Galfenol Energy Harvesting

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Introduction

Pumps and motors are ubiquitous in industrial, commercial, and defense activities. All of these pumps and motors, including attached structures, exhibit vibrations of various frequencies during operation. Other structures such as buildings, ships, bridges, and roadways also exhibit extraneous vibrations during everyday use. While these vibrations are generally accepted as a nuisance, there has been considerable research on harvesting this vibration energy to power remote or wireless sensor networks or provide power for other uses such as alarms or GPS locaters. This article focuses on harvesting vibrational energy using an iron-gallium based magnetostrictive material, Galfenol.

Galfenol is a magnetic smart material that responds to external stresses by changing its magnetic state. These changes in magnetic state can induce voltage in coil(s) which is then converted to useful power.

Galfenol Background

Table 1. Typical Galfenol Magnetic and Mechanical Properties.*

Saturation Strain	200 – 250 ppm
Piezomagnetic Constant, d_{33}	15 – 30 nm/A
Saturating Magnetic Field	100 – 250 Oe
Saturation Magnetic Flux Density	1.5 Tesla
Magnetic Permeability, μ_r	75 – 100
Coercivity, H_c	10 Oe
Hysteresis (major loop)	1000 J/m^3
Curie Temp.	950 K
Density	7800 kg/m^3
Hard Young's Modulus	75 GPa
Soft Young's Modulus	40 GPa
Tensile Strength	350 MPa
Elongation	1%

*Measured on Galfenol polycrystalline material, 18.4 at% Ga, produced by ETREMA Products, Inc., Ames, IA 50010.

Galfenol ($Fe_{100-x}Ga_x$), an iron-gallium alloy, is a mechanically robust magnetostrictive smart material discovered in 1999 where x can be varied to achieve the desired magnetic and mechanical properties[i]. Interest in Galfenol has been increasing over the past several years as it is integrated into new magnetostrictive devices such as actuators, sensors, and energy harvesters. This alloy system exhibits several unique advantages over legacy smart materials such as Terfenol-D and piezoceramics. These legacy material systems lack the mechanical robustness and their performance is more sensitive to temperature. Galfenol offers a tensile strength 20 times that of typical piezoceramics[ii] making it applicable for use in harsh and shock-prone environments. Galfenol can be readily machined using conventional machining techniques, formed using standard metal working practices, forged, rolled, drawn, and welded to other ferrous materials while maintaining excellent magnetic properties. Galfenol offers a tensile strength of approximately 350 MPa and has elongation at fracture of 1%, which means that the material can operate magnetically while in tension. Therefore, there is no need to apply a compressive pre-load to Galfenol, a key differentiator. Another characteristic which makes Galfenol desirable is that it is possible to machine threads and form Galfenol into complex shapes allowing for easy integration into new and existing designs. The combination of these attributes makes Galfenol an attractive technology for next-generation transducers, sensors, and energy harvesters. A list of Galfenol properties measured on samples produced by ETREMA Products, Inc., is shown in Table 1.

Simplified behavior of magnetostrictive materials can be represented by a set of linear, coupled magnetostrictive equations:

$$S = s^H T + d_{33} H \tag{1}$$

$$B = d_{33}^* T + \mu^T H \tag{2}$$

where S is strain, s^H is mechanical compliance (m^2/N) at constant H, H is magnetic field (A/m), T is stress, d_{33} is the magnetostrictive coefficient or change in strain with H at a constant stress, B is magnetic flux density, d_{33}^* is the inverse magnetostrictive coefficient or change in B with stress at a constant H, and μ^T is the magnetic permeability at constant T. Equation (2) is of most interest for energy harvesting applications since the change in magnetic flux density with changing stress is the phenomenon used to harvest vibrational energy using these materials.

Other energy harvesting methods

Off-the-shelf vibration energy harvesters are readily available. These energy harvesters work efficiently by matching their primary resonant frequency with the operating frequency of the vibrational source. In practice, matching the frequencies requires tuning the harvesters for each specific application. A small deviation, less than ± 5 Hz, from that resonant frequency drops their power output by more than 50%. There are two basic technologies used in this type of energy harvester: piezoelectric materials and magnetic induction.

Piezoelectric materials are solid-state smart materials which respond to applied stress by generating an electrical charge. Piezoelectric materials typically respond well to large forces and small displacements. One typical arrangement for a piezoelectric energy harvester is to incorporate it into a resonant bending beam which is tuned to a specific operating frequency.[iii] This type of energy harvester has a very limited bandwidth and tends to be fragile due to the brittle nature of piezoelectric materials.

