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THE EFFECT OF INHERENT NONLINEARITIES IN COUPLED PIEZO-MAGNETO-ELECTRIC VIBRATION ENERGY HARVESTER

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Abstract. This work deals with the experimental observation of inherent material nonlinearities occurring due to the magnetic plucking in a nonlinear piezoelectric vibration energy harvester. A piezoelectric cantilever is actuated via magnetic forces with a robotic arm at different constant velocities, in the range of 0.5 m/s - 2.5 m/s. The Fast Fourier Transforms of the voltage, in open circuit conditions, show that as the impulsiveness of the magnetic force increases, the peak of the first bending mode of the beam shifts toward lower frequencies. Such phenomenon should be taken into account for a reliable simulation and thus for the evaluation of the optimal electrical condition of power extraction.

1 INTRODUCTION

Vibration-based energy harvesting has gained increasing scientific interest in recent times [1]. This can be attributed to the growing need to interconnect smart objects looking for alternative energy sources to battery consumption. Among the various possibilities, piezoelectric resonators have achieved great success thanks to their excellent power density for a large range of voltages [2]. However, the linear systems suffer from a well-known problem: due to the mismatch between the environmental frequencies (1 - 100 Hz) and those typical of the devices (hundreds/thousands of Hz) [3] the dynamic amplification is weak and only low amount of energy can be scavenged. This issue can be managed with the introduction of intentional nonlinearities to widen the operating band. A successful solution concerns the application of permanent magnets on a moving low-frequency mass and the harvester to achieve the so-called frequency up-conversion [4]. The moving system typically vibrates at a low-frequency (less than 10 Hz) and interacts through the space-dependent magnetic forces with the piezoelectric harvester. Such a fact induces an additional coupling to the problem which becomes piezo-magneto-electric. The impulsive force induced by the magnetic coupling is responsible for the frequency up-conversion. In this work, it is shown that by increasing the velocity between the interacting magnets through a robotic system, the impulsiveness of the magnetic force increases, and gradually inherent material nonlinearities appear. Such a fact is observed by means of shifts in the right peaks of the FFTs which represent the first bending mode of the harvester in terms of open circuit voltage. The experiments show also that by increasing the gap between the magnets, the material nonlinearity decreases since only a slight shift is recorded. It is also shown that the phenomenon cannot be efficiently simulated with a linear piezoelectric reduced order model. Inherent nonlinearities should be taken into account to more reliably capture the behavior of the harvester.

2 INVESTIGATION

The experimental investigation is conducted on an operational scheme as depicted in Figure 1a). A piezoelectric cantilever with a magnetic tip mass interacts with a magnet attached to a moving mass. The latter is actuated at constant velocity and the electrical voltage response of the beam is recorded in open circuit condition (i.e. load resistor R $\to \infty$). The magnets are put in the repulsive configuration since it is more interesting in the framework of energy harvesting [4]. The whole experimental apparatus is shown in Figure 1b). The actuator for the moving magnet is represented by a Fanuc M-710iC45/M (High inertia version) robotic arm. The trajectory of the robot can be numerically programmed. A rectilinear trajectory has been used considering the following constant velocities for the interaction: 0.50 m/s, 1.00 m/s, 1.50 m/s, 1.75 m/s, 2.00 m/s, 2.25 m/s, and 2.50 m/s. The upper bound has been set by considering that the tolerance on the robot's trajectory varies with the velocity. Above 2.5 m/s the tolerance values in the orthogonal direction to the motion of the moving mass are such as to compromise the gap distance values (h in the Figure 1a)) between the permanent magnets. In particular, two values of gap distance between the magnets will be considered: 1.5 mm and 2.0 mm. The overall working range in terms of distance of the mechanical arm is 2606 mm, which is largely huge to reach the predefined velocity during the interaction with the piezoelectric harvester.

The operational conditions of the robot can be managed through an integrated control pad. The moving magnet has been fixed to the end of the robotic arm by means of a very stiff rod made of wood. Such a choice is aimed to avoid magnetic interaction between the experimental observations and the robotic arm. The piezoelectric cantilever beam is depicted in Figure 1c). It is a bimorph RS 285-784, RS Components, and its technical features are summarized in Table 1. The clamp is made of Polyamide (PLA) and it is constrained onto a workbench with a vise. The recording of the voltage signals of the beam in the open circuit (OC) has been carried out with an oscilloscope Agilent Infiniivision MSOX2021A, which offers a maximum sample rate of 1 GSa/s per channel (four channels) and an operational bandwidth of 200 MHz.

