Magnetostrictive Materials and Energy Harvesting for Structural Health Monitoring Applications

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Abstract. Wireless sensors to monitor the state of the health of a civil structure could be widely adopted as a prompt and automatic solution to safeguard the cultural heritage and to guarantee safety. Nowadays, sensors are supplied by the electric grid or batteries, but in both cases some issues can occur. Batteries need to be recharged or replaced, thus increasing the operating cost of maintenance. The Energy Harvesting concerns with those actions focused on the exploitation of low-power, but widespread available, ambient energy sources, which otherwise would be normally wasted. In particular, the harvesting of vibrational kinetic energy could be a valid solution to the abovementioned problems, because of its large presence due to the anthropic activities and because it may overcome the strict rules to which historical sites often have to obey. Here a kinetic energy harvesting device based on magnetostrictives rods is presented. Its behavior is experimentally verified and discussed.

1. Introduction

During the last decades a lots of efforts have been spent to efficiently and promptly monitor and control the aging of civil structures, infrastructures, or historical buildings, structures and sites. Eventually, the aim of the monitoring is the prediction of the lifetime or impending issues. Mostly, this is done with the help of visual inspection conducted by specialized technicians. However, it is apparent that this approach is costly, prone to unreliability and, finally, unfeasible for the wide cultural heritage of countries like Italy.

Instead, this purpose may be persecuted through the Structural Health Monitoring (SHM) which is a methodology of in-service health assessment for a structure within an autonomous monitoring system [1]. Health monitoring is necessary for civil structures, especially for historical and cultural buildings, since they may exhibit premature deterioration, structural damage and performance problems, or they may even have aged beyond a state of imminent collaps. In particular, SHM system should be able to automatically detect, locate, and assess damages or anomalies everywhere over the structures, and sometimes alarms or early warnings could be provided when the continuously measured sensitive data meet suitable alarm criteria. Hence, it plays a key role of cost-effective strategies for condition-based maintenance during the entire life-time [1, 2, 3]. The quantification of damage and the setting of alarm criteria are definitely the most challenging problems in SHM strategies and it is out of aim of this paper.
The sensitive data of monitoring can be about the structural response (accelerations, displacements, etc) or the operational environment conditions (temperature, humidity, etc) and are periodically measured by means of suitable sensors and devices interconnected in a so-called Wireless Sensor Network (WSN). Generally speaking, a single sensor node is composed by four main parts: the proper sensors to collect data, the wireless trans-receiver to exchange data with the gateway or other interconnected wireless nodes, the power source to supply the electronics and, finally, the CPU which manages all the previous components. The most widely used power supplies for WSN are batteries. Indeed they have a great energy density and, with their reduced dimensions, contribute to the compactness of the sensor node. Furthermore, their long lifetime guarantees autonomy of years, depending on the power consumption of the on-board electronics. Nevertheless, batteries have to be substituted or recharged by leading several issues: in the first case the component’s materials of a battery are energetically and economically heavy to be disposed resulting in an environmental impact while, in the second case, batteries have to be periodically replaced by specialized worker with a consequent disadvantage in terms of cost of use [4]. These factors could penalize the use of WSN for SHM in civil structures, especially for cultural heritage, and then reduce the spread of such kind of applications.

Energy Harvesting (EH) techniques could be a valid alternative to the problems outlined above [5]. In particular, EH applications scavenge small quantities of energy around the environment [6, 7]. These quantities are converted into electrical energy in order to supply low-power consumption electronics, such as a single sensor node. Moreover, EH tries to avoid the power transfer system installed between energy source and load, such as power cords, in order to reduce losses, then EH systems, harvesters, are often placed in close proximity of the electric load. Ambient energy is present substantially everywhere in the form of vibrations, thermal gradient, pressure gradient, electromagnetic radiations, etc, and it represents energy which, if not captured, would otherwise be wasted. The advantage of EH is the possibility to minimize the maintenance frequency of batteries (charging or replacing) or even to eliminate the maintenance for the whole devices lifetime [8, 9]. Nevertheless, batteries still have practical advantages in comparison with EH techniques, in particular energy capacity, reliability and initial cost.

Figure 1. Rendering of a walkway in an archeological site (etruscan tomb “caccia e pesca“, Tarquinia, Italy) with an embedded energy harvester.

