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ENHANCED FREQUENCY UP-CONVERSION OF VIBRATION ENERGY HARVESTERS VIA MODIFIED MAGNETIC FORCES

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ABSTRACT

In this work, a technique to improve the magnetic frequency up-conversion (FuC) of piezoelectric energy harvesters at low velocities of interaction (0.4 m/s – 0.6 m/s) is proposed. The magnets used in the FuC are shielded with additional magnetic material and opposite polarization with the aim of making the force-distance curve between the magnetic blocks sharper. The concept is investigated both analytically and experimentally. A mesoscale energy harvester is then simulated at low-frequency (5 Hz). The results show that the proposed technique improves the impulsiveness of the magnetic interaction and a power gain of about 36x is obtained with an amplitude of velocity equal to 0.6 m/s.

KEYWORDS

Vibration energy harvesting, Magnetic plucking, Frequency up-conversion.

INTRODUCTION

The progress of low-power electronics enables the development of autonomous or nearly autonomous sensors, in the sense that they do not require any battery or they are characterized by a dramatically reduced battery consumption. The alternative source of energy can be represented by the environment, provided that a suitable device for energy harvesting is introduced. In this field, huge attention is devoted to vibration based energy harvesting, in view of the ubiquitous presence of undesired vibrations [1]. Among various transduction mechanisms, the use of piezoelectric materials in specific resonators has proved successful due to their excellent power density over a large range of voltages. Resonators, in the form of cantilever beams, are usually adopted in the linear regime; however, this entails a serious drawback since linear systems usually show a huge mismatch between their natural frequencies (hundreds or thousands of Hz) and the environmental ones (1-100 Hz), which leads to low amounts of scavenged energy. This problem can be addressed by widening the operating band with nonlinear techniques [2] or, more efficiently, by means of frequency up-conversion based on magnetic plucking [3], impact-based mechanisms [4], and snap-through buckling [5]. The magnetic interaction is advantageous since it is contactless and it avoids damage to the adopted material. On the other hand, it is possible to prove that magnetic plucking is effective only in the case of high relative velocity between the electromechanical system and the low-frequency system equipped with magnets [3]. As a matter of fact, there are many operational contexts in which the velocity connected to the environmental oscillation is very low (e.g. less than 1 m/s), as in the case of human motion, and the frequency up-conversion does not occur. The present work is devoted to an enhanced technique for frequency up-conversion, based on magnetic force manipulation, to induce the occurrence of plucking at low velocity [6]. The results confirm that the proposed technique is able to activate the structural mode of interest also in the case of low relative velocity. The paper is organized as follows: first, the concept and the investigation on the magnetic force is presented both on the experimental and the numerical side. Then, a case study is presented to show the effect on piezoelectric energy harvesting. Closing remarks are provided in the last section.

INVESTIGATION ON THE MODIFIED MAGNETIC FORCE

The schematic of a magnetically frequency up-converted piezoelectric energy harvester is represented in Fig. 1. A piezoelectric beam equipped with a magnet interacts with an external moving mass also equipped with a magnet. The mass is able to move at low frequency and via nonlinear magnetic interaction it should activate high frequency vibrations of the beam. However, as it is known [3], if the involved velocities are not sufficiently high, the structural vibration is not activated. The idea is to introduce a technique for manipulating magnetic forces to overcome this issue, making the magnetic force sufficiently impulsive even at low interaction speeds between the piezoelectric beam and the mass.

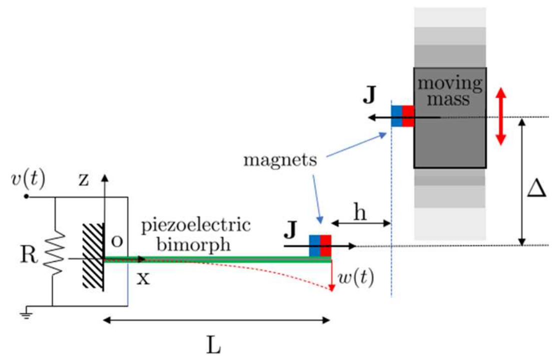

Figure 1: Schematic of the frequency up-converted piezoelectric energy harvester.

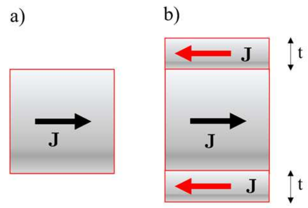

Figure 2: Lateral view of a cubic permanent magnet a), and magnet with the addition of polarized magnetic material in the opposite direction.

