MAGNETIC BEAM PLUCKING IN A PIEZOELECTRIC ENERGY HARVESTER WITH ROTATING PROOF MASS

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Abstract: This article presents a simplified model for studying the main parameters for magnetically plucking piezoelectric beams in energy harvesting devices. The advantage of magnetic plucking is that there is no impact on the brittle piezo material. However, achieving a good release of the piezo beam is more difficult than with fingers or plectra. The influence of different magnet arrangements, the gap size and the velocity of actuation is discussed and the model is supported by experimental voltage measurements on a harvesting device with rotational proof mass. The results show an advantage for repulsive magnet arrangements and a small initial gap size.

Keywords: energy harvesting, piezoelectric, plucking, magnetic, inertial

INTRODUCTION

There are many reasons why wireless power supplies are of great interest. They allow portability, they can bring down wiring and maintenance cost and provide power in harsh or inaccessible environments. Energy harvesting from surrounding sources, e.g. vibration, temperature difference, solar illumination, has the potential to achieve these benefits [1].

In the field of inertial energy harvesting from low frequencies, a technique often described as plucking, impulse excitation or frequency up-conversion has recently gained in popularity. Compared to resonant devices, this method is suitable when the external excitation is of low and variable frequency and the amplitudes are bigger than the device size. One such application is human motion energy harvesting for biomedical sensors and implants.

In the piezoelectric case, the basic principle of impulse excitation is to excite the higher natural frequency of a piezoelectric element by a proof mass oscillating at low frequency. This can improve the electromechanical coupling. Devices include a cylindrical harvester in the shape of a common battery using magnetic actuation [2]. A simple beam arrangement, where an elastic beam with low resonance frequency actuates a piezoelectric beam, is described in [3]. A design using the beam plucking approach for a non-inertial knee joint harvester can be found in [4]. Impact driven devices, where a sliding proof mass hits piezoelectric beams, are presented in [5,6] as well as variations on this principle in [7,8].

The purpose of this article is to investigate the best parameters for magnetic beam plucking in a rotational harvester, first introduced in [9]. Figures 1 and 2 show descriptive drawings and figure 3 the corresponding experimental set-up. An eccentric mass mounted onto a shaft is free to rotate around its axis. A permanent magnet is installed inside this rotor, facing another permanent magnet bonded to the tip of a fixed piezoelectric beam. As the rotor oscillates under external excitation the two magnets pass each other and the piezoelectric beam is consequently plucked and left to vibrate at its natural frequency. The advantage of this contactless coupling is that it prevents impact on the brittle piezoelectric material.

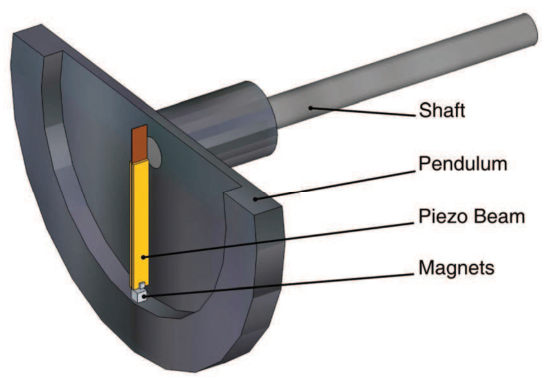

Fig. 1: Piezoelectric rotational harvester

Other devices with magnetic coupling have been presented. In [10] a linear set-up, intended for car tyre pressure sensors can be found. A rotational piezoelectric windmill is presented in [11], with the main difference to our device being that the magnets are directly driven by the windmill and it is thus not an inertial design.

MODEL OF THE MAGNETIC COUPLING

Ideally, the plucking should provide a sudden release and an unimpeded free oscillation of the beam. This is more complicated to achieve when using a magnetic coupling instead of fingers or plectra. To understand the interactions, the simple model depicted in figure 4 was used. The piezoelectric effect is not considered and the beam is reduced to a mass-spring-damper system, with k, the spring stiffness, c, the damping and m_1, a lumped mass representative of the tip magnet and the beam.