In the context of cultural heritage, certain environments do not have the availability of some types of energy as solar or such radiowaves while kinetic energy is always available because of anthropic actions as the walking of site visitors. Then kinetic energy harvesting could be a non-intrusive method of feeding a sensor node. For example, Fig. 1 shows the rendering of an
In an etruscan tomb where, it is apparent, out of the electrical network, the only form of available energy is the visitors walking inside the tomb. Then, an instrumented walkway would both preserve the flooring, if of any artistic value, and accommodate and hide an energy harvester, as it is shown in Fig. 1. In such an application, the harvester would produce a total amount of energy that is proportional to the number of visitors.

Smart materials, such as piezoelectrics and magnetostrictives, are becoming widely adopted in this EH [1] branch since they are able to couple (directly or indirectly) mechanical quantities with electromagnetical ones showing great potentialities. In particular, due to their high coupling, lack of depolarizing effects and high energy densities, magnetostrictive materials have attracted the interest of the research in this field. More recently, the availability of a new magnetostrictive Fe-Ga alloy, almost behaving as a common steel from the mechanical viewpoint, increased their application range in EH tasks [10, 11].

In the scientific literature, there are very few examples [12] of applications of energy harvesting based on magnetostrictives, directly driven by human activities and none for applications to SHM. Then, in this paper, it is presented and experimentally characterized a Kinetic Energy Harvesting (KEH) device based on multiple magnetostrictive rods. It is experimentally demonstrated that such a device can convert energy from human activities. Experimental tests have been performed to measure the harvested energy by applying impulse-like force to verify the possibility to supply a single sensor node for SHM.

2. Magnetostrictive Harvester

Magnetostrictive materials like Galfenol, a iron gallium alloy [13], have the relevant property of the so called Villari effect: a variation of the mechanical stress gives a variation of the magnetization [14]. This effect can be exploited for energy conversion. Indeed, if a coil is placed around the material, then the variation of magnetization produces a change of the linked magnetic flux. Then, a voltage is produced between the coil terminals, according to the Faraday’s law [15]. The devices exploiting this effect are named magnetostrictive harvesters. Here, it is considered a device where the force source is in direct mechanical contact with the active material, in the so called longitudinal mode. A representative device of such a harvester is shown in the left sketch of Fig. 2, where the main elements are summarized. The active material of force-driven harvesters has a rod shape and the mechanical stress and the magnetic field are coaxial. A frame of ferromagnetic sheets, with suitable permanent magnets, is needed to provide a magnetic bias field to the magnetostrictive material and this improves the energy conversion [11].

The device considered here is shown in the right image of Fig. 2. It is enclosed within two steel disks (6 mm height and 52 mm diameter), connecting three Galfenol rods (21 mm length and 6 mm diameter), 120° spaced and 18 mm far from the center, with a total volume of about 1.78 cm³. The rods have pilot pins (6 mm height) entering in the disks. Furthermore, the top disk accommodates a steel sphere (10 mm diameter) to offer a single point of mechanical contact with the external force source, in order to equally transfer the stress to each rod. One centered stack of neodymium disks behaving as permanent magnets provides the almost optimal magnetic bias to the Galfenol rods [16, 17]. Indeed, the two steel disks have a twofold purpose: they are a low reluctance path for the permanent magnets flux, also allowing the mechanical stress transfer to the active elements [11]. Each rod is equipped with a 2000-turn pickup coil in order to convert external applied mechanical stress into electrical energy. The pickup coils are connected in electrical series by means of a printed circuit board, shown in Fig. 2. The series resistance of the coil is $R = 525 \, \Omega$. More details on the harvester and its design are presented in [11, 16, 17].
3. Experimental

A force-driven magnetostrictive harvester can be characterized either in sinusoidal/periodic regime or time domain. The first type would be useful if the device is exploited with narrow frequency band vibrations, as with electric motors or combustion engines. The latter would be useful if the device is exploited with impulse-like force, as with human steps or the ongoing traffic on a road. So, for our final application, we are more interested in the second type. Then, the performances of the magnetostrictive harvester are experimentally evaluated with a setup composed by an impulse force test hammer, PCB piezotronics model 086C03, with an embedded load cell devoted to the real-time measurement of the applied force (maximum force of 2224 N and sensitivity of 2.25 mV/N). The acquisition and visualization of the signals, i.e. the force and the generated voltage, are performed with a digital oscilloscope with 12 bit resolution, triggered by the force signal. For the sake of simplicity, the electric load is represented by different resistors. In the following, the description of two different type of tests are presented.

3.1. Impulse-like tests

In order to verify the proposed energy harvesting device behavior in real operating conditions, tests with impulse-like force have been performed. Indeed, this method represents a similar approach, but in controlled conditions, to the stresses experienced by the KEH system device placed under a walkway, caused from human steps. The test is performed by hitting the steel spherical head with the hammer. The typical duration of the hit is within hundreds of microseconds.