Magnetic induction-based energy harvesters consist of a spring attached to magnets which move inside a coil, thus inducing voltage in the coil due to changing magnetic flux.[iv,v] These energy harvesters are resonant devices and also exhibit limited bandwidths.

Unfortunately, the frequency spectrum of vibrations is often not predictable especially during power-up, power-down, and under variable loading conditions. A move toward variable frequency drives to improve energy efficiency of industrial processes will further reduce the applicability of highly resonant vibration energy harvesters.[vi] The majority of commercially available energy harvesters are also fragile in nature and cannot survive exposure to significant forces excluding them from use where large forces and vibrations are possible. Etrema has developed a new family of Galfenol-based vibrational energy harvesters that have the potential to overcome the bandwidth and robustness limitations of existing energy harvesting devices.

Design considerations for Galfenol energy harvesters

The Galfenol energy harvester configuration best suited for a specific application depends entirely on the mechanical environment in which it is used. By tailoring the configuration to match different mechanical loads (forces and displacements) the energy harvester can be very efficient at harvesting vibration energy. The vibrations induce changing stresses in the Galfenol resulting in magnetic flux density changes in the material (Eq. 2), which in turn induce a voltage in a coil. Three Galfenol energy harvester configurations that have been demonstrated for different applications will be discussed.

A bolt-like configuration was demonstrated that operates under forces from 10’s – 100’s of N and displacements on the order of 10’s of µm, a photo is shown Figure 1. Because the energy harvester is driven directly by forces applied to it, the bandwidth is limited only by the input energy; operation of the hardware has been demonstrated from 10-500 Hz. This configuration is very robust and could potentially replace or augment existing fasteners with ones that harvest energy. Galfenol’s unique ability to be machined and welded was leveraged in this design.

Figure 1. “Bolt” type Galfenol energy harvester shown disassembled (left) and assembled (right). Starting from left: Galfenol with welded ends, half of the magnetic return path with permanent magnets integrated, Galfenol with welded ends and coils installed, half of return path with permanent magnets, outer protective housing and end caps, assembled energy harvester.

A second type of Galfenol energy harvester, developed by Dr. Toshiyuki Ueno, Kanazawa University, Japan, utilizes a bending beam similar to the piezoelectric type with correspondingly similar resonant characteristics, ~80 Hz for the device shown in

Figure 2. However, the Galfenol energy harvester is extremely robust and has been demonstrated on scales from <10 mm beam lengths up to >100 mm beam lengths. This design has the potential to be scaled up for harvesting power in the W, kW and MW range depending on the volume of Galfenol material incorporated in the device. While it is similar in concept to the piezoelectric beam, Galfenol's unique properties enable a large scale, more robust energy harvester with significant energy harvesting capability.

