high coupling between mechanical & electrical domain. These types of active materials are mainly piezoelectric and magnetostrictive type. Energy harvesters using piezoelectric materials can be utilized as the source of capacitive power [3]. Piezoelectric materials are fragile in nature and they are weak against bending, impact & tensile forces. Their output impedance is high, thus, very small amount of electrical energy can be transmitted to external loads [4].

Magnetostrictive materials are free from those drawbacks. Magnetostrictive materials like Galfenol, Terfenol-D, Metglass etc. are inductive in nature. Their impedance at fundamental frequency is low for various sources of mechanical vibration. Magnetostrictive materials are able to change their shape under the application of external magnetic fields. This phenomenon occurs because magnetic domains inside the material tries to align in accordance with the applied magnetic field & thus, a change in magnetization occurs inside the material. These materials also experience a reverse effect where change in magnetization occurs due to applied stress. Iron-Gallium alloy (Galfenol) is particularly one of the most promising energy harvesting material because it provides high compressive and tensile mechanical property with predominant ductility [5, 6]. It also provides high robustness & high coupling coefficient (>0.75) [7]. Magnetostrictive energy harvesters are categorized as bending & axial type in accordance with the direction of application of stress on the active elements. Frequency bandwidth for axial type harvesters are very limited and their optimum performance can be found only when these harvesters are installed along the load path. whereas, bending type energy harvesters can able to extract electrical energy efficiently from any kind of vibrating surfaces. A particular amount of applied force can generate much higher stress level in a bending type harvester compare to an axial type. Present magnetostrictive bending type energy harvesters can be classified

by their configurations as single layer beam of magnetostrictive material, double strips or bimorph beam & a special arrangement of magnetostrictive and passive material known as unimorph. In this paper, a bending type, Galfenol based cantilever structured unimorph energy harvester has been proposed. Electrical energy in this type of devices is developed from the well-known inverse magnetostrictive phenomenon; where applied variable input mechanical stress changes the magnetic flux density inside the material and hence, an alternating voltage generates across the coil wound over the Galfenol strip due to electro-magnetic induction. Presently, a large number of bending type vibration energy harvesting device based on magnetostriction have been developed. Zucca et al. [8] designed & performed experiments on a bending type energy harvester where a longitudinal force was applied at the head of the moving part of the beam. The output power of the energy harvester was found to be $18 \mu\text{W}$ at an input frequency of 300 Hz. Adly, Davino et al. [9] have done experiments on a magnetostrictive energy harvesters and also done its modelling. Maximum power of 0.44 mW was derived at 50 Hz frequency & 8 MPa stress. Wang et al. [10] proposed a vibration energy harvesting device using Metglas 2605SC. Maximum power was reached around $200 \mu\text{W}$ at frequency of 58 Hz. Ueno et al. [11] developed a Galfenol based bending type harvester. It was made of two parallel Galfenol strips. From the experimental results, it has been seen that the efficiency of energy conversion of this device was 16% at 395 Hz. Kita et al. [12] have developed a Galfenol based bending type energy harvester. Maximum 35% of conversion efficiency was achieved at input frequency of 202 Hz. 25 N impulse force was applied at the tip of the device. Another embodiment has been given by Wang & Yuan [10]. They developed an energy harvester using magnetostrictive bimorph which was directly attached on the top of a non-magnetic beam. The average power was achieved around $576 \mu\text{W}$ under 1.1 kHz base excitation. Zhang et al. [13] developed an axial type harvester. 0.09 W/m^2 of output power was generated from that harvester. Liu et al. [14] made a similar type of structure using pre-stress mechanism and that energy harvester was installed & tested inside vehicle tires. Yoo & Flatau [15] later created an iron-gallium based energy harvester and experimented the performance of the device under different base excitations. Ueno [16] developed a novel U shaped configuration of a magnetostrictive energy harvester. The average output power in that structure was 3.7 mW. Mori et al. [18] made an embodiment of a Terfenol-D based energy harvester to extract electrical energy for a broad range of frequency. However, in most of the energy harvesters in previous studies, input vibration was given by using electromagnetic shaker & the effect of leakage magnetic flux created from the solenoid of the shaker affects the performance of the harvester. Also, significant studies have not seen on the improvement of conversion efficiency of such magnetostrictive energy harvesters.