Fig. 3 shows the performed measurements. Different resistance values have been used as electrical load and, among all the tests, those with a peak force of about 600 N are shown. It is worth noting that relevant voltages, up to tens of Volt, are obtained. The right plot of Fig. 3 shows the case of $R = 2200 \, \Omega$, with also the time plot of the electric power over the resistor with a peak of about 320 mW. Some relevant results are summarized in Table 1 with the resistance of the load, the peak force measured by the load cell, the peak to peak voltage on the resistor, Root Mean Square voltage, peak electric power, Root Mean Square electric power and total energy. The latter value is the most interesting one, representing the converted energy from one hit.
Figure 3. Left: time plots of the impulse-like tests: force (top), normalized voltage produced by the harvester (bottom). The legend shows actual resistances and peak voltages. Right: time plots of one of the impulse-like tests: force (top), voltage produced by the harvester (middle) and electric power over a $R = 2200 \, \Omega$ resistor (bottom).

Table 1. Results of the impulse-like tests with a peak force of about 600 N, columns: resistance of the load, peak force measured by the load cell, peak to peak voltage on the resistor, Root Mean Square voltage, peak electric power, Root Mean Square electric power and total energy.

| Resistance ($\Omega$) | Peak Force ($F_p$) (N) | Peak to Peak Voltage ($V_{pp}$) (V) | Root Mean Square Voltage ($V_{rms}$) (V) | Peak Electric Power ($P_p$) (mW) | Root Mean Square Electric Power ($P_{rms}$) (mW) | Total Energy ($Energy$) ($\mu$J) |
|----------------------|------------------------|-------------------------------------|----------------------------------------|----------------------------------|----------------------------------|-------------------------------|
| 10                   | 574.8412               | 0.2137                              | 0.0409                                 | 3.7396                           | 0.6363                           | 0.3312                         |
| 470                  | 613.5383               | 8.5012                              | 1.5482                                 | 106.3510                         | 17.8922                          | 10.1997                        |
| 2200                 | 594.1355               | 33.1707                             | 5.4333                                 | 320.3195                         | 52.6415                          | 26.9734                        |
| 10k                  | 583.8452               | 71.7005                             | 10.3826                                | 292.6456                         | 43.2962                          | 21.6558                        |

3.2. Walkway tests

In order to investigate a possible application to walkway placed in historical sites, as discussed in the introduction, the device, representing a preliminary implementation of an energy harvester, has been inserted in a rung of a pedestrian walkway. The harvester would substitute one of the strut holding the walkway piece, sketched in Fig. 1. The preliminary device has been assembled with the aim to be a simple demonstrator and it is apparent that a possible final design would be far different. Nevertheless, from the electromagnetic point of view, it is representative of what can be expected. The device is shown in the left plot of Fig. 4. It is composed by an iron bulk piece with a load cell on one side and the harvester on the other. Another iron bar is placed on top, with a spike as a central reference for the foot steps. The device is exploited as a stairstep. The right plots of Fig. 4 show three snapshots of a test. The device is terminated with resistive loads. Fig. 5 shows the time plots of the force on the strung-like device (top), the voltage produced by the harvester (middle) and the electric power over a $R = 470 \, \Omega$ resistor (bottom). The force measured by the load cell is indicative of the force experienced by the harvester because the foot is deranged to the harvester. So, the effective force is more than what measured by the load cell. Nevertheless, thanks to the central spike, the foot position is repetitive and different tests can be compared by comparing the measured force. It is worth noting that the peak to peak voltage and peak power are more than 0.6 V and 267 mW, respectively. It is impressive to note that such a simple device can be employed in this severe test with little precautions. This makes apparent of the intrinsic robustness of the magnetostrictive materials with respect to
Figure 4. The rung-like device with the energy harvester placed as a strut (left). Three snapshots of a walking, by a 70 kg person, on the device are shown on the right three plots.

Figure 5. Time plots, from a single step, of the force on the rung-like device (top), the voltage produced by the harvester (middle) and the electric power over a $R = 470 \Omega$ resistor (bottom).

other employed smart materials as the piezoelectrics. The relevant results, as in the impulse-like test, are summarized in Table 2. The performed tests shows that for the same resistance load the available energy is within the same order of magnitude. The best case achieves about 5 $\mu J$ from one step, i.e. one visitor.

