Harvesting vibratory energy with magnetostrictive materials

Zhangxian Deng and Marcelo Dapino[*]

Smart Vehicle Concepts Center, Department of Mechanical and Aerospace Engineering, The Ohio State University, Columbus, OH, USA, 43210

[*]Email: dapino.1@osu.edu

Abstract

Energy harvesters convert vibrations into usable electrical energy thus providing sustainable power sources for wireless and portable devices. Although much of the literature on smart material harvesters focuses on piezoelectric materials, this article deals with the utilization of magnetostrictive materials such as Galfenol (iron-gallium) and Terfenol-D (iron-terbium-dysprosium) as vibration energy harvesters. Because the power delivery depends on the configurations of energy harvesters and the properties of vibration sources, no single performance metric is suitable for providing a comparison between harvester materials. In this article, various performance metrics are considered and a quantitative comparison of existing magnetostrictive energy harvesters is established for both axial-type and bending-type harvester designs.

1. Introduction

Power reduction in integrated circuits enables wireless sensor networks in a variety of applications including health monitoring systems, space systems, and vehicle systems. Key technologies behind the wireless sensors such as the central processing unit (CPU) and the random-access memory (RAM) have experienced rapid development in the past few decades, as shown in Fig. 1. However, current wireless devices are usually driven by electrochemical batteries, which are only suitable for short-term operations due to the constrained battery size and the limited power density. For long-term applications, batteries require time-consuming recharging or replacement.

Energy harvesters convert structural vibrations into usable electrical energy thus complementing and in some cases replacing batteries. The amplitude and frequency of vibration sources vary significantly in different environments of interest. For instance, vibrations in bridges are in low frequencies and low amplitudes;[18] vibrations in household appliances such as microwave ovens have moderate frequencies and amplitudes.[18] Multiple types of vibration energy harvesters, such as electromagnetic and electrostatic devices,[7–9,14–16] have been developed in the literature using passive materials. Certain smart materials can be an attractive energy transduction technology due to the fast frequency response and solid state operation. Much of the literature on smart material harvesters focuses on piezoelectric materials. However, piezoelectric materials

Figure 1. Relative improvements in computer technology from 1995-2015. The Intel® central processing unit (CPU) is evaluated in terms of the transistors count per integral circuit chip; the speed of random-access memory (RAM) is evaluated in terms of module bandwidth; the Li-ion battery (LIB) is evaluated in terms of energy storage density (W·h/Liter).
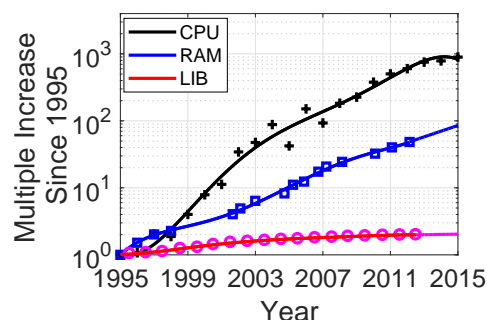
are brittle thus requiring complicated protection mechanisms. The reliability of piezoelectric materials are also limited because of depolarization.

Magnetostrictive materials coupling mechanical and magnetic energies have recently been investigated in energy harvesting applications. These materials convert mechanical stress into magnetization change, which can be converted into stored voltage using electronic circuitry. Some magnetostrictive materials, such as Galfenol (iron-gallium) and Alfenol (iron-aluminum), are mechanically robust and can be conventionally machined into a desired shape. Unlike existing piezoelectric harvesters, which require additional power management circuits, magnetostrictive energy harvesters exhibit relatively low output impedance, thus are able to directly drive electrical loads.

This article reviews the state of the art of magnetostrictive vibration energy harvesters. Energy harvesting mechanism is presented in Section 2. Typical harvester configurations and associated performance metrics for axial force excitation and base excitation are summarized in Section 3. Following the proposed performance metrics, Section 4 provides a quantitative comparison of existing energy harvesters based on magnetostrictive materials, especially Galfenol and Terfenol-D.

2. Energy harvesting mechanism

A typical magnetostrictive harvester consists of mechanical, magnetic, and electrical systems, which are coupled via two mechanisms. The magneto-mechanical coupling is provided by magnetostrictive materials. According to the Stoner-Wohlfarth (SW) approximation,[23] the magnetostrictive materials are assumed to be a collection of non-interacting magnetic domains where each exhibits a local magnetization M_s, as shown in Fig. 2.