3 RESULTS AND DISCUSSION

As a first experimental observation, the natural frequency of the first bending mode of the piezoelectric beam (with the tip magnet) has been identified through an experimental modal analysis. The polyamide clamp of the beam has been hit with a hammer and the time histories of voltage have been recorded. From such recordings, the Fast Fourier Transform of the signals was computed. Ten observations all identified a peak at 656.97 Hz. By computing the frequency with a reduced order model working in linear piezoelectricity through a MATLAB code [4] 672.52 Hz is obtained, while using the finite element software ABAQUS we get 675.64 Hz. The adopted models adopted are more rigid than the experimental value due to the spatial discretization. However, the difference could be attributed also to the bending stiffness of

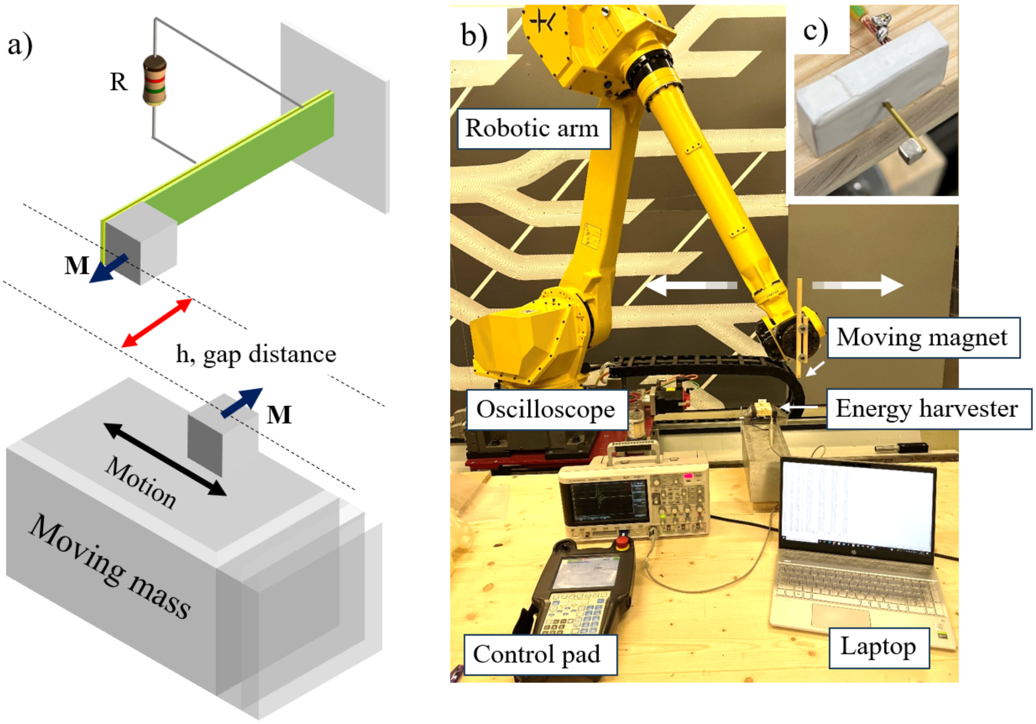

Figure 1: a) Schematic of experimental concept, b) whole experimental apparatus, c) zoomed view on the piezoelectric cantilever

Table 1: Physical and geometrical data of the piezoelectric cantilever

Description	Symbol	Value	Unit Measure
Total beam length	l^*	15	mm
Overhang length	l	10	mm
Width	b	1.5	mm
PZT layer thickness	t_p	0.280	mm
Titanium layer thickness	t_p	0.065	mm
PZT mass density	ρ_p	7500	kg/m^3
Titanium mass density	ρ_t	4500	kg/m^3
PZT Young's modulus	E_p	60	GPa
PZT Poisson ratio	ν_p	0.3	-
Titanium Young's modulus	E_t	115	GPa
Titanium Poisson ratio	ν_t	0.3	-
PZT dielectric constant	ε_{33}	17.7	nF/m
PZT piezoelectric constant	d_{31}	212	pC/N

the real clamp. Via the logarithmic decrement method [5] a quality factor Q=16 has been obtained. In the plots of Figure 2 the experimental and also the linear-based numerical results are represented for increasing values of the velocity of the robot and gap distance h between the magnets equal to 1.5 mm. By considering increasing velocity, gradually the structural mode is activated. Furthermore, the vibration has not a symmetric trend with respect to the time axis, and such a fact is a typical indication of the presence of nonlinearities.