The idea for manipulating the magnetic forces between permanent magnets that is presented below is similar to the concept of magnetic flux concentrator (MFC), in which soft ferromagnetic material immersed in a magnetic field is used to direct the field lines through the geometry of the MFC with high permeability [7]. In this case, instead of using an MFC, additional permanent magnets are used, applied to the central magnet (Fig. 2a) but with opposite magnetization, as illustrated in Fig. 2b. The arrangement of the additional magnetic material is referred to below as shielding. Both the main magnet and the shielding are made of Neodymium-Iron-Boron (NdFeB) alloy. The proposed technique is implemented on cubic magnets with a side of 3 mm, and a magnetization 1.32 T. To experimentally investigate the concept, the shielding was chosen with a thickness t (Fig. 2b) equal to 1 mm and was applied on the 4 faces of the magnet parallel to the magnetization vector. The investigation involved the experimental comparison of the proposed solution with the non-shielded case but also its comparison with the analytical formula proposed by Akoun and Yonnet [8]:

$$F_i = \frac{\boldsymbol{J}\cdot\boldsymbol{J'}}{4\pi\mu_0} \sum_{m,n,p,q,r,s} (-1)^{m+n+p+q+r+s} \cdot \phi_i \tag{1}$$

J and ***J'*** in (1) are the magnetization vectors, μ_0 is the magnetic permeability of vacuum. The parameters *m, n, p, q, r, s* identify the corners of the two magnets, They can be equal to 0 or 1. The coefficients Φ_i depend on the geometry of the magnets. The formula is valid for cuboidal magnets with parallel and rigid magnetization. In this work the formula is extended to the presence of the shielding which ideally consists of several magnetic blocks, interacting with all the other blocks of the system. The experimental setup is composed of electrical integrated servo-positioner (SM2316D, max 48 vdc, rated velocity 66 rpm), an handcrafted actuator, a load cell S2 tech 514QD (full scale 30 N, total error: ≤ ±0.023%, sensivity:2mV/V/FS), a displacement sensor. The acquisition system is a DAQCard™-6062E (12 bit resolution and maximum sampling rate of 500 kHz).

In the following, the investigation is focused on the component of the magnetic force orthogonal to the magnetization vector (odd component), because it is used to achieve manetic plucking (according to the schematic of the Fig. 1). The Figures 3 and 4 show the results in the case of double shielded magnets respectively in the case of gap h=1 mm and gap h=2 mm. From both graphs, looking at the experimental results, the validity of the idea is confirmed: due to a multiple sign inversions, the force-distance curve in the shielded cases has a sharper appearance, which leads to greater impulsivity in the time domain. Furthermore, the shielded experimental curves present excellent agreement with the simulations carried out with the Akoun-Yonnet formula defined in the Eq. (1).

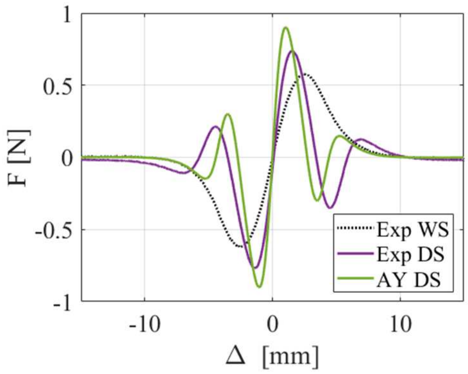

Figure 3: Magnetic forces for gap h=1 mm. Exp WS: experimental without the shielding, Exp DS: experimental with double shielding, AY DS: Akoun-Yonnet with double shielding.

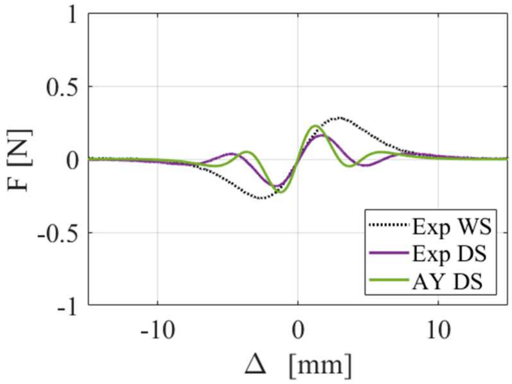

Figure 4: Magnetic forces for gap h=2 mm. Exp WS: experimental without the shielding, Exp DS: experimental with double shielding, AY DS: Akoun-Yonnet with double shielding.

