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DYNAMICAL BEHAVIOR OF FREQUENCY UP-CONVERTED PIEZOELECTRIC VIBRATION ENERGY HARVESTERS AT DIFFERENT VELOCITIES OF MAGNETIC INTERACTION

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ABSTRACT

This work proposes an experimental investigation on the dynamical behavior of a magnetically frequency up-converted piezoelectric energy harvester. The magnetic interaction arises between a tip magnet on a piezoelectric bimorph and a moving magnet. The latter is controlled through a low-frequency shaker at a fixed frequency of 3 Hz (typical of human motion). The analysis shows that the activation of the first mode of vibration is linked to the velocity of the magnetic interaction. Also, inherent material nonlinearities appear as a frequency shift of the first mode on the Fast Fourier Transforms of the output voltage near short circuit condition.

KEYWORDS

Piezoelectric vibration energy harvesting, Nonlinear dynamics, Magnetic frequency up-conversion

INTRODUCTION

Vibration-based energy harvesting has received growing attention in the last two decades [1-3]. The increasing interest is mainly due to the progress of low-power electronics that makes it possible to power small components, such as sensors, by means of energy recovered from the environmental vibrations.
Low-power harvesting fits perfectly with the increasing necessity of Internet of Things, which leverages large networks of communicating devices to exchange data. The energy harvesting technology could allow to limit or even eliminate costs associated to maintenance and replacement of batteries. The conversion of vibrational energy into electrical energy is possible through different transduction mechanisms, such as electrostatic, electromagnetic, and piezoelectric [3,4]. Among them, piezoelectric behavior has received great interest because of its high power density [5] with respect to the other mechanisms. In a first phase, researchers focused on the basic working principle of vibration energy harvesters. In many cases these were electromechanical systems which could be described by linear physics. The investigations show that, generally speaking, linear systems are not so effective. They guarantee efficient behavior in terms of energy conversion only if they are dynamically excited near their natural frequencies (i.e. strong dynamic amplification). Unfortunately, environmental frequencies are typically distributed below 100 Hz [6] whereas energy harvesters are stiff and light small devices with high natural frequencies in the order of hundreds or thousands of Hertz. To enhance the performance at low-frequency vibration conditions, different solutions have been proposed. Among different possibilities [7-9] a promising solution is the frequency up-conversion (FuC) technique by means of permanent magnets. It exploits the magnetic force to create an impulsive phenomenon on a piezoelectric transducer [10] and it provides a contactless interaction, avoiding impact and potential damage of piezoelectric crystals.

Many works on magnetic FuC have been developed in the past years especially on rotational mechanisms [11]. However, the effectiveness of the technique depends on a conscious management of the magnetic interaction and it is essential to have a deep understanding of the phenomenon. Xue and Roundy studied different magnetization orientations to understand the best operating layout between magnets [12]. Other groups investigated directly the performance of the magnetically-actuated energy harvester by performing parametric analyses for varying frequencies of rotor mechanisms [13]. Dauksevicius et al. investigated the dynamics of plucking, identifying different operational conditions: quasi-static, transition regime and dynamics on rotor mechanism [14].
In this work, we experimentally investigate the dynamical behavior of a frequency up-converted piezoelectric cantilever through the interaction between a tip magnet and a moving magnet that is mounted onto a low-frequency shaker moving at different velocities. We analyze the effect of velocity of magnetic interaction, gap distance between the magnets, and load resistance. The paper is organized as follows: first, the concept of the investigation is presented, then the experimental setup is described and the results are presented and discussed. Closing remarks are provided in the last section.

DESCRIPTION OF THE INVESTIGATION

The magnetic force is space dependent [14], and in this work we would like to observe how this fact is reflected in terms of the dynamical response of a piezoelectric energy harvester in a magnetic FuC process. More specifically, since the magnetic force depends on the relative distance between the magnets, the load will be more impulsive the more rapid in time the change in configuration (i.e. the speed at which the two magnets move relative to each other). The success of the FuC, that is the migration of the signal from low frequency of the input signal to high response frequencies of the transducer obviously depends on this aspect. If the interaction is not so fast, the load is quasi-static and there is no response from the vibration-modes of the structure. If the velocity of the relative motion between the magnets gradually increases, the time interval of the magnetic interaction (i.e. force) decreases and the inertial effects become non negligible, activating the dynamic response of the structure. To experimentally investigate this phenomenon, we consider a cantilever transducer with a tip magnet that is actuated through a moving permanent magnet with controlled motion. To realize this system, a permanent magnet is constrained to an electrodynamical long-stroke shaker moving on a straight line. The schematic of this concept is depicted in figure 1.