The prototype presented in the paper is the modified form of the structure proposed by Kita et al. [12, 17]. Continuous mechanical excitation is given at the tip of the

harvester by using a vibrating motor (1600 rpm). Thus the influence of leakage magnetic flux on the energy harvester due to use of electromagnetic shaker has been eliminated. This also reduces the cost of experimentation. In this paper, force & free vibration characteristics have been examined on the harvester for accruing electrical energy. The prototype can able to generate sufficient amount of electrical energy even below its first resonating frequency, 61 Hz. It is also seen that conversion efficiency of the device has been improved significantly in compare to other existing bending type magnetostrictive energy harvesters.

2. Methodology

The proposed structure is a modified form of bending type energy harvester. The harvester is made of parallel beams using rods of non-magnetic stainless steel yoke and Galfenol strip which offers high inverse magnetostrictive effect. It converts mechanical vibration into electrical energy efficiently. The Galfenol [5] (longitudinal direction is the direction of magnetically easy axis) has made with Bridgeman process by ETREMA Products, Inc., Iowa. The configuration of the prototype is depicted in Fig. 1.

The cantilever structured prototype is consisting of fixing, generation and moving part. The Galfenol is having the dimension of 7.0 mm width, 2 mm thickness and 42 mm in length. The whole prototype is 114 mm long. Generation part of the prototype consists of parallel beam of Galfenol and non-magnetic stainless steel SS-304 plates in which Galfenol strip is wound with copper coil having 1500 turns and it is joined inside the yoke firmly by adhesive glue. The Galfenol strip is inserted parallel to the yoke with appropriate air gap for the coil winding. Thickness of steel yoke parallel to the Galfenol strip is 2 mm & thickness of moving part is 3 mm width (b) of the entire steel structure is kept 7 mm. The fixing part of the generator was fixed in a wooden structure firmly by using screw. Length of the fixed part is around 40 mm & length of actual generation part is 36 mm. The moving part is kept long &

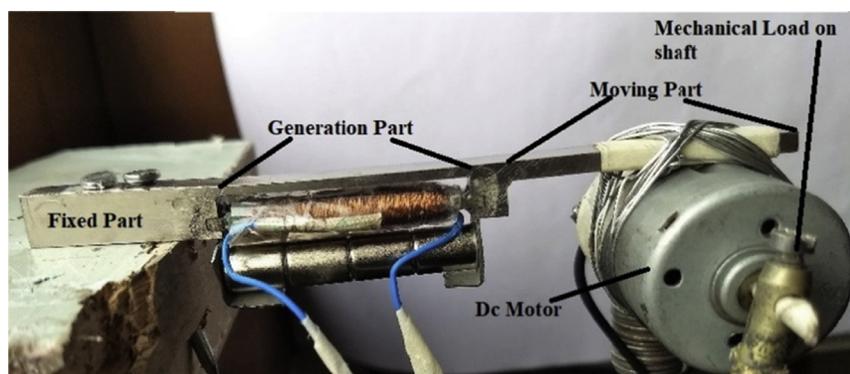


Fig. 1. Structure of the prototype.

moderation is done by reducing the thickness of the moving part by cutting a cubical block of dimension $7 \times 5.6 \times 41.6$ mm from the stainless steel part (Fig. 2). This leads towards the reduction of stiffness of the whole structure & improvement in conversion efficiency.

Parallel beam configuration amplifies small amount of tip force to large axial force applied on the Galfenol material. This mechanism of force conversion leads to high energy conversion ratio & high output power.

Fig. 2 depicts the configuration of proposed prototype after modification. The conventional structure developed by Kita et. al [12] has been depicted in Fig. 3. Vibration is given at the tip of the harvester by attaching a small dc motor (12 V, 1600 rpm) there. Ends of the shaft of the motor was mechanically loaded for creating larger inertial force. By exciting the motor, forced vibration has been created and thus emf induces across the coil of the Galfenol strip by Faraday’s Law. Also that motor inheritably acts as a tip mass which thus reduces the natural frequency of the prototype sufficiently and increases the overall Q factor.