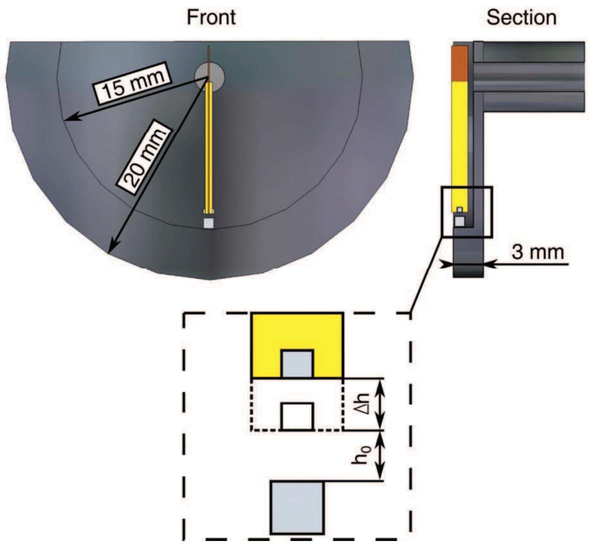

Fig. 2: Front and section views of the piezoelectric rotational harvester, detailing the arrangement of the magnets

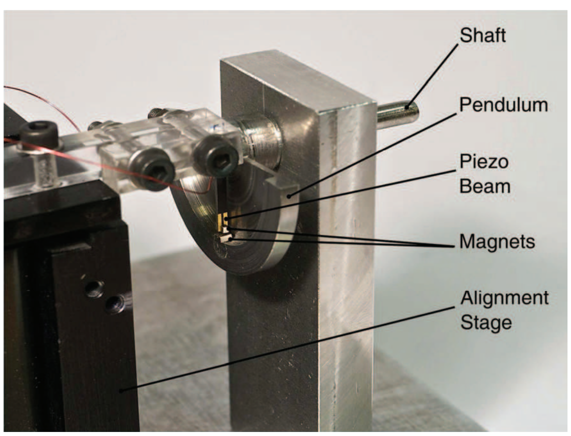

Fig 3: Experimental set-up of the rotational harvester

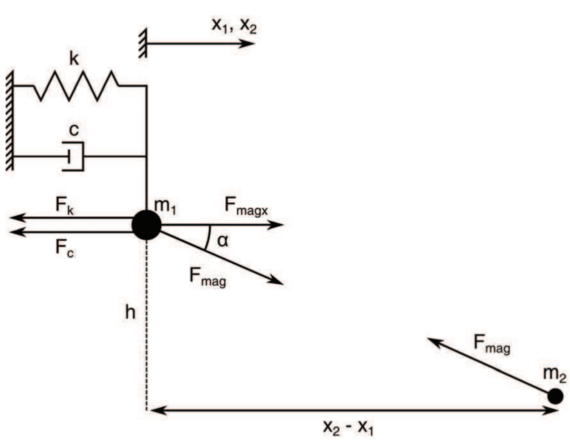

Fig. 4: Model of magnetic plucking

In the diagram, m_2 describes a second magnet, passing m_1 at a constant velocity v_0 along the x-direction with a vertical gap h separating them. The relevant forces in the system are F_k, resulting from the spring, F_c, from the damper and the magnetic force F_{mag} and its component in x-direction, F_{magx}. The magnetic force is assumed to follow an inverse square relationship with the distance r, separating the magnets, according to the following equation:

$$F_{mag} = \frac{F_0 h^2}{r^2} \tag{1}$$

Here F_0 describes the initial magnetic force, when both magnets are horizontally aligned in their zero position; positive values are for an attractive force, and negative values for a repulsive force, depending on the polarity of the magnets relative to each other.

Equation (1), together with basic trigonometric rules, can be used to determine F_{magx} as:

$$F_{magx} = F_0 h^2 \frac{(x_2 - x_1)}{(h^2 + (x_2 - x_1)^2)^{3/2}} \tag{2}$$

The entire system can then be characterised by the following governing equation:

$$\ddot{x}_1 = -\frac{k}{m_1} x_1 - \frac{c}{m_1} \dot{x}_1 + \frac{F_0 h^2}{m_1} \cdot \frac{(x_2 - x_1)}{(h^2 + (x_2 - x_1)^2)^{3/2}} \tag{3}$$

Bearing in mind that this model is meant to help understand the conditions and relevant parameters for magnetic plucking and not to exactly replicate the response of the prototype, the values were chosen arbitrarily to be in the same order of magnitude as they are for the experimental set-up.