The bulk magnetization is determined by the stress- and field-induced domain orientation. When the mechanical energy dominates, as shown in Fig. 2(a), magnetic domains prefer the basal plane which is perpendicular to the stress direction thus inducing zero bulk magnetization. When magnetic energy dominates, magnetic domains are forced in parallel to the field direction, thus creating the maximum bulk magnetization M_s, as shown in Fig. 2(c). When the mechanical and magnetic energy are comparable, as shown in Fig. 2(a), any variation in mechanical input can rotate the magnetic domains thus causing varying magnetization. For small coaxial stress and magnetic field perturbations, the nonlinear magneto-mechanical coupling can be linearized as

$$\Delta B = d\Delta T + \mu^{H_0}\Delta H,$$
$$\Delta S = s^{H_0}\Delta T + d\Delta H,$$
(1)

where d is the piezomagnetic constant, s^{H_0} is the elastic compliance, μ^{H_0} is the magnetic permeability, ΔH is the magnetic field increment, ΔT is the stress increment, ΔB and ΔS are the corresponding increments of flux density and strain along the input direction, respectively.

The electro-magnetic coupling connecting magnetic and electric systems is provided by coils around the magnetostrictive components. According to Faraday's law, the electrical voltage V induced by the varying mechanical input is

$$V = -N_c A_c \frac{\partial B}{\partial t} = -d N_c A_c \frac{\partial T}{\partial t},$$
(2)

where A_c is the coil's cross section and N_c is the total number of turns. Equations (1) and (2) apply to both stress sensors and energy harvesters. For sensing applications, the priority in system design is to improve the linearity between the voltage V and the excitation stress T. For energy harvesting applications, system design focuses on maximizing the electrical power generated ($V.I$) when the harvester is connected to a storage impedance.

Figure 2. Orientations of magnetic domains under bias magnetic field H_0 and varying stress: (a) magnetic domains are aligned in perpendicular to the applied stress when mechanical energy dominates; (b) magnetic domains rotate due to the interplay of mechanical and magnetic energies; (c) magnetic domains are aligned in parallel to the applied magnetic field when magnetic energy dominates.
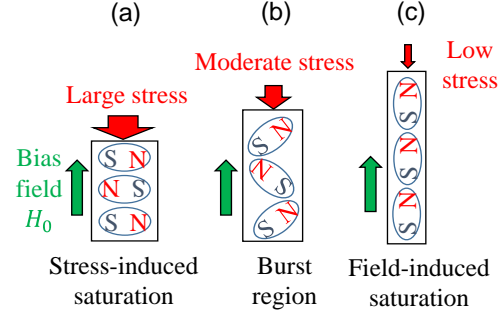
3. Configurations and performance metrics

Following the aforementioned energy harvesting mechanism, two types of magnetostrictive energy harvesters have been developed for axial excitations and base excitations, respectively. Performance metrics describing the power delivery in each excitation type have been proposed.

3.1 Axial-type

A typical axial-type magnetostrictive energy harvester is presented in Fig. 3. AC-DC converters and charging circuits have been designed to charge batteries or capacitors.[27] To simplify the discussion, most studies attached a resistor R_L to the coil and equated the energy harvesting capability to the joule heat dissipated on R_L.

The performance of the axial-type energy harvesters is usually described by the energy conversion efficiency η and

$$\eta = \frac{W_{out}}{W_{in}}, \tag{3}$$

where W_{out} is the electrical energy dissipated on R_L and W_{in} is the total mechanical energy input. For impulsive excitations,

$$W_{out} = \int_0^{+\infty} \frac{V_L(t)^2}{R_L} dt; \quad W_{in} = 0.5F_0D_0; \tag{4}$$

where $V_L(t)$ is the voltage across R_L, F_0 is the amplitude of the impulsive force, and D_0 is the initial deflection due to the applied force.[25] For periodic force excitations,

$$W_{out} = \int_0^{T_0} \frac{V_L(t)^2}{R_L} dt; \quad W_{in} = \int_0^{T_0} F(t)\dot{D}(t)dt; \tag{5}$$

where T_0 is the period of the input stress and $D(t)$ is the corresponding displacement induced by the input force $F(t)$.
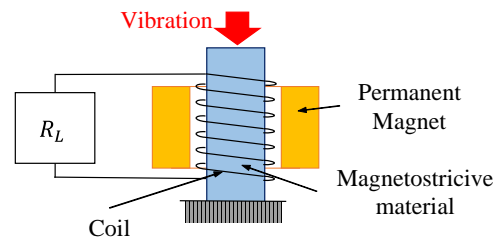

