

MAGNETOSTRICTIVE-PIEZOELECTRIC COMPOSITE STRUCTURE FOR ENERGY HARVESTING

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Abstract: Harvesters coupling magnetostrictive and piezoelectric materials are investigated. The energy conversion from slow magnetic field variations to electricity is detailed. Experimental results are exposed for two macroscopic demonstrators based on the translation and rotation of a permanent magnet, using a choice of piezoelectric (fiber composite and bulk PZT) and magnetostrictive (amorphous FeSiB ribbon and bulk Terfenol) materials. Quasi-static (sub-Hz) harvesting is achieved with exploitable output voltages. Integrated micro-harvesters using sub-micron multilayers of active materials have been built and are currently being characterized.

Keywords: magnetostrictive, piezoelectric, energy harvesting.

INTRODUCTION

We report investigations on composite structures for energy harvesting. Many harvesters exploit electromechanical conversion to transform, without contact, mechanical energy into electricity. Several kinds of such converters are already in use, but most of them suffer from low output voltage and poor efficiency issues at low scale ($< 1\text{cm}^3$), especially in quasi-static mode. In order to outperform those harvesters, we suggest a new kind of converter based on the coupling of piezoelectric and magnetostrictive materials. Such so-called artificial “magneto-electric” or “multi-ferroic” composites have already been studied in actuators [1,2] or sensors [3], and are only very recently being considered for generators [4].

THEORY

Limitations of Faraday’s Law at low speeds.

Electromechanical energy conversion is described by Faraday’s law, which links the time variation of magnetic flux ϕ to the electromotive force e :

$$e = -\frac{d\phi}{dt} \quad (1)$$

For miniature devices the magnetic flux ϕ is correspondingly small since it is proportional to the coil area and the moving magnet’s volume. Moreover the dt term is very large for quasi-static movements. To overcome these limitations, our approach is based on the coupling between piezoelectric and magnetostrictive materials.

Coupling magnetostriction and piezoelectricity

Piezoelectric materials are not time dependant if “leaks” are neglected, and thus they may prove useful for our purpose. However, in order to produce high voltage, piezoelectrics require high stress over small displacements, provided through contact forces.

Magnetostrictive materials can produce high stress

to deform the piezoelectric over small deformations. They are compatible with small strain and can be “activated” remotely, via magnetic field interactions.

In a variable magnetic field, a magnetostrictive material stretches or shrinks. When coupled to a piezoelectric, this deformation displaces electric charges in the material, thus achieving the electromechanical conversion. Figure 1 details the various conversion stages:

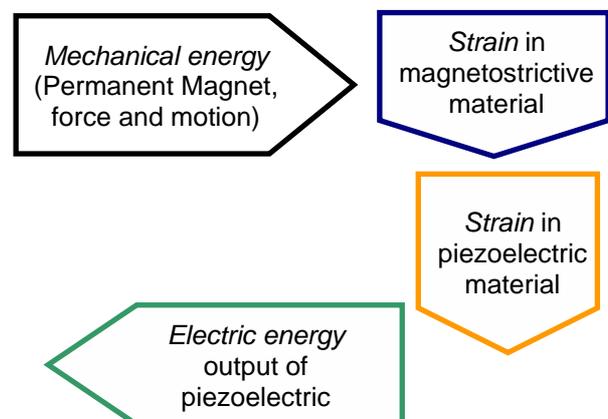


Figure 1: Diagram of conversion.

The coupling of these two materials allows energy conversion from magnetic/mechanic to electricity. The quasi-static motion of a permanent magnet near the magnetostrictive element can produce a relatively high voltage at the output of the piezoelectric element, regardless of the device’s scale. Figure 2 presents the operating principle of the conversion:

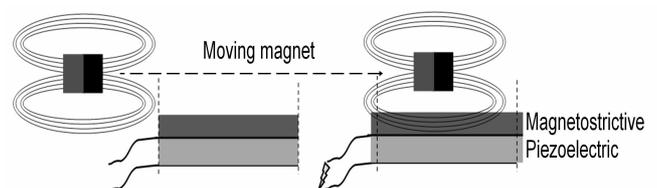


Figure 2: Magneto-electro-mechanical conversion.