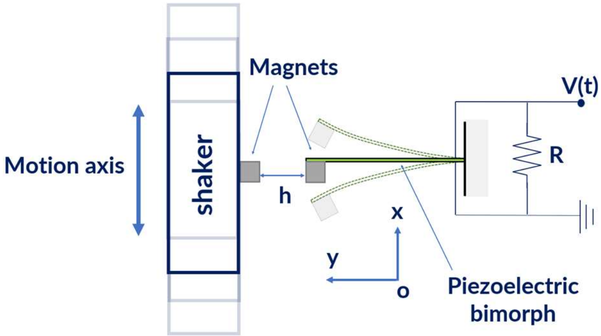

Figure 1: schematic of the experimental concept

The idea is to implement on the shaker various harmonic monochromatic input signals at different amplitudes of velocity: 0.3 m/s, 0.4 m/s, 0.5 m/s, 0.6 m/s, 0.7 m/s. Since we are interested in low-frequency applications (e.g. wearable electronics for human motion), a fixed frequency of 3 Hz is considered for all the experimental tests, as indicated in figure 2. The aforementioned values of velocities have been implemented in such a way that their maximum value (i.e. the amplitude) is reached when the distance between the magnets is minimum.

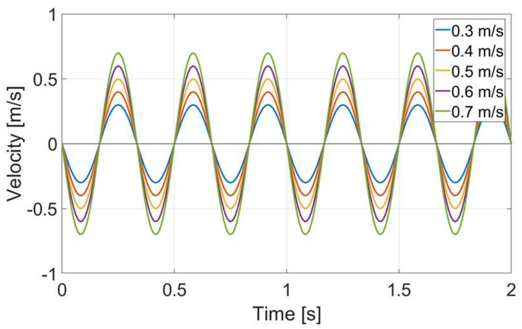

Figure 2: velocities of the moving magnet at a frequency of 3 Hz considered for the experiments

During the experiment, the response of the piezoelectric beam is recorded both in terms of tip velocity and output voltage across a resistive load. Another considered aspect is the magnet gap distance h in figure 1. The response is studied for different values of gap distance that affects the input mechanical work (i.e. energy) on the cantilever because of the positional nature of the magnetic force.

EXPERIMENTS AND DISCUSSION

The sample used in the experiment is a brass-reinforced piezoelectric bimorph with two PZT-5A layers connected in series (Piezo Systems, Inc. T226-A4-103X). The sample is clamped between two conductive plates at one end. Geometric and material properties of the bimorph provided by the supplier are summarized in Table 1. Above a certain level of stress-strain, inherent nonlinearities can become significant. The nonlinear material properties of this bimorph have been found in a previous work [15]. At the free end of the beam, a cubic NdFeB tip magnet is attached with a side length of 3.18 mm and a residual induction of 13200 Gauss (K&J Magnetics, Inc. B222). For the magnetic interaction tests the cantilever is fixed onto a linear precision positioner which is bolted to an optical table as seen in figure 3. Another magnet is attached onto an aluminum plate mounted on a long stroke shaker (APS-113). Aluminum is used to avoid magnetic interaction between the magnets and the equipment.

Table 1: geometric and material properties of the bimorph

Parameters	**Value and U.M.**
Total length	31.8 mm
Overhang length	26.1 mm
Width	3.16 mm
PZT-5A layer thickness	0.265 mm
Brass layer thickness	0.125 mm
PZT-5A Young's modulus	66 GPa
Brass Young's modulus	100 GPa
Piezoelectric constant e_{31}	20 kC/m^2
PZT-5A permittivity	14.6 nF/m
PZT-5A mass density ε_{33}	7800 kg/m^3
Brass mass density	8500 kg/m^3

Output voltage is recorded across different load resistance values in the range 1 kΩ - 100 MΩ realized using a box resistor (IET RS-201W). The tip velocity of the beam has been measured with a laser Doppler vibrometer (Polytec OFV-505). The velocity of the moving magnet is also measured by means of a laser Doppler vibrometer (Polytec PDV-100). Different gap distances between the magnets are considered: 2.5 mm, 3.0 mm, 3.5 mm. The duration of each test has been fixed to 2.5 s to collect a good number of magnetic interactions between the transducer and the moving magnet on the shaker.

