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Petroleum & Petrochemical Engineering Journal
ISSN: 2578-4846

Macroscale Velocity Driven Harvester Using Galfenol

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Research Article

Volume 2 Issue 4

Received Date: May 28, 2018

Published Date: June 12, 2018

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Abstract

In this paper, a macroscale magnetostrictive velocity driven energy harvester is presented. This harvester has non-vibrating base and the external harmonic force is applied to the tip of the cantilevered harvester by a rotary DC motor. Due to ductility, high stiffness, machinability and suitability for welding, Galfenol is selected as the active material of this harvester. The performance of the presented macroscale harvester in the presence of various magnetic fields, various exciting frequencies and different resistive loads is measured. The harvester shows the highest performance, when it is excited in its natural frequency. The energy density extracted from this harvester is 1535 μW/cm^3 in the presence of 2 A current bias across resistive load of 98 Ω. This promising amount of energy density shows that the harvester is a reliable energy source for photovoltaic solar Gilders in cloudy and windy weathers.

Keywords: Magnetostrictive; Velocity Driven Harvester; Macroscale; Galfenol

Introduction

Nowadays, mechanical harvesters are employed everywhere to increase the efficiency of systems with vibrational sources. Impulse harvesters under the fan's foot on the sport stadiums and recharging the battery of pacemakers using body motion are good examples to scavenge the energy from dissipated energy. the generated power by vibrational base harvesters seems very low, however, this amount of energy is enough to energize health monitoring systems of mechanical, civil and aerospace structures or any other wireless sensor networks. Most of the vibrational based scavenging sources are electromagnetic [1-7], electrostatics [8-13], piezoelectric [14-20] and magnetostrictive [21-23] harvesters. Electromagnetic harvesters are suitable for low frequencies ($f < 5Hz$) ambient applications. Electrostatics needs external voltage source, which is not suitable for compact applications. Although, piezoelectric harvesters are suitable for wide frequency bandwidth, their poor electromechanical coupling coefficient and brittleness of piezolelectric makes piezoelectric material unreliable for long life operation [24-26]. Magnetostrictie materials have wide applications in actuators [27-37], sensors [38,39], and harvesters [40-42]. Although, the hysteresis behavior and presence of Eddy current in magnetostrictive materials [42-45] cause complicate modeling process for harvester, high stiffness combined with high magneto-mechanical coupling coefficient [31,32] make them suitable for harvesters that have long life and operate with high efficiency in wide range of temperature [34]. Usually harvesters are categorized as force driven and velocity or displacement driven.

Force driven harvesters consist of a magnetostrictive rod and a pick-up coil [40]. Displacement or velocity driven harvesters are normally a cantilever beam covered by a pick-up coil. Based on the Villari effect, when the rod is under normal stress or the cantilever beam is under lateral bending, the change of the magnetization induces voltage in the pick-up coil. In this research, we concentrated on the velocity driven harvester. Most of the developed velocity driven magnetostricve harvesters are in miniature size with base-excitation [40]. Thanks to closed magnetic circuits [46-48] for higher performance, Ghodsi developed a novel magnetostrictive harvester [48]. Meticulous investigations highlighted this fact that in some of the developed devices, the combination of electromagnetic and magnetostrictive are the sources of energy. However, the main percentage of the developed energy is because of the change in operating point of permanent magnet when the velocity driven harvester is under bending.

The aim of this research is to develop a velocity driven magnetostrictive harvester for macroscale applications. It means that the beam is not excited from the base. Macroscale magnetostrictive harvesters can be installed in the wing of photovoltaic glider to generate power in the cloudy and windy atmosphere that the performance of the photovoltaic is very low. In the experiments, the harvester is evaluated under different excitation frequency ranges, resistive loads and magnetic field.

Principle of Macroscale Harvester and Experimental Setup

The schematic of a harvester is shown in the Figure 1. The harvester is made of an oscillating magnetostrictive rod inside a pickup coil. The ends of the magnetostrictive rod are clamped in iron yokes by screws. To avoid the noisy disturbance generated by the oscillating system on the pickup coil, the source of vibration is allocated far from the pickup coil by an aluminum bar. There is a permanent magnet attached to the tip of the aluminum bar. A drum armed with an array of PMs on its circumference is connected to a DC motor. Rotation of the DC motor instigates an attraction/repulsive force between permanent magnets of the drum and tip of aluminum bar. Therefore, the frequency of oscillation can be controlled by the rotary drum connected to the DC motor. To investigate the performance of harvester in the presence of magnetic field, a magnetic bias coil is installed over the pickup coil to generated bias magnetic field. Significant parameters in the developed harvester are beam oscillation frequency (*f*), intensity of bias magnetic field (I_{bias}) and resistive load (*R*). The displacement of the beam can be defined by Euler-Bernoulli beam equation as:

$$EI\frac{\partial^4 w(x,t)}{\partial x^4}+\mu\frac{\partial^2 w(x,t)}{\partial t^2}+r_{ext}\frac{\partial w(x,t)}{\partial t}+r_{\text{int}}\frac{\partial^5 w(x,t)}{\partial x^4\partial t}=0$$
(1)