MATERIAL CHOICE

Piezoelectric properties

Piezoelectric materials displace electric charges under mechanical deformation, and vice versa. Nowadays, PMN-PT (lead magnesium niobate-lead titanate) ceramics have the best coupling coefficient. This coefficient qualifies the capacity of converting energy between electricity and strain. However, we choose PZT ($\text{PbZr}_x\text{Ti}_{1-x}\text{O}_3$) oxides which also have good coupling coefficients: PZTs are widely available and thin films can be produced by SolGel method.

PZTs work along several modes, each mode having its own coupling coefficient. The highest mode, d_{33} , is when deformation and polarization are in the same direction, as shown in figure 3. Often, to maximize the electric field E , piezoelectrics are used in d_{31} mode where polarization and deformation are orthogonal.

We use Micro Fiber Composites (MFC, from Smart Material [5]), made of $130 \times 150 \mu\text{m}$ micro fibers of monocryalline PZT-5, polarized along their length, and encased between two Kevlar/Kapton sheets. MFCs use the PZT material in its best mode, and exhibit strains of up to 1500 ppm under 1500 V.

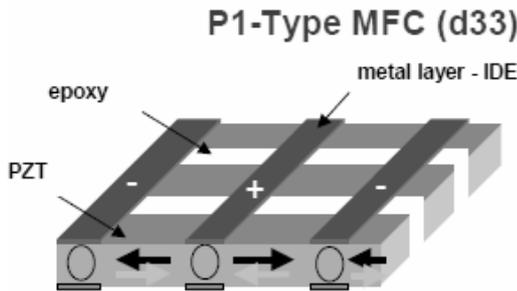


Figure 3: MFC in d_{33} mode.

Magnetostrictive properties.

Table 1 compares various magnetostrictive materials according to their magnetostriction coefficient λ_s and the magnetic induction needed to reach this magnetostriction. The magnetostrictive coefficient λ_s qualifies the maximum strain that can be obtained from the material.

Table 1: Magnetostrictive materials

| | λ_s (ppm) | Induction (mT) |
|----------------------|-------------------|----------------|
| Metglass (FeSiB) | 30 | 0,05~30 |
| Terfenol-D | 1500~2000 | 300 |
| Galfenol | 400~500 | 10 |
| FeCo (bulk) | 80 | 10~50 |
| FeCo (film) | 50~120 | 1~20 |
| TeFe/Fe (multilayer) | 500 | 10~20 |

Terfenol-D (TbDyFe-based compounds) exhibits the best magnetostriction coefficient but under large magnetic induction. In contrast FeSiB metglass has poor magnetostriction, but it can be stressed easily.

EXPERIMENTAL RESULTS

Three piezoelectric-magnetostrictive devices are investigated. First, a mono-directional device in which a permanent magnet translates above the device. Secondly, a prototype where the permanent magnet rotates. Third, the integration of the rotating device.

Translation

First, we investigate a device where the permanent magnet is translating. This prototype works along the preferred direction imposed by the geometry and structure of the Terfenol-D element.

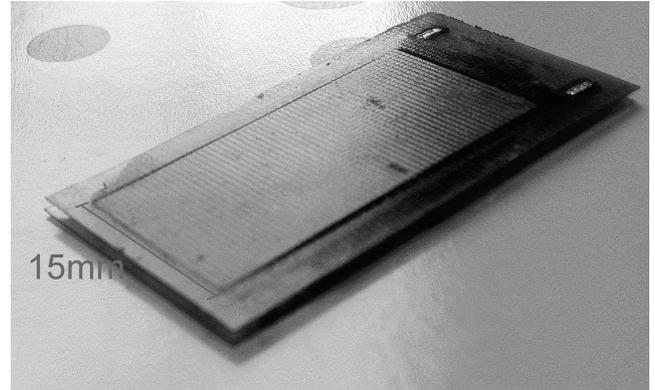


Figure 4: Terfenol-D plate glued between 2 MFC.

Figure 4, the macroscopic harvester is composed of a Terfenol-D plate ($30 \times 15 \times 1 \text{ mm}$) glued between two MFC piezoelectrics. All elements have an active area of $28 \times 14 \text{ mm}$, thus ensuring a good match between their surfaces and volumes. We choose to use two MFCs to keep the symmetry of the device.