Four permanent magnets of 3.5 mm diameter \times 10 mm length connected in series are attached parallel to the Galfenol strip to provide adequate bias flux (0.8T for Galfenol). Such arrangement leads to the reduction of reluctance offered by air and provides more uniform flux path (Fig. 1). Maximum magneto-mechanical coupling effect can be obtained in a magnetostrictive material when both of its mechanical & magnetic energies are in the state of equilibrium. The vibration source determines the mechanical stress level inside magnetostrictive energy harvester. Hence, a

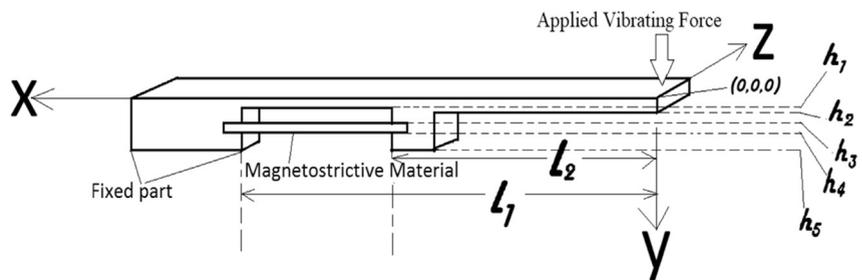


Fig. 2. Geometric 3D configuration of the modified prototype.

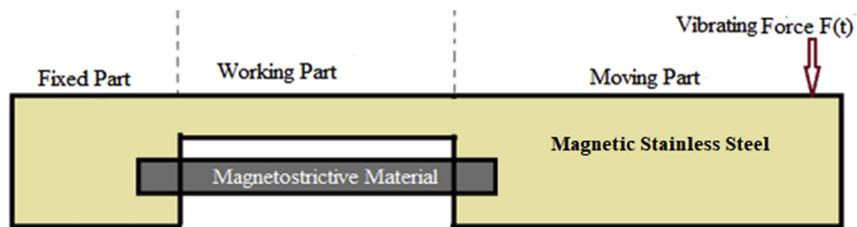


Fig. 3. Configuration of conventional prototype structure in 2D proposed by Kita et al [12].

permanent magnetic field is required for biasing purposes to balance that mechanical energy. The magnetic flux density inside any magnetostrictive material is related by the Eq. (1).

$$B = dT + \mu H \quad (1)$$

where d is piezo-magnetic constant, T is the applied mechanical stress, μ is the relative permeability & H defines external magnetic field. If magnetic field is kept constant with respect to time, then $\frac{\partial H}{\partial t}$ becomes zero. So, in that case, the flux density depends only in applied stress. This has been done by external biasing by using permanent magnet across the prototype. This also helps proper alignment of magnetic domains inside the magnetostrictive material so that vibration will have its desired effect. Now writing the Eq. (1) in two-dimensional coordinate form, we have

$$\frac{\partial}{\partial t} B(x, y) = d \cdot \frac{\partial}{\partial t} T(x, y). \quad (2)$$

here x-y plane is considered in Eq. (2) because the vibration takes place along the x-y plane. In this experiment, H is kept constant by providing the bias field. So, its variation with respect to time becomes zero.

An inertial force is applied at the tip of the harvester during forced vibration. When direction of the bending force is applied in the upward direction, a tensile stress is exerted on the strip. On the other hand, when bending occurs in the downward direction, compressive stress will occur on the Galfenol strip. As a result, magnetic flux inside the material will also change due to change in applied force. And due to alternating flux caused by oscillation of continuous vibration generates alternating voltage across the coil by electro-magnetic induction. The emf induced across the coil occurs due to time variation of magnetic flux ϕ inside the Galfenol strip & the generated emf is directly proportional to the velocity of input vibration applied at the tip of the harvester. Magnetic flux ϕ inside the Galfenol strip can be expressed by Eq. (3).

$$\phi = b \int_{h_3}^{h_4} \left(d \frac{\int_{l_2}^{l_1} T(x, y) dx}{l_1 - l_2} + \mu \frac{\int_{l_2}^{l_1} H(x, y) dx}{l_1 - l_2} \right) dy \quad (3)$$

Again generated emf is directly proportional to the input velocity. Hence, it can be expressed by Eq. (4) as:

$$e \propto v$$

$$e = \gamma v = N \frac{\partial \phi}{\partial t} = Nd \frac{\partial}{\partial t} \left[b \int_{h_3}^{h_4} \frac{\int_{l_2}^{l_1} T(x,y) dx}{l_1 - l_2} dy \right] \quad (4)$$

here H is assumed to be constant due to constant bias field. So, Eq. (4) represents the expression of emf e induced across the Galfenol wound coil having N no. of turns, v is the input vibrational velocity, b is the width of the material (7 mm) & the constant γ stands for electro-mechanical coupling coefficient. The prototype structure examines forced & free vibration characteristics at input frequency 30 Hz. New structure is advantageous over the conventional [12, 17], due to reduction of mechanical stiffness of the moving part. Thus, structure requires much smaller force to yield adequate response.