RESULTS

Figure 5 shows the calculated response of the mass-spring-damper system for initial parameters according to table 1, where the magnets are arranged in a repulsive way. The response in figure 6 uses the exact same parameters except for the initial magnetic force being positive, corresponding to an attractive arrangement. The two graphs exhibit a significantly different behaviour with the main finding being that with an attractive arrangement there is a distinct catch phase where the primary magnet, representing the tip of the beam, first flicks towards the approaching driving magnet and vibrates at higher frequency (785 Hz) while travelling along with it before being released and oscillating at its natural frequency (370 Hz). The oscillation frequency in the repulsive arrangement is 450 Hz. Furthermore, comparing the position of the driving magnet x_2 and the displacement of the primary magnet x_1 just before release, it can be seen that x_1 leads x_2 in the repulsive set-up as it gets pushed away and then "snaps" through upon release.

The attractive arrangement shows x_2 dragging x_1 along. This seems to result in a more abrupt release and stronger oscillation for the repulsive arrangement.

Table 1: Initial simulation parameters

Parameter	Value	Units
k	6320	N/m
c	0.05	Ns/m
h	0.2	mm
v_0	20	mm/s
m_1	1	g
F_0	-10	N

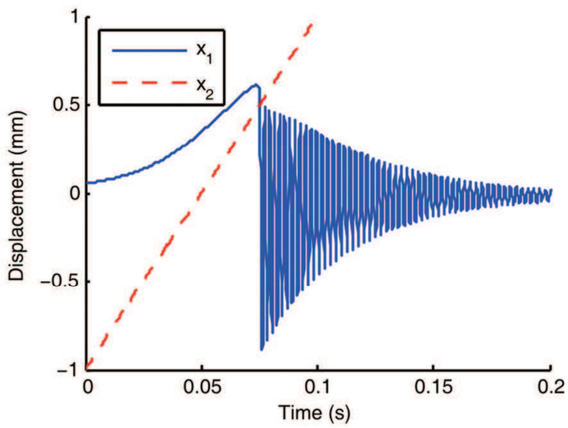

Fig. 5: Simulated plucking, repulsive arrangement

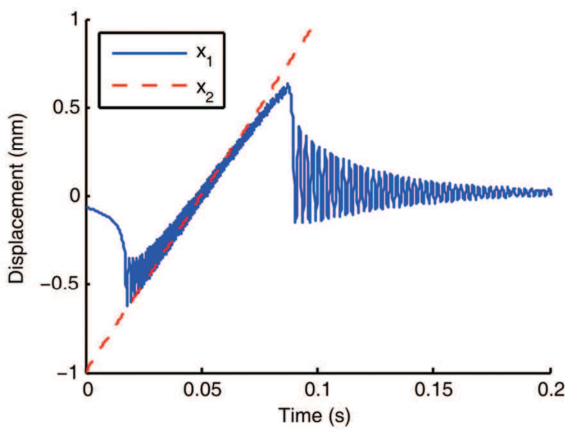

Fig. 6: Simulated plucking, attractive arrangement

As can be seen from figures 6 and 7, this behaviour can be replicated in the voltage output of the piezo beam in the experimental set-up, tested under harmonic excitation on a rocking table at 2 Hz and 2.7 m/s^2 acceleration. Compared to the repulsive arrangement, the voltage curve for the attractive arrangement shows distinct catch and release phases with an increase in oscillation frequency while the rotor and beam tip travel together. It is assumed that this increased frequency results from an additional stiffness introduced to the system by the strong magnetic force when the magnets are at their closest. The beam is clamped only on its center shim, with the piezo layers not covering the whole length. This introduces a discontinuity at the base and explains why the free oscillation does not follow an exponential decay.