Figure 3. Typical configuration of axial-type magnetostrictive energy harvesters.
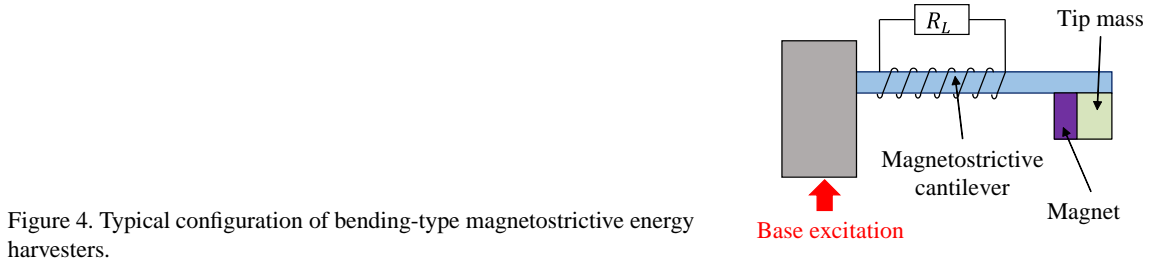
Figure 4. Typical configuration of bending-type magnetostrictive energy harvesters.

The other performance metric for the axial-type harvester is the power density PD, which describes the output power generated by a unit volume of magnetostrictive materials.[4,25,27,31] The power density PD is

$$PD = \frac{W_{out}}{T_0 V_a}, \tag{6}$$

where V_a is the volume of active material.

3.2 Bending-type

The axial-type energy harvester needs to be installed in the load path. In contrast, the bending-type energy harvesters, as shown in Fig. 4, are able to scavenge useful electrical energy from any vibrating surfaces. Base excitation causes bending in the cantilever beam especially when the excitation frequency is around the beam's resonance. Stress due to the bending is converted into magnetization change, which is then converted into electrical voltage on the coil. The energy conversion efficiency η and power density PD have been applied to the evaluate the bending-type harvesters in previous studies.

However, performance of the bending-type harvesters also relies on the properties of vibration sources. To eliminate the source dependence, a normalized power density PD_{norm} is defined as[6]

$$PD_{norm} = PD \frac{f_0^2}{A_0^2} = \frac{W_{out}}{T_0 V_a} \frac{f_0^2}{A_0^2}, \tag{7}$$

where A_0 is base acceleration amplitude and f_0 is the excitation frequency.

4. Selected harvester designs

4.1 Axial-type

Implementing the configuration in Fig. 3, Berbyuk[1] applied a 6.35 mm diameter and 50 mm long Galfenol rod as the active component. A maximum energy conversion efficiency of 6% and a maximum power density of 284 mW/cm^3 were observed from a 60 Hz, 55 MPa amplitude sinusoidal axial stress. Deng[3] implemented a 7 mm diameter and 10 mm long Terfenol-D rod as the active component. The maximum power density and energy conversion efficiency are 190.1 mW/cm^3 and 19%, respectively, when a 750 Hz, 7.3 MPa sinusoidal axial stress was applied.

The axial-type magnetostrictive harvester has been implemented to scavenge electrical energy from impulsive sources, such as human walking[26,29,30,32] and vehicle tires.[13] Commercial products generating electrical energy from ocean waves have reported to reduce the electricity cost to 2-4 cents/kWh.[17]

One of the drawbacks associated with the axial-type harvester is that a large axial force is required. Staley and Flatau[21,22] installed the axial-type harvester underneath a long cantilever beam, as shown in Fig. 5. Magnified by the leverage, the inertia force due to the tip mass can induce large axial stress, thus causing significant flux density variation in the magnetostrictive rod. The other drawback is that the power output from an axial-type harvester is limited at high frequencies due to the mechanically-induced eddy currents.[20] Berbyuk and Sodhani[2] inserted a 15 mm diameter and 50 mm long laminated Terfenol-D rod into a coil, as shown in Fig. 3. The maximum energy conversion efficiency was improved to 25% at 500 Hz.
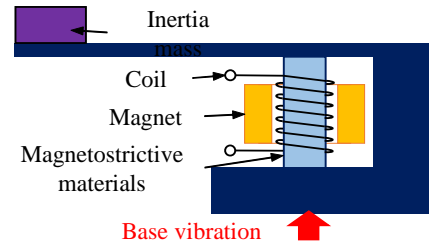

Figure 5. Axial-type magnetostrictive energy harvester that can scavenge energy from base excitations.