3. Results & discussion

Inverse magnetostrictive effect has been verified in this prototype by applying continuous vibration. The device has been vibrated at low frequency below the first bending resonance frequency. Input forced vibration applied at the tip of the prototype is around 30 Hz. It has also been observed that the harvester also oscillated in forced vibration at a frequency very close to the input vibration applied at the tip by exciting the dc motor gradually. The vibration is continuous and thus we get a continuous voltage output. In practical application, force vibration always not occurs at resonating conditions. The proposed structure is able to convert low frequency periodic input into higher amplitude of output voltage and energy efficiently. Obviously the output depends on the amplitude of the input frequency and at resonance, much higher output voltage can be observed.

Fig. 4 shows the experimental set up. In this experiment, bending force was exerted at the tip of the moving part by exciting the dc motor attached at the tip gradually up to 12 Volts. As excitation increases, vibration also increases (though frequency is low). Tip displacement was measured by a laser displacement sensor. The coil wound to Galfenol strip has 1500 turns. As mentioned before, 4 Nd-Fe-B magnets of total 0.8 T flux density are used for biasing purposes and also their novel arrangement show more uniform flux distribution. Mass of the dc motor attached at the tip is 150 gm & the effective mass of the whole system is around 182 gm. The generated voltage e at open circuited condition or by connecting load resistance R has been measured by a digital storage oscilloscope. Displacement at the tip of the moving part of the harvester was measured by a laser displacement sensor & it is around 1.8 mm (peak to peak). The structure has 1st resonating frequency around 61 Hz.

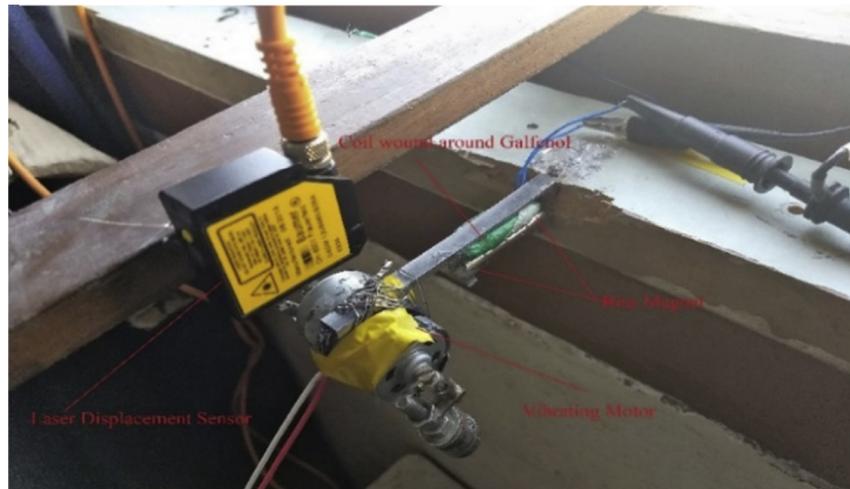


Fig. 4. Experimental set up of the energy harvester.

In this experiment, the response of such prototype below its resonating frequency has been checked. The prototype was vibrated at 30 Hz. Fig. 5 shows the time responses of open circuit voltage generated across the coil at input tip velocity 0.205 m/s. The frequency of output voltage response is 28.66 Hz. The maximum generated output peak to peak voltage is 23 volts.

Various voltage responses were measured for open circuit condition and for various load resistances connected in series across the Galferol coil at different low input velocities. And it was observed that high output voltage was generated for low input vibrational frequency.