3.3. Discussion
The method presented above is suitable to feed a single sensor node. By considering that a typical low-power sensor node absorbs few milliwatts, the energy requirements, $E$, depend on the on-time, $T_{on}$, of one measurement. Then, it can be written

$$E = P_m T_{on} N_{meas}$$

where $N_{meas}$ is the number of measurements per day. Then, for example, let us consider $P_m = 1.5 \text{ mW}$, $T_{on} = 0.3 \text{ s}$, $N_{meas} = 1$, then $E = 450 \mu \text{J}$. So, by considering the best case of Table 2, about 90 visitor should hit the proposed harvester for a minimum of one measurement and trasmission per day. More measurements would need more visitors that may be not available on average in the site. On the other hand, as commented above, the proposed design is still preliminar and more energy may be harvested from a more engineered device or a more larger device. Indeed, the harvested energy is proportional to the volume of magnetostrictive material.
Table 2. Results of the walkway tests, columns: resistance of the load, peak force measured by the load cell, peak to peak voltage on the resistor, Root Mean Square voltage, peak electric power, Root Mean Square electric power and total energy.

| R (kΩ) | Fp (N) | Vpp (V) | Vrms (V) | Pp (µW) | Prms (µW) | energy (µJ) |
|--------|--------|---------|----------|---------|-----------|-------------|
| 0.025  | 271.6627 | 0.0116  | 0.0013   | 1.3621  | 0.1770    | 0.1381      |
| 0.025  | 293.1095 | 0.0193  | 0.0017   | 7.4909  | 0.5233    | 0.2366      |
| 0.025  | 294.3917 | 0.0247  | 0.0019   | 11.3685 | 0.6183    | 0.3001      |
| 0.025  | 293.7400 | 0.0247  | 0.0019   | 12.7827 | 0.7573    | 0.3001      |
| 0.470  | 264.6386 | 0.1394  | 0.0135   | 17.5056 | 1.5027    | 0.7767      |
| 0.470  | 217.5155 | 0.2642  | 0.0174   | 57.1117 | 3.3948    | 1.2846      |
| 0.470  | 275.8379 | 0.4039  | 0.0235   | 92.9956 | 6.1683    | 2.5313      |
| 0.470  | 265.6409 | 0.2063  | 0.0173   | 35.5882 | 2.8212    | 1.2710      |
| 0.470  | 286.7081 | 0.2556  | 0.0187   | 44.3441 | 3.2559    | 1.4893      |
| 0.470  | 280.0380 | 0.6079  | 0.0349   | 267.7422| 14.9581   | 5.1938      |
| 3.27   | 277.7284 | 0.4240  | 0.0262   | 18.1248 | 0.9570    | 0.4198      |
| 3.27   | 262.2239 | 0.8031  | 0.0394   | 67.3923 | 2.5038    | 0.9515      |
| 3.27   | 214.3561 | 0.2077  | 0.0271   | 6.4249  | 0.8442    | 0.4483      |
| 3.27   | 245.9891 | 1.1639  | 0.0455   | 109.3689| 4.9808    | 1.2648      |
| 3.27   | 236.3067 | 0.3430  | 0.0274   | 11.7910 | 0.9581    | 0.4581      |
| 3.27   | 293.9605 | 0.4853  | 0.0298   | 32.2719 | 1.8417    | 0.5447      |
| 3.27   | 278.0862 | 0.1783  | 0.0169   | 4.9220  | 0.3683    | 0.1742      |
| 10     | 270.4900 | 1.3089  | 0.0429   | 48.8946 | 1.1340    | 0.3678      |
| 10     | 240.2998 | 0.2485  | 0.0325   | 2.0405  | 0.3174    | 0.2116      |
| 10     | 306.9245 | 0.3346  | 0.0322   | 5.9000  | 0.4042    | 0.2071      |
| 10     | 248.5935 | 0.5405  | 0.0414   | 12.3711 | 0.8425    | 0.3424      |
| 10     | 320.4742 | 1.1576  | 0.0561   | 53.7178 | 2.3174    | 0.6302      |
| 10     | 312.7307 | 0.0405  | 0.0023   | 0.0677  | 0.0033    | 0.0011      |

4. Conclusions

In this paper, the reasons of adopting energy harvesting devices based on magnetostrictive to feed wireless sensors have been presented. A conceptually simple device with three rods of Galfenol, two steel disks and pickup coils is able to recover fraction of watts from a single hammer hit and fraction of milliwatts from a single step of a person. The harvested energy may be not sufficient for an ubiquitous application, since energy is not sufficient for poorly visited sites or for massive SHM measurements. On the other hand, energy is more than sufficient for popular sites.

Finally, a suitable development of energy harvesters based on smart materials may help the spread of structural health monitoring for historical and archeological sites, where other types of energy harvesting are not available.

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