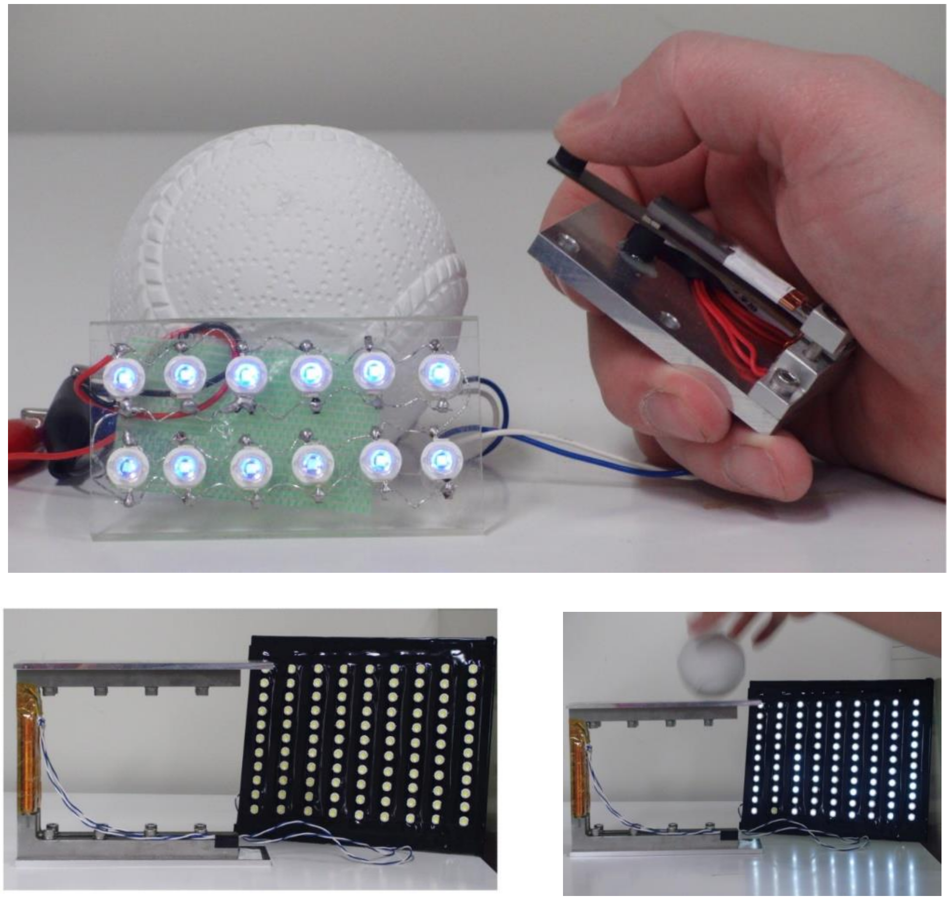

Figure 2. Galfenol resonant beam energy harvester. Photo courtesy of Dr. Toshiyuki Ueno, Kanazawa University, Japan. Galfenol beams are in the same region as the coils and have dimensions of 3 mm thick x 15 mm width x 80 mm length

A third configuration of energy harvester is targeted for pump or motor mount applications, shown in Figure 3. Spring-like elements are used to match the stiffness of the overall device with that of existing motor mounts. The spring elements also serve to amplify the forces transferred to the Galfenol active material. This type of energy harvester responds directly to forces and displacements of the pump or motor and is not bandwidth limited. Operation of the hardware has been demonstrated from 10-200 Hz and under 100 µm of displacement at low frequencies.

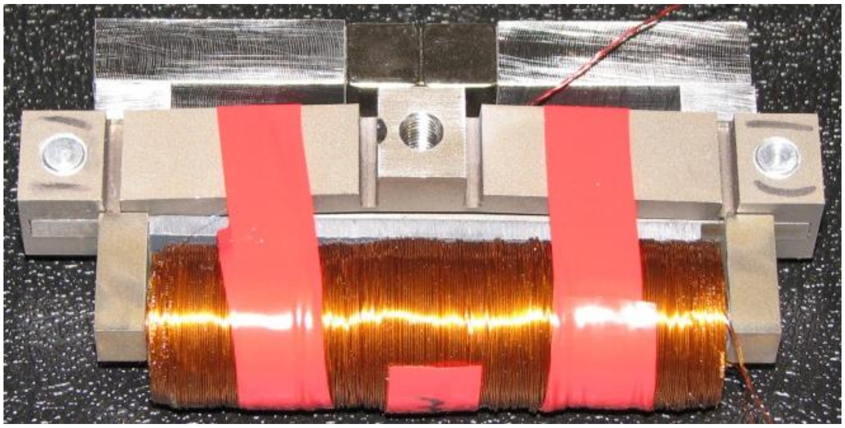

Figure 3. Proof-of-concept pump/motor mount Galfenol energy harvester. Coil in foreground, "spring" mount element with Galfenol in center, permanent magnets in rear. Overall dimensions for the Galfenol are 4.6 mm thick x 15.2 mm width x 111.3 mm length.

In addition to the mechanical aspects of a Galfenol energy harvester design, there are magnetic considerations. In order to maximize changes in flux density, a permanent magnet is needed to magnetically bias the Galfenol. Other components which make up the magnetic circuit include high flux density magnetic return paths and air gaps. In order to maximize the changing magnetic flux in the Galfenol, air gaps should be minimized and particular attention paid to the overall efficiency of the magnetic circuit.

The changing magnetic flux is converted to useful electrical energy via a wire-wound coil. Voltage induced in a coil from a changing flux density is given by Faraday's law where *V* is the induced voltage, *N* is the number of turns in a coil, *A* is the cross-sectional area of the Galfenol,

$$V = -NA\frac{dB}{dt} \qquad (3)$$

and *dB/dt* is the change in magnetic flux density with time. Equation 2 can be used to estimate the changing flux density with a changing stress by taking a time derivative which results in an expression for *dB/dt*. Assuming that the magnetic field, H, is constant and substituting for *dB/dt* in Eq. 3, the open-circuit voltage in a Galfenol energy harvester can be estimated as shown in equation 4.

$$V = -NAd_{33}^{*}\frac{dT}{dt} \tag{4}$$

Maximum power output from a particular energy harvester configuration can then be estimated by assuming a purely resistive load of the same value as the magnitude of the coil impedance, *R*, shown in equation 5. This value provides a good estimate of the potential of an energy harvester.