From the above figures, it has been observed that by applying continuous vibration, maximum peak to peak open circuited voltage generation is around 23 Volts even at low input frequency of 30 Hz (Fig. 5). Voltage vs time response for load resistance 620 Ohm has been depicted in Fig. 6. The voltage responses (Figs. 5 and 6) show non-linear behaviour which is mainly due to structural, the force exerted at the tip of the harvester is not entirely unidirectional (vertical) in nature due to non-uniform circular motion of the shaft of vibrating motor. Also, the use of non-

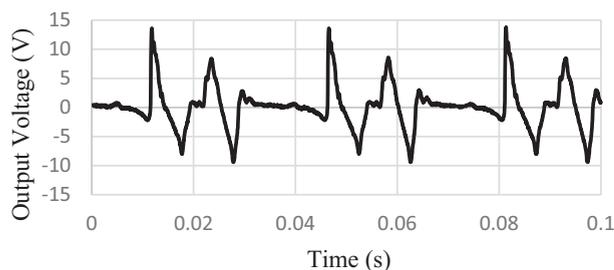


Fig. 5. Open circuit voltage at input frequency of 30 Hz under forced vibration.

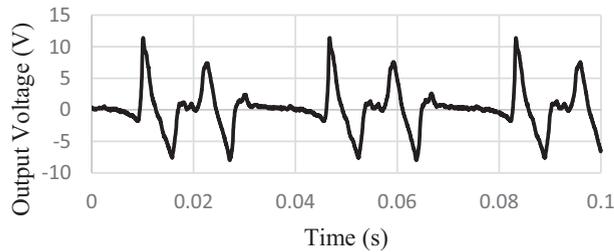


Fig. 6. Terminal voltage at 620 Ω load resistance.

magnetic steel yoke does not provide closed magnetic path. There is a change of magnetic state of the core in the generating coil due to the inverse magnetostrictive effect & highly non-linear material characteristics of iron-gallium alloy. But due to reluctance offered by the yoke, more number of flux lines try to pass to the Galfenol strip, as a result, generation becomes higher.

Fig. 7 shows Fast Fourier Transform to show the time response of open circuit output voltage under forced vibration at different frequencies that will appear in addition with excitation frequency. It gives the RMS value of output voltage at different frequencies. It is observed that highest peak occurred near 90 Hz which is around 3 times the fundamental vibration frequency.

The measurements of output power with load resistances was also conducted. It has been observed that maximum obtained average power was 51 mW for 72 Ohm load resistance. Hence this fact implies the condition for maximum power transfer theorem. **Fig. 8** shows average power vs resistance characteristics at 0.205 m/s (30 Hz) input velocity. Average power has been calculated by using the formula $P_{av} = \frac{1}{T} \int_0^T \frac{e^2}{R} dt$. Where e is the load voltage. **Fig. 9** shows output energy and efficiency vs. load resistance characteristics. Output energy is the integral of joule loss over a complete time period. Efficiency of the prototype has been calculated by the ratio of output joule loss for a particular resistance to maximum

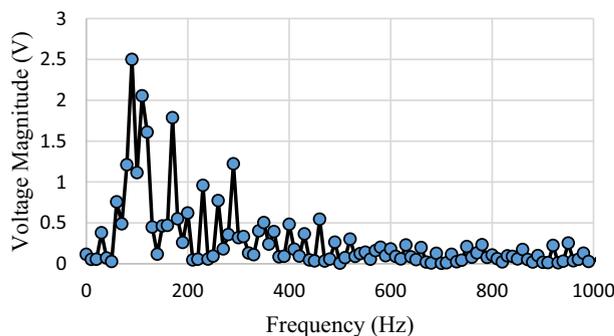


Fig. 7. FFT for the time response of open circuit voltage.

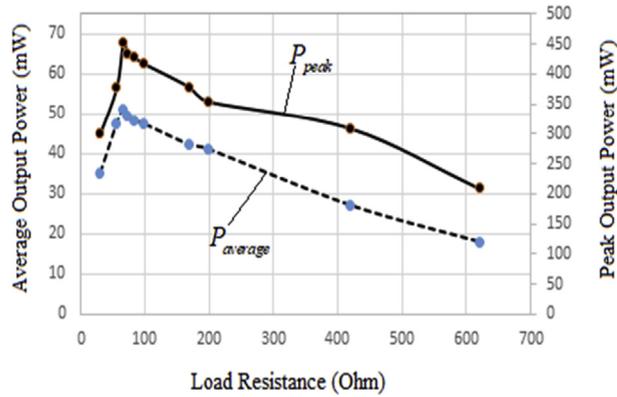


Fig. 8. Peak output power & average output power change with terminal resistance.