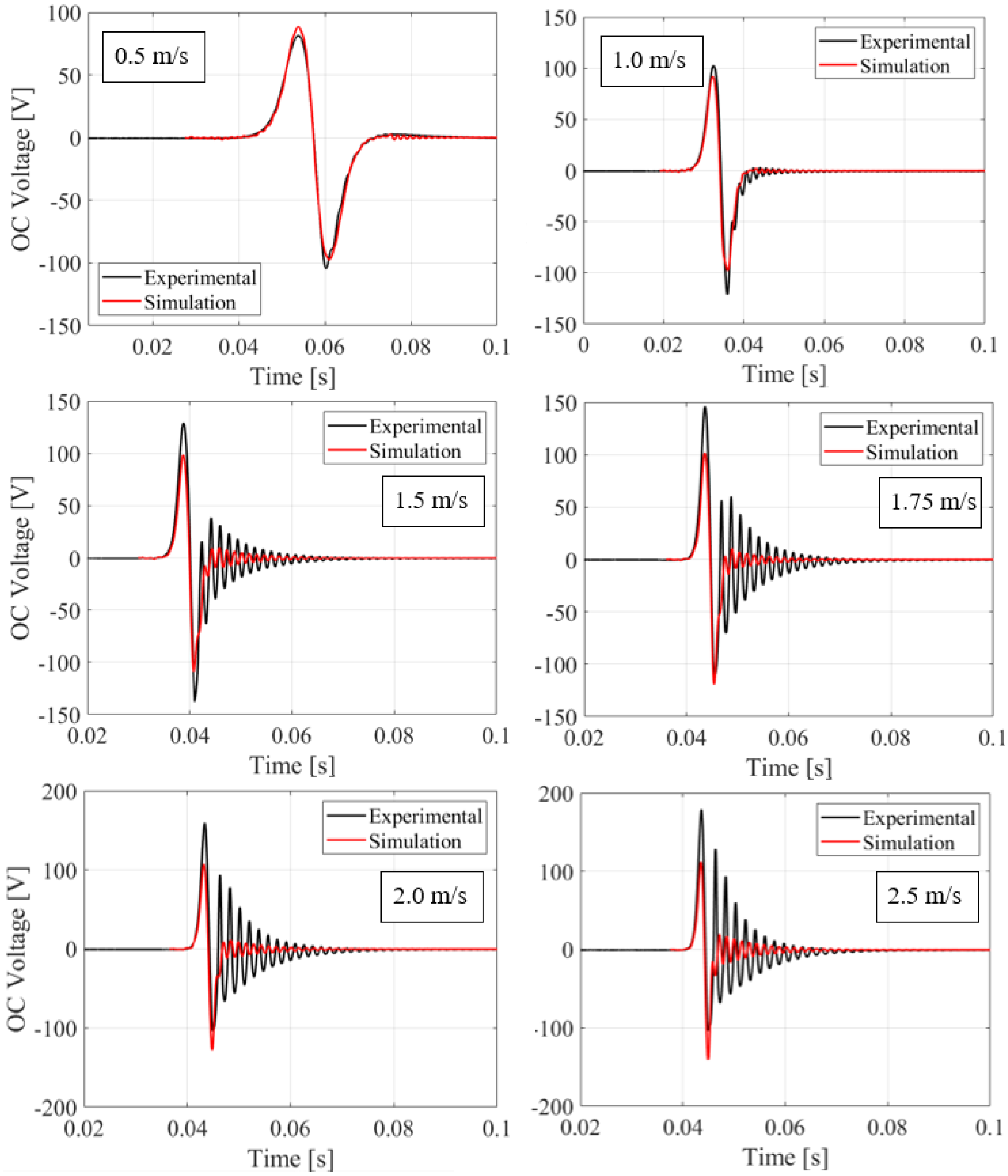

Figure 2: Experimental vs numerical voltage time histories at different velocities of magnetic interaction in the range 0.5 m/s - 2.5 m/s, gap $h = 1.5$ mm

The simulation results based on a linear model show that the magnetic plucking and subsequent free vibration phenomenon can be reasonably captured only in case of very low velocity (0.5 m/s, quasi-static phenomenon). As the velocity increases, the agreement is lost also qualitatively. An underestimation of the stiffness is observed by means of the amplitudes which indicates possible softening of the piezoelectric cantilever. The softening is justified if the values of the electric field and of the electric voltage involved are considered. The manufacturer does not provide the coercive field value of the piezoelectric but in accordance with [6], it can be assumed around 8e10^5 V/m for their PZT-5H. However, at much lower values such as 3e10^5 V/m irreversible depolarization phenomena may be present. Assuming for the sake of simplicity a linear trend of the voltage in the piezoelectric layer, which is justified by the fact that the piezoelectric layer is very thin, the field value corresponds to 84 V per layer. It can be seen from the plots of Figure 2 that this value is certainly exceeded.