The results are also confirmed in the case in which only one magnet is shielded as it can be seen in the Figures 5 and 6. However, in the case of the gap h=1 mm (Fig 5), the shielded case does not present an increase of the peak value of the force, because less magnetic material contributes to the localization of the field, in comparison with the double shielding.

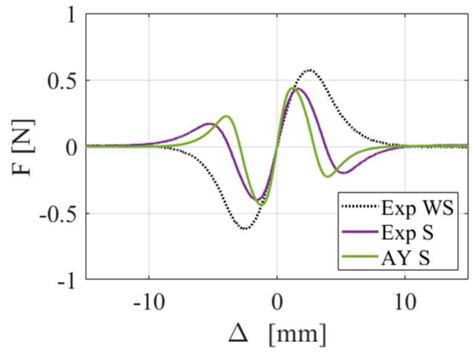

Figure 5: Magnetic forces for gap h=1 mm. Exp WS: experimental without the shielding, Exp S: experimental with single shielding, AY DS: Akoun-Yonnet with single shielding.

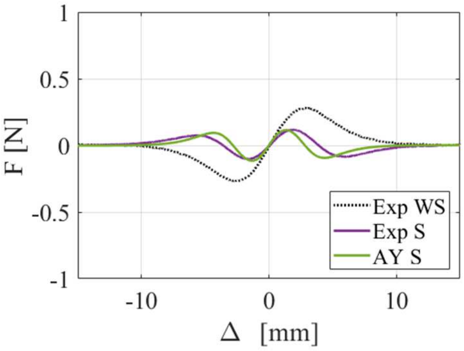

Figure 6: Magnetic forces for gap h=2 mm. Exp WS: experimental without the shielding, Exp S: experimental with single shielding, AY DS: Akoun-Yonnet with single shielding.

Given the good agreement between the experiments and the Akoun-Yonnet analytical formula, it is possible to use the latter to carry out parametric analyzes in the shielding thickness t. The Figures 7 and 8 show the results for gaps h=1 mm and h=2.5 mm respectively, and shielding thickness increasing up to 1 mm. As it can be seen, even as the gap grows almost to the size of the magnet (Fig. 8), the concept of force sharpening does not lose its validity. However, it can be seen that in the case of the gap h=1 mm (Fig. 7) the increase in thickness t of the shielding leads to an increase in the peak force. On the contrary in the case with h=2.5 mm (Fig. 8) the peak force is obtained for t=0 mm (i.e. without shielding). It is reasonable to state that this is due to the loss of local shielding effect if the gap h increases.

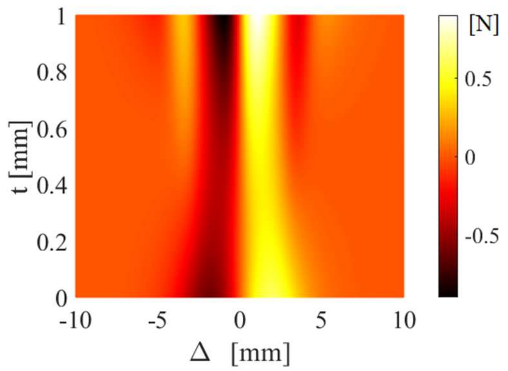

Figure 7: Analytical simulation of the magnetic force with gap distance h=1 mm and double shielding.

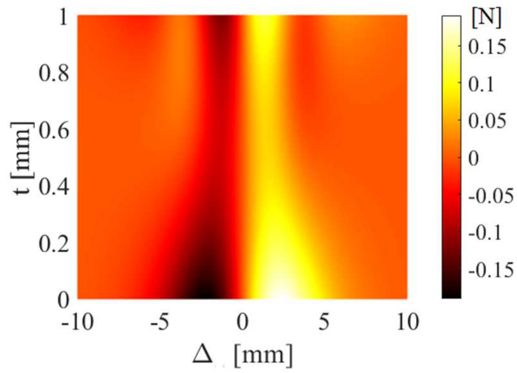

Figure 8: Analytical simulation of the magnetic force with gap distance h=2.5 mm and double shielding.