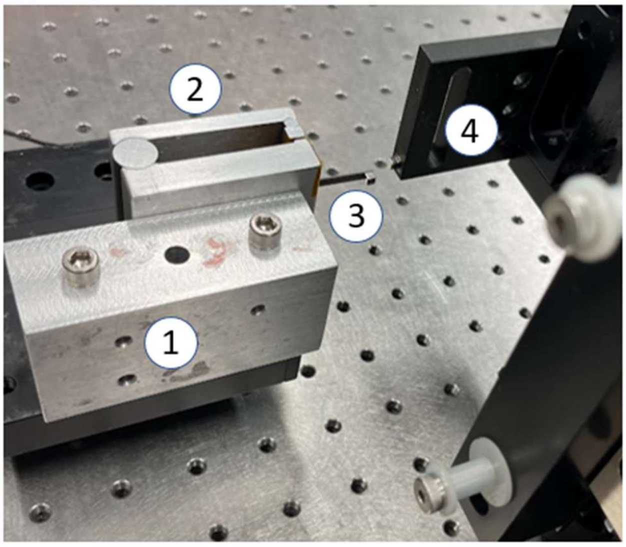

Figure 3: Zoomed view of the experimental setup with (1) system of aluminum blocks to support the cantilever, (2) clamp, (3) piezoelectric bimorph with a tip magnet, (4) actuating plate mounted on the shaker with a magnet

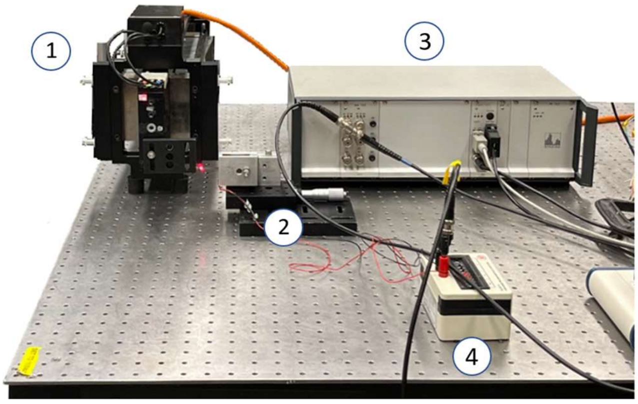

Figure 4: frequency up-conversion experimental apparatus with (1) shaker, (2) linear precision positioner with cantilever, (3) controller, (4) resistor box

The whole experimental apparatus is shown in figure 4. From the experimental responses of the cantilever, the effect of different velocities of magnetic interaction is analyzed first. Sample voltage time histories are shown in in figure 5 for a representative case with R = 10 kΩ, gap distance h = 2.5 mm, and velocities ranging from 0.3 m/s up to 0.7 m/s. For the case with 0.3 m/s the first mode of vibration does not appear. There is only the presence of a snap in voltage that is associated with the duration of the magnetic interaction. By incrementing the velocity (i.e. from 0.4 m/s to 0.7 m/s) the first mode gradually appears: after the snap associated to the magnetic plucking, free damped vibration behavior emerges. Due to electromechanical coupling, the tip-velocity follows the same behavior but is not reported for the sake of brevity. This trend appears also for the other values of gap distance (3.0 mm and 3.5 mm) but with decreasing values of voltage for increasing h. The plots in the figure 5 show also that for the same gap distance at the considered load resistance, by increasing the velocity, the voltage amplitude also increases and this is due to the inertial effect described in the previous section. By analyzing the Fast Fourier Transforms (FFTs) of the voltage output for the case with 100 kΩ, in the figure 6, it is possible to observe the gradual migration of the frequency content of the input signal for varying velocities. The peak below 100 Hz is related to the magnetic plucking and the other peak that gradually appears at 260 Hz arises due to the response of the first bending mode of the piezoelectric beam.