The Figure 3 a) shows the plots of the FFTs for the case of gap distance h=1.5 mm and Figure 3 b) for the case of h=2.0 mm. In both plots the presence of two peaks can be observed: the first peak of each FFT with the lowest frequency identifies the frequency associated with the magnetic interaction. The second, at higher frequencies, is the first flexural mode of the beam. In both cases (Figs. 3a) and 3b)) it can be seen that for the cases with a velocity equal to 0.5 m/s and 1.0 m/s the second peak is absent: this is due to an interaction that is not impulsive enough to activate the dynamic of the first bending mode. For increasing velocities of the robot, a shift of the second peak towards lower frequencies is also observed. This is a feedback of activation of inherent material nonlinearities of the beam. The phenomenon is much more pronounced in the case of a gap equal to 1.5 mm, as the magnetic force values are in that case higher than in the case of gap 2.0 mm. Such a fact is reasonable because the higher the force, the higher the strains and the voltage values via piezoelectric coupling. The electric field values are much higher than those experienced in [7], and so a ferroelastic nonlinear model could be not enough to capture the effects of the inherent material nonlinearities. It might be necessary to implement a model that also takes into account the ferroelectric nonlinearities [8]. Other nonlinear phenomena such as the buckling are excluded since the magnetic force is much less than the Eulerian critical load. The nonlinearity is therefore due to the electromechanical behavior and dissipative phenomena.

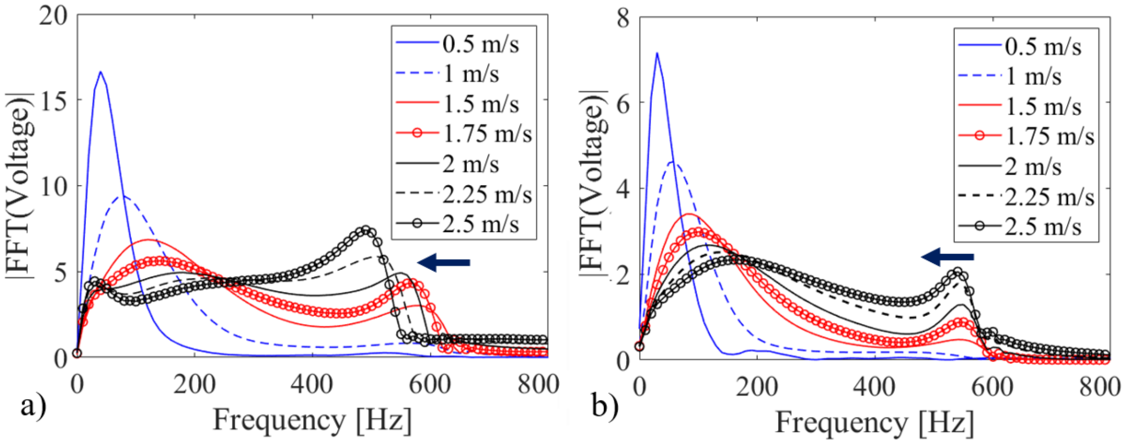

Figure 3: Experimental FFTs at different velocities of magnetic interaction in the range 0.5 m/s - 2.5 m/s, for gap distance h=1.5 mm a), and 2.0 mm b).

4 CONCLUSIONS

The presented work experimentally showed that due to the magnetic plucking phenomenon, inherent material nonlinearities can occur for increasing magnetic interaction velocities. The phenomenon is not correctly simulated by a reduced order model with lumped parameters in linear piezoelectricity [4]. The tested voltage values are associated with electric fields such as not to exclude the presence of ferroelectric nonlinearities and not only ferroelastic ones [9]. From the energy harvesting point of view, the observed phenomenon is very important for a reliable determination of the optimal electrical load for power extraction which, as is known, depends on the frequency [1]. More in detail, the fact of having a space-dependent (magnetic) force implies the need to carry out parametric analyses to determine the optimal electric load: a priori assumptions on the constitutive behavior are reflected in the outcome of such electrical conditions. However, the experimental results are encouraging as the softening of the beam makes the voltage values higher than the numerical simulations, even if we consider the open circuit situation only. Finally, the result of this work also shows how it is necessary to implement more refined constitutive models for the reliable simulation of energy harvesters with frequency up-conversion via permanent magnets.

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