Where *w(x,t)* is the displacement of the beam at point *x* at time *t* and μ is the effective mass of the harvester in unit length. *E* is Young's modulus and *I* is the moment of inertia of the cross-section of the beam. r_{ext} and r_{int} are the external and internal damping respectively. On the other hand, the magneto-mechanical model of Galfenol can be written as:

$$\begin{cases} B=\mu^{\sigma}H+d^{*}\sigma \\ \varepsilon=dH+\dfrac{\sigma}{E} \end{cases} \quad (2)$$

where *B* and *H* are magnetic flux density and magnetic field, respectively, σ and ε are applied stress and strain. μ^{σ} is the magnetic permeability in constant mechanical stress. *d* and *d** are two magnetostrictive coefficients. The combination of the magneto-mechanical equation and the solution of equation (1) gives the generated voltage of the harvester in the form of:

$$v(t)=\frac{G_2}{1+j\omega G_1}\left(e^{j\omega t}-e^{\frac{-t}{G_1}}\right) \quad (3)$$

where

$$G1=\frac{N^2A\mu}{Rl} \quad (4)$$

$$G2=\frac{j\omega NAdEz}{l}\int_{l_1}^{l_2}X^{"}(x) \quad (5)$$

and $X^{"}(x)$ is the second derivation of the displacement, which is found from the solution of equation (1).
In the experiment, the harvested voltage is measured by data acquisition system with an input impedance of 1MΩ. The specifications of the pickup coil and magnetic bias coil are presented in Table 1.

The manufactured macroscale harvester is shown in Figure 2. In this setup, the Galfenol rod, with 51 mm length and 10 mm diameter, is clamped between two iron rods and at the end, an aluminum rod is attached to them and all together have made a cantilever beam. The beam is fixed in one end, and the other end is free to vibrate. There are 6 permanent magnets around the disk attached to DC motor and another permanent magnet is attached to the end of beam. The interaction of these magnets produces a vertical displacement at the free end of the cantilever beam (the gap between rotary and fixed magnet is 25 mm). The frequency of the vibration can be easily adjusted by the input voltage of DC motor.

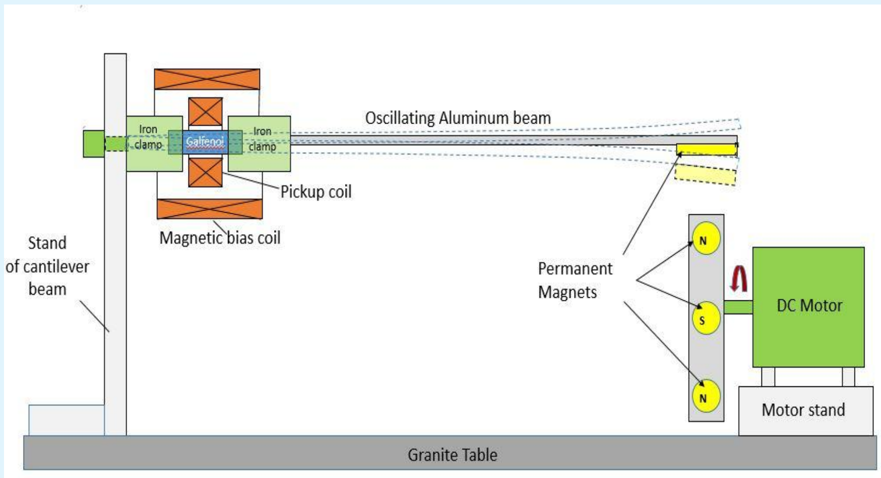

Figure 1: Schematic structure of the harvester.

	Pickup coil	DC bias coil
Number of turns	1500	567
Wire thickness (mm)	0.3	1
Dimension (mm)	l=20 d_{in}= 22 d_{out} = 38	l=42 d_{in}= 75 d_{out} = 95
Resistance (Ω)	33	3.7

Table 1: Pickup coil and magnetic bias coil specifications.