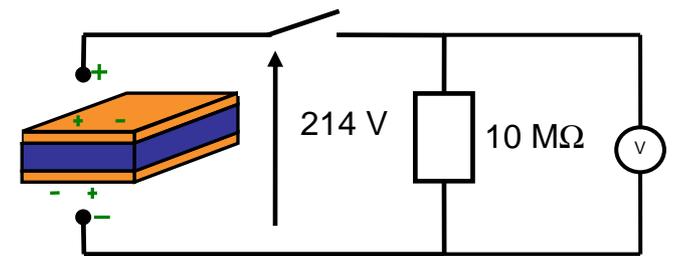


Figure 5: Measuring circuit.

The device is subjected to a variable magnetic field which rises to 0.3 T in 1 second. The voltage produced by the piezoelectric is measured several seconds after the stress is applied. The piezoelectric needs to be in open circuit to maintain its maximum output voltage: the circuit is thus closed after applying the stress. The output voltage and the energy dissipated in a $10 \text{ M}\Omega$ load are measured as shown in figure 6. The energy produced is around $95 \mu\text{J}$ and the measured stress is around 650 ppm. Figure 6 shows a maximum voltage at 214 V. A specific electronic circuit must be built to convert and exploit this voltage.

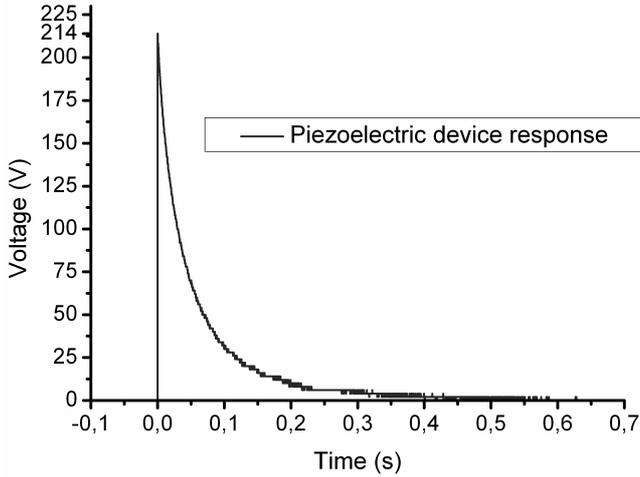


Figure 6: Terfenol/PZT device response under 0.3 T.

A self-powered wireless switch from ENOCEAN needs 50 μJ to send a 64 bit frame. Our device may thus be used as a wireless sensor for opening doors or windows. Even a slow movement can create enough energy to send a frame to a distant control base.

Figure 7 shows the voltage output measured on the piezoelectric after various waiting times. It appears that after 10 minutes (600 s) around 50 % of the voltage is still available. This is possible thanks to the MFC constitution (encapsulated fibers), whereas in bulk ceramics electrical leaks seem much larger [7].

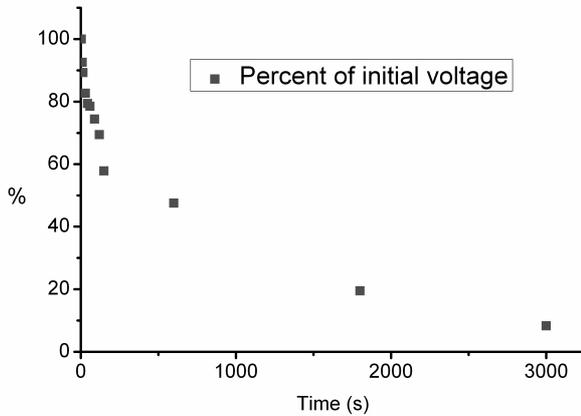


Figure 7: Charges leaking in piezoelectric vs time

Rotation

In the second device investigated (Figure 8), the permanent magnet rotates above the device, instead of translating. The magnetostrictive material's properties and shape should not induce any preferential magnetization direction. Consequently the device is composed of a disc of FeSiB ribbon (diameter 10 mm, thickness 23 μm) glued between two MFCs. FeSiB metglass is amorphous, with full in-plane isotropy.

When a permanent magnet rotates above the device, the easy axis in the metglass also spins [2]. Consequently the metglass disc stresses the MFC piezoelectrics alternately: they are stretched and shortened twice for 1 turn of the magnet.