SIMULATION OF PIEZOELECTRIC ENERGY HARVESTER

The concept is now applied to the simulation of an energy harvester as in the schematic of the Fig. 1. The piezoelectric beam is a bimorph and is modeled in a linear regime both in terms of material and kinematics. The only source of nonlinearity in the system is induced by the presence of magnetic force. A lumped parameter approach is adopted with w mechanical degree of freedom which is the tip displacement of the beam and v electrical voltage at the electrodes. The differential system that governs the problem is the following:

$$\begin{cases} m\ddot{w}+c_m\dot{w}+k_l w-\theta v=F_{mag} \\ C\dot{v}+\theta\dot{w}+v/R=0 \end{cases} \tag{2}$$

where m is the inertial term, c_m the damping coefficient that can be computed from the quality factor Q_m [9], k_l is the linear stiffness, C the equivalent capacity and All the geometric and physical characteristics of the beam are listed in Table 1. The dielectric constant in vacuum is assumed to be equal to ε_0=8.854x10^{-12} F/m. Two magnetic load layout are used: the unshielded case with equal magnets of size 5 x 5 x 3 mm^3 and a case with shielded magnets in which the central core is a cubic magnet of 3 mm side.

Table 1: geometrical and physical parameters of the harvester

Parameter	***Value***	***Description***
b	2 mm	Cantilever width
L	12 mm	Cantilever length
t_{PZT}	280 μm	PZT thickness
t_{tit}	70 μm	Titanium thickness
ρ_{PZT}	7.5 g/cm^3	PZT unit mass
ρ_{tit}	4.5 g/cm^3	Titanium unit mass
E_{PZT}	60 GPa	PZT Young's modulus
E_{tit}	115 GPa	Titanium Young's modulus
d_{31}	-212 pC/N	31 piezoelectric constant
ε_{33}^s (ε_0)	2000	Relative dielectric constant
Q_m	20	Cantilever quality factor
h	1.0 mm	Gap between magnets
R	50 kΩ	Load resistance

The external mass equipped with a magnet is assumed to be driven at a frequency of 5 Hz and two amplitude of velocity of the harmonic signal were considered: 0.4 m/s and 0.6 m/s. For the case of 0.4 m/s the results of the instantaneous power are represented in the Figures 9 and 10 for the shielded and unshielded case, respectively. In Fig. 9 it can be see the free vibrations of the beam (at 395.39 Hz) which are activated due to the magnetic force and the peaks reach 25.5 mW, while without the shielding no significant vibrations of the beam are observed (Fig. 10) and peaks in the order of 476 μW are computed.

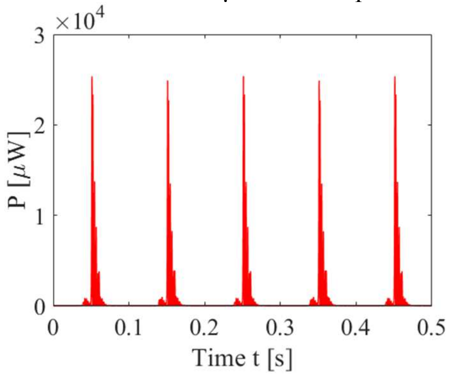

Figure 9: simulated instanteous power for amplitude of velocity equal to 0.4 m/s, with shielding.

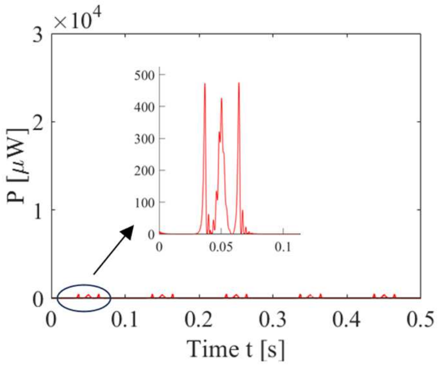

Figure 10: simulated instanteous power for amplitude of velocity equal to 0.4 m/s, without shielding.

Even for the case of 0.6 m/s, the situation is qualitatively similar, a peak power of 45.6 mW and 1.26 mW is obtained with and without the shielding, respectively.

CONCLUSIONS

In this work, a promising technique has been presented to improve magnetic frequency up-conversion in vibration energy harvesting at low velocities of interaction (<1 m/s) through the modification of magnetic forces. The technique has been experimentally validated and preliminary simulations on a mesoscale harvester with harmonic input motion show gains of tens of times in terms of power with respect to the case in which the technique is not adopted.

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