$$P_{max} = \frac{V^2}{4R} \tag{5}$$

Once a voltage is generated in the coil the resulting power output from the energy harvester must be conditioned in order to provide a useful form of energy to power sensors or other electronics. A critical aspect of power conditioning is the coil. Coil design is a balance between matching the in-coming energy with the requirements of the power conditioning electronics. Voltage is increased by adding turns to the coil, however, there is a corresponding increase in coil resistance. Impedance matching between the coil and power conditioning electronics is important for maximizing the amount of power transferred. In addition, space for the coil may be limited and there is a weight penalty associated with larger wire gauges and additional turns.

Power conditioning electronics for Galfenol energy harvesters typically consist of voltage rectification to convert the raw voltage output response to a DC signal and voltage regulation to regulate the DC power to the level(s) required for the down-stream electronics. Figure 4 shows an example layout of a complete energy harvesting system. This particular system provides a 3.3V DC signal to the down-stream components. Also shown are the rectification and regulation circuitry along with the power management and energy storage components. The Charge Pump provides a positive and negative voltage to the Active Rectification component in order to “boot strap” the entire circuit from a completely discharged state. Operation of bread board hardware similar to the schematic shown consumed 106 µW of power and was 60% efficient with respect to supplying power to the load.

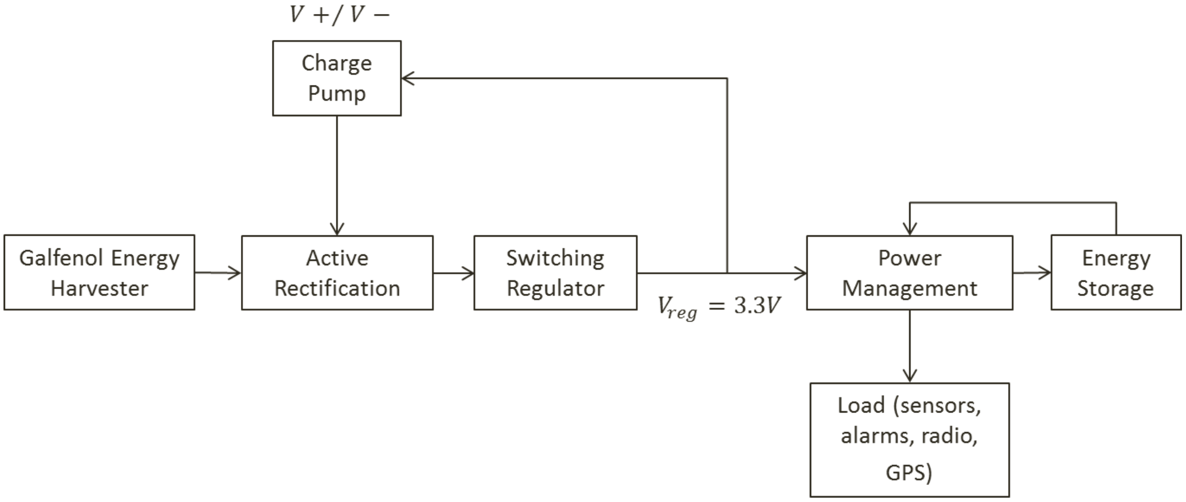

Figure 4. Schematic layout of a complete Galfenol energy harvesting system. Represented are the power conditioning electronics, power management circuitry, and energy storage components; in addition, to the Galfenol energy harvester and load.

Applications

Galfenol energy harvesters are suitable for use in a wide range of applications, especially those with broadband input energy or with varying operating frequencies. The bolt-type energy harvester, Figure 1, generated power in excess of 60 mW with force inputs on the order of 100 N in a package size of ~ 30 cm^3. Instantaneous peak powers of 2 W have been demonstrated using a resonant-beam type energy harvester,

Figure 2, with overall dimensions on the order of 250 mm length. Motor-mount type energy harvesters, Figure 3, are predicted to produce on the order of 10's of mW with typical vibrations present in vacuum pumps and motors, as examples; however, this capability is still in development.

Laboratory demonstrations have shown that different configurations of Galfenol energy harvesters can provide "free" energy to operate remote sensors and radios. The most promising applications include fasteners, mounts and mounting bolts for large industrial pumps and motors and large-scale energy harvesters where significant forces and/or displacements are present.

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[ii] J. Atulasimha, A.B. Flatau, Smart Mater. Struct. **20,** (2011) 043001 (15pp).
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