4.2 Bending-type

Most axial-type magnetostrictive energy harvesters need to be placed in the load path and exhibit limited performance at high frequencies. On the contrary, the bending-type are ideal for scavenging energy from any vibrating surfaces. Depending on the configuration of the magnetostrictive cantilever, existing bending-type magnetostrictive harvesters can be sorted into four categories: a single layer magnetostrictive beam, a bimorph beam, a composite beam, and a unimorph beam, as shown in Fig. 6.
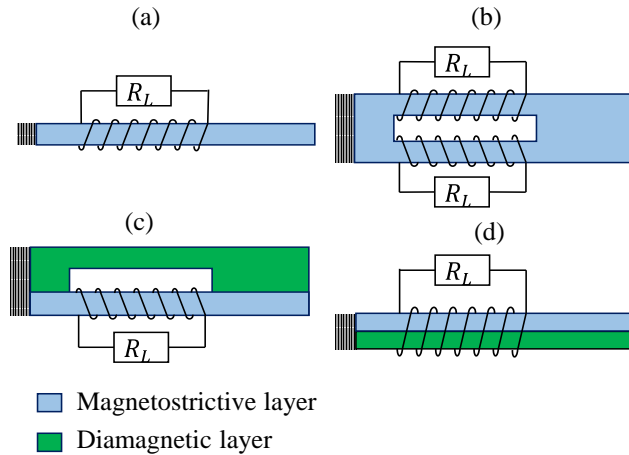

Figure 6. Cantilever beam configurations of bending-type magnetostrictive energy harvesters: (a) single magnetostrictive layer; (b) magnetostrictive bimorph; (c) magnetostrictive composite beam when the coil is wound around the magnetostrictive layer only; (d) magnetostrictive unimorph when the coil is wound around the entire beam.

Zucca et al.[33] studied a single-layer magnetostrictive beam as shown in Fig. 6(a). Since half of the magnetostrictive layer operates in compression and the other half is in tension. Stress-induced flux density in each half compensate each other. Thus, the output power in the single-layer configuration is negligible.

Ueno and Yamada[25] first proposed a bimorph configuration, as shown in Fig. 6(b), which consists of two parallel Galfenol beams. The gap between the two Galfenol layers provides enough space for a pair of pickup coils. Each Galfenol beam is away from the mid-plane and thus operating purely in tension or, alternatively, purely in compression. Similar to the axial-type harvesters, such tensile or compressive stress

is able to induce electrical voltage on a pair of coils. Experimental results have shown that the energy conversion efficiency of a Galfenol-based bimorph harvester can reach 16%. However, the output power from the bimorph configuration is constrained, due to the negligible flux density variation associated with the shear deformation and the saturation induced by the tensile stress.

To eliminate the saturation effect, Kita et al.[10] has recently developed a composite beam structure which consists of a diamagnetic layer and a magnetostrictive layer, as shown in Fig. 6(c). The cantilever beam is initially deflected due to its body weight. Due to the pre-deflection, the magnetostrictive layer always operates in compression and is able to induce flux density variation in a full cycle. Experimental results show that the maximum energy conversion efficiency is increased to 35%.

Wang and Yuan[27] eliminated the shear stress by creating a unimorph beam, where the magnetostrictive materials are directly bonded to a passive layer, as shown in Fig. 6(d). However, most of these unimorph harvesters were tested too close to the electromagnetic shaker in previous studies.[10,27,31] Deng and Dapino[4–6] improved experiments by shielding the unimorph from the shaker and enhanced output power density through electrical impedance matching. The maximum power density and normalized power density are 6.88 mW/cm^3 and 14.88 μWs^2/m^5, respectively, under a 3 m/s^2 amplitude, 139.5 Hz sinusoidal base excitation.

5. Summary

Energy harvesters that scavenge usable electrical energy from ambient vibrations are able to provide sustainable power sources for current wireless sensor networks. This article reviewed the state of the art of the vibration energy harvesters based on magnetostrictive materials.

Depending on the stress state in the magnetostrictive component, this article categorized existing magnetostrictive harvesters into the axial-type and the bending-type. The axial-type harvesters are able to generate significant electrical power over a broad frequency range. However, the output power level drops dramatically at high frequencies due to the eddy current loss. Hence, lamination is required to further expand frequency bandwidth. The axial-type harvester also needs to be installed in the load path, which is not always possible in practice. Certain mechanically-robust magnetostrictive materials such as Galfenol, Alfenol, and Metglas enables the bending-type harvester that can scavenge electrical energy from any vibrating surfaces. Four different bending-type magnetostrictive harvesters were investigated in this article. The composite beam provides the maximum energy conversion efficiency and the unimorph configuration is able to provide the maximum output power density.

One of the key limitations of the bending-type harvester is that the device generates significant amount of energy only near system resonance. Future studies should explore bandwidth enhancement techniques, for instance, combining bistable structures with magnetostrictive unimorph harvesters.[6] The other key limitation is that a coil is always necessary to convert magnetic energy to electrical energy. To eliminate the bulky coil from magnetostrictive systems, previous studies have developed magnetoelectric composites[11,12] and manufactured micro-scale magnetostrictive systems.[19,24,28] Future studies should investigate potential solutions following these paths.

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