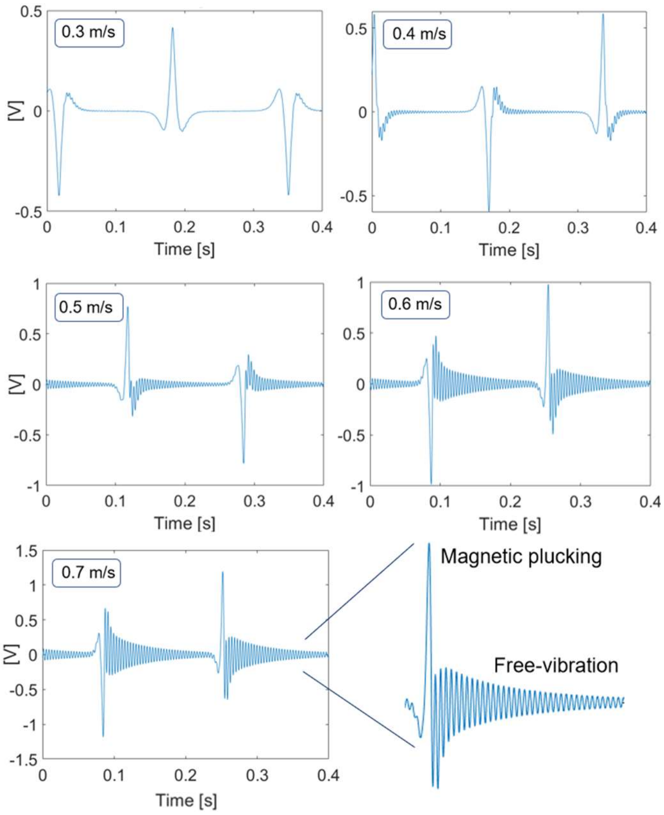

Figure 5: voltage response of the bimorph for varying velocities of magnetic interaction at R=10 kΩ, h=2.5 mm

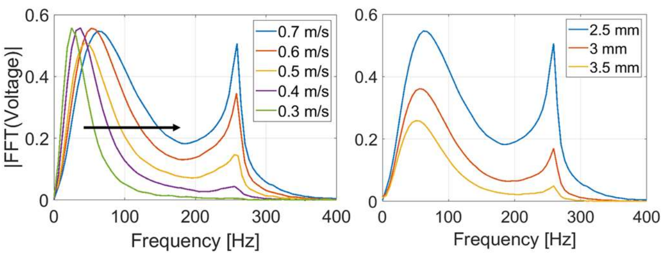

Figure 6: left, FFTs of voltage for varying velocities of magnetic interaction at R=100 kΩ, h=2.5 mm. The black arrow indicates increasing velocity. Right, FFTs at R=100 kΩ, velocity of 0.7 m/s and different gap distance h

Another interesting aspect is observed near the short circuit condition. In such cases the stiffening effect provided by the resistor disappears and the cantilever experiences magnitude of strains such that inherent nonlinearities (i.e. softening [15]) arise. This is showcased by the plot in figure 7 for the case with R=5 kΩ, in which the FFT on the left, without considering the plucking phase, has an amplitude-dependent resonance frequency. For the case with gap equal to 2.5 mm, the average power by means of the voltage RMS is also presented in figure 8. An optimal load is observed at around 500 kΩ at 0.7 m/s but it changes also depending on the velocity and this is inherently linked to the nonlinearity of the problem (i.e. presence of the first mode depending on the interaction velocity).

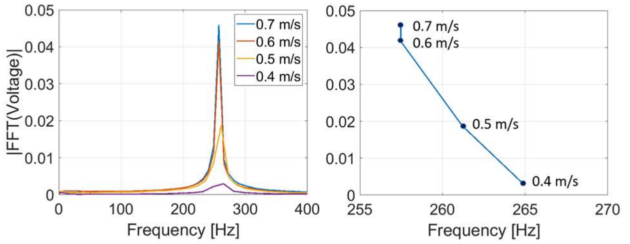

Figure 7: left, FFTs of voltage for varying velocities of magnetic interaction at R=5 kΩ, h=2.5 mm. Right, peaks of the FFT for different velocities of interaction

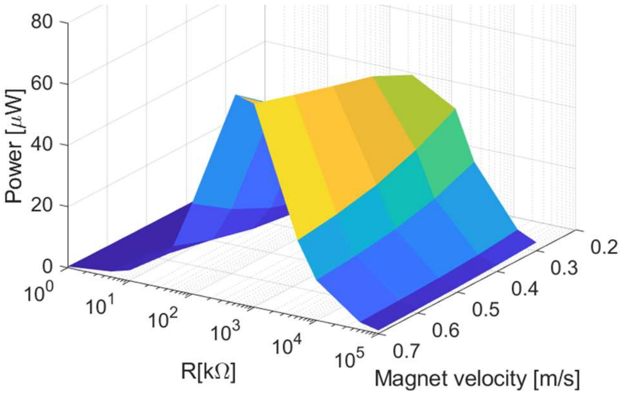

Figure 8: average power for the case of gap between magnets equal to 2.5 mm

CONCLUSIONS

In this work we experimentally investigated the dynamical behavior of a frequency up-converted piezoelectric energy harvester by means of magnetic forces between permanent magnets. The experiments showed that at a fixed low-frequency of 3 Hz of an input signal, the FuC occurs only for high velocities. The results of this work show that the design of a magnetic FuC mechanism is strictly linked to the expected operational speeds of the moving magnet. This can be a limitation but it opens also new perspectives in terms of strategies to design FuC systems when the velocity of the input signal is not sufficient to trigger the harvester. A possible solution could be to combine the magnetic interaction with multistable systems able to accumulate potential energy and release it suddenly in terms of kinetic energy to increase the velocity of the interaction.

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