With an angular offset of 45° between the MFCs, 2 voltage sinusoids are obtained with an electrical offset of 90° .



Figure 8: 100 mm FeSiB Metglass disc glued between 2 MFCs composites.

Figure 9 shows the measured output voltage of one MFC when a permanent magnet is rotated above the device. Above a given speed, the voltage does not depend on the rotation speed. However, self discharge of piezoelectric MFCs becomes problematic under a minimum rotation speed. Figure 6 gives the time constant of MFC capacitance coupled to the 10 $\text{M}\Omega$ load of the measurement instrument: approximately 100 ms. The measurement in figure 9 can be approximated by a first order equation (2) with time constant $\tau = 300$ rpm. This is the mechanical period, which matches the 10 Hz / 100 ms for the electric period. Indeed the magnetostriction is an even function: 1 turn of the magnet produces 2 shrinks and 2 strains in the magnetostrictive disk, so the electric frequency is twice that of the mechanical speed.

$$\frac{V}{V_{ref}} = 1 - e^{-t/\tau} \quad (2)$$

In figure 7, for open circuit, the time constant for self discharge is around 10 minutes. So we calculate a mechanical time constant of 0.05 rpm. We deduce that with a quasi-static rotation speed, even less than 1 rpm, we may still obtain the maximum voltage with the device coupled with a high impedance load.

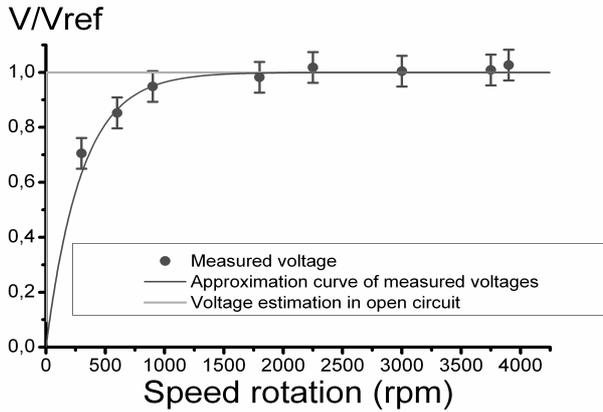


Figure 9 : Output Voltage vs Magnet rotation speed for the prototype described on Figure 8.

Moreover with a constant output voltage, the electronic circuit used to adapt the output can be designed and optimized for this maximum voltage without any risk of exceeding.

Integrated device.

Figure 10 shows a similar “rotating” micro-harvester which couples piezoelectric (PZT, SolGel) and magnetostrictive (FeCoB) layers (Fig 10). The magnetostrictive sub-micron film works in plane, but the piezoelectric layer (“membrane”) works along the d_{33} mode, i.e. vertically, between the planar electrodes on either side. The devices have been manufactured, and the tests must now be performed.

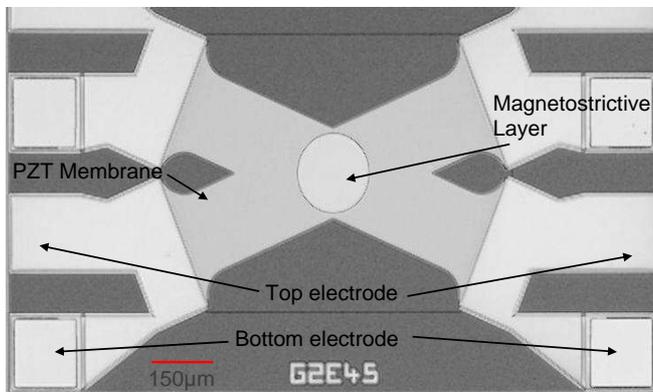


Figure 10: Micro-harvester coupling piezoelectric and magnetostrictive sub-micronic layers.

CONCLUSION

This paper presents our investigation on macroscopic harvesters for slow movements and for small devices which work without contact. Coupling piezoelectric and magnetostrictive materials allows exploiting quasi-static phenomena. Two types are investigated, both based on MFC PZT composites: a translation device using bulk Terfenol-D, and a rotation device using an amorphous FeSiB film.

Both devices exhibit exploitable voltage outputs for quasi-static movements of the magnet.

Integrated micro-harvester has been designed. A first batch of wafers is currently being investigated.

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