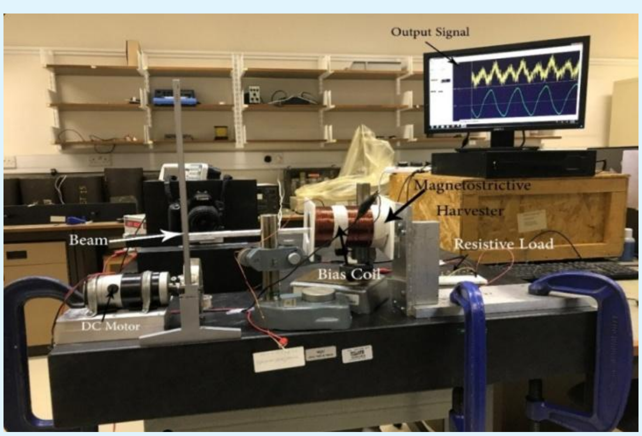

Figure 2: Experimental setup of magnetostrictive harvester.

The strain of the Galfenol, because of bending, produces a variable magnetic field inside the Galfenol. Based on the Faraday's law, a pickup coil, around the Galfenol, is responsible to convert the variable magnetic field to electricity. The pick-up coil is 1500 turns coil with 33 ohm resistance and 20 mm length and its wire is 0.3 mm thickness. The pickup coil is connected to a wide range of resistors (1 to 4700Ω). The generated voltage and power are measured across the resistive loads. The tests are done in different frequencies by adjusting the rotational speed of DC motor. It is revealed that the frequency coincident with the natural frequency of the cantilever beam (19.2 Hz) shows the highest performance.

Results of Experiments

The relationship between induced voltage in the pickup coil and resistor loads in the presence of different magnetic fields are shown in Figure 3. The generated voltage is enhanced by increasing the resistor loads. In most of the bias magnetic fields, the induced voltage saturates at 1500 Ω. Furthermore, the induced voltage improves in the presence of bias magnetic fields and reaches its maximum value, 933 µV, at 2 A current bias. By increasing the magnetic bias to more than 2 A, the generated voltage is reduced. Figure 4 illustrates the general behavior of the generated power across various load resistors. The generated power increasing and reach its maximum value at 98Ωand reduces by higher value of resistive load. It is also obvious that magnetic bias enhances the generated power and the maximum power, 2654 μW, is achievable at 2 A current bias. The main reason to have higher voltage or power in a certain magnetic bias field can be referred to the fact that magnetic permeability of magnetostrictive materials depends on the bias magnetic fields. In other words, the maximum magnetic permeability occurs in certain value of magnetic field. For example, in this harvester the maximum permeability happens in 2 A current bias. Another important issue is the energy density generated by this macroscale harvester that is almost 1535μW/cm³.

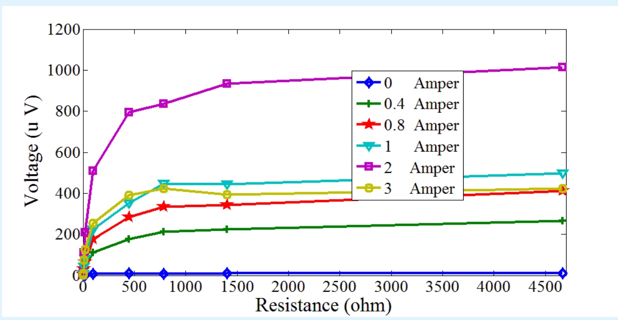

Figure 3: Generated voltage in different resistances and biases.

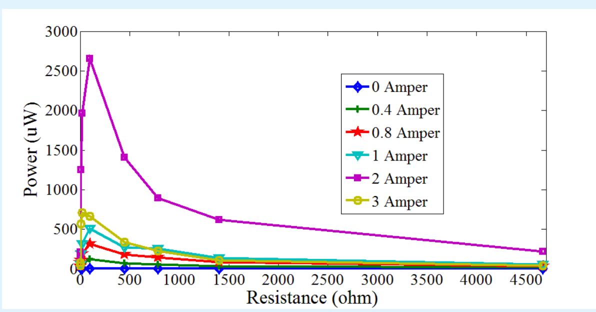

Figure 4: Generated power in different resistances and biases.

Conclusions

In this paper, a macroscale magnetostrictive velocity driven energy harvester is proposed. This harvester has non-vibrating base and the external transverse force can be applied at any point of the beam. Due to ductility, high stiffness, machinability and suitability for welding, Galfenol has been chosen as the active material of this harvester. The performance of the presented macroscale harvester was measured in the presence of various magnetic bias by different resistive load. The harvester showed the highest performance when it was excited by 19.2 Hz that is the natural frequency of harvester. The energy density extracted from this harvester was 1535 μW/cm³ in the presence of 2A current bias across load resistance of 98 Ω. Such an energy density generated by this harvester shows its reliability as an energy source for photovoltaic solar Gilders in cloudy and windy weathers.

Acknowledgment

This work was done under the project number (CL/SQU-UAEU/16/05) which was funded from the joint research project in Sultan Qaboos University in Oman.

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