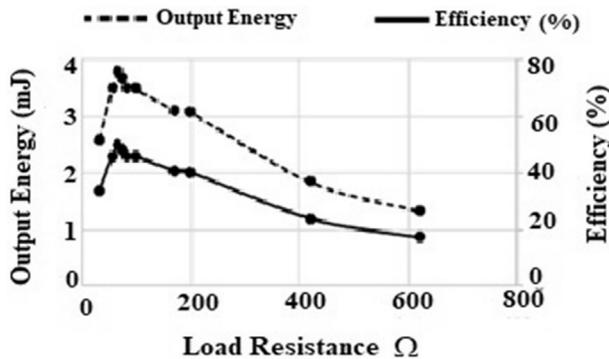


Fig. 9. Output energy vs. load resistance & efficiency vs. load resistance characteristics.

input kinetic energy. $\eta = \int \frac{e^2}{R} dt / \frac{1}{2} M v_{\max}^2$. Here, $M = m_{tip} + m_{effective}$. Maximum input velocity is appeared to be 0.205 m/s.

Maximum extracted output energy is 3.9 mJ at an impedance matching of 72 ohm and maximum efficiency is calculated to be roughly around 49% at an input frequency of 30 Hz which is significantly higher than other magnetostrictive harvesters which were operated under similar level of excitation. The output energy increased with increasing input mechanical energy. Though it was observed that efficiency decreased exponentially with an increment in input energy. From the formula of efficiency, it has been observed that the mechanical input to the harvester varies with the square of the input velocity at the base. For a particular load resistance, efficiency becomes maximum.

Fig. 10 shows open circuit voltage characteristics at free vibration of the Galfenol prototype by applying an impulsive force of 20 N. It was done by hanging a mass of 2 kg at the tip position of the harvester via string & free vibration was created by cutting the string. Maximum peak to peak 50 volts was generated.

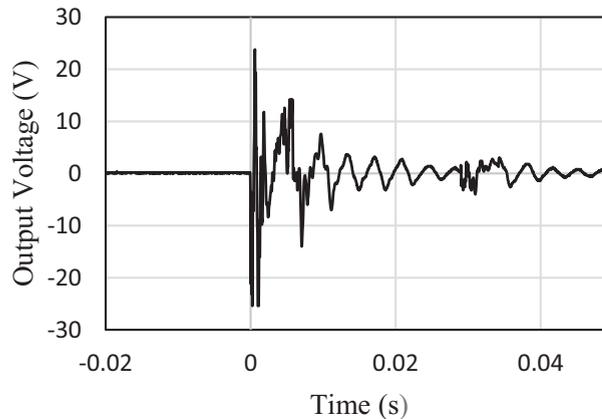


Fig. 10. Free vibration characteristics of same structure.

4. Conclusion

In this paper, an experiment has been carried out for demonstrating the qualitative performance of a Galfenol-based magnetostrictive energy harvester under low input vibration frequency. The prototype can able to generate several tens of mille-watts below its natural frequency which is sufficient for powering various micro-sensor networks in automobile where vibration from engine and road is available for power supply for such electronic devices. Such prototypes can also be used for monitoring the structural health of bridges and factory. Use of dry cells can also be eliminated in various wireless sensor systems by using such magnetostrictive energy harvesters as a power source. The experiment in this paper was done in such a way where resonant condition of vibration was not always available but one need adequate response for sensor applications. Though the output response can be much higher at resonating conditions, but due to equipment constrains, resonating condition was not performed here. Use of non-magnetic stainless steel reduces the corrosive effect of the generator structure. Also, the efficiency of the prototype is found to be much higher. The overall efficiency can be enhanced by joining a capacitor parallel to the load resistance across the pickup coil. Based on the proposed structure, a parametric analysis in order to maximize the overall efficiency along with output response at resonating condition will be developed soon in future. Also structural optimization can be done along with magnetic flux path designs. We can maximize the output of the harvester by doing these improvements and we can apply this as an energy source of various micro wireless sensor system in future.

Declarations

Author contribution statement

Subhasish Dey: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Soumyabrata Patra: Performed the experiments.

Debabrata Roy, Tapan Santra: Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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