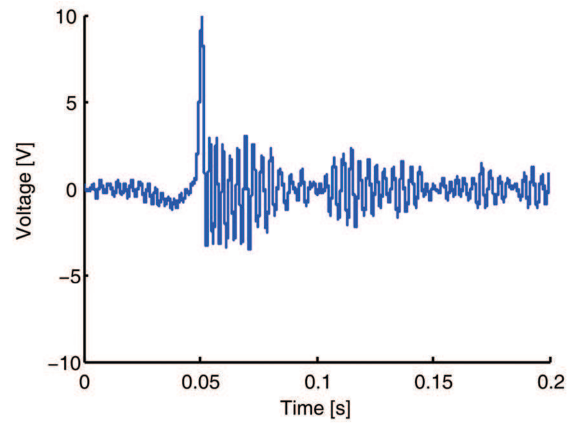

Fig. 7: Measured voltage, repulsive arrangement

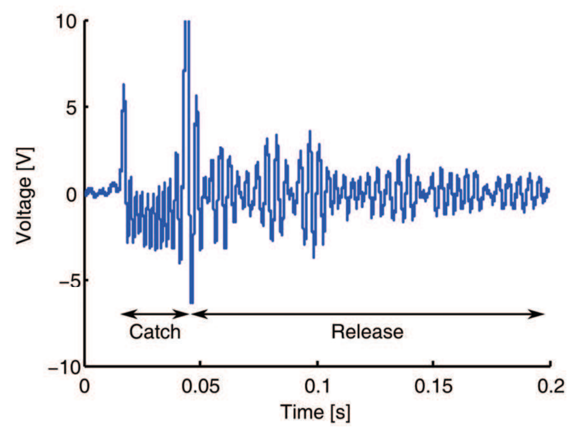

Fig. 8: Measured voltage, attractive arrangement

In figure 9 the calculation parameters have been changed to double the gap to h=0.4 mm and accordingly reduce the initial force by a factor of four down to F_0=2.5 N. The vibration of x_1 completely disappears leaving only a very slow and gradual displacement. This is the worst case of operation since the beam does not get plucked and the advantages of this method disappear, resulting in lower power output and the transduction not being independent of the excitation frequency any longer.

Finally, figure 10 shows the effect of a drastically increased driving velocity v_0=200 mm/s. The catch phase, where the two magnets travel together, becomes significantly shorter. In an extreme case, depending not only on the velocity, but also on the natural frequency of the system, the catch phase would disappear completely. Still, comparing to figure 5, the repulsive arrangement should provide a more abrupt release with stronger oscillation.

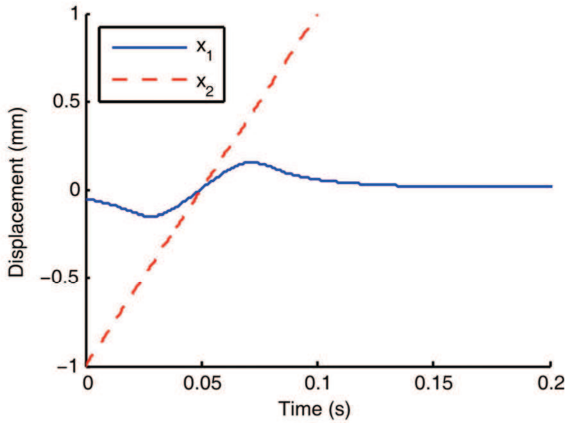

Fig. 9: Simulated plucking, attractive arrangement with larger gap

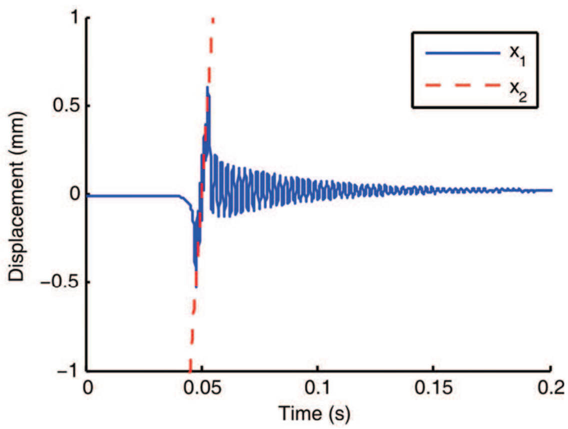

Fig. 10: Simulated plucking, attractive arrangement with higher driving velocity v_0

CONCLUSIONS

This paper introduces a simplified model for magnetic beam plucking in piezoelectric energy harvesting devices. Comparison of the simulated results with measurements on a prototype support the validity of the model to further study the influence of various parameters. The differences between the repulsive and attractive arrangements are particularly interesting and suggest that a repulsive magnet set-up could have advantages due to a stronger plucking of the beam. The magnetic force does have an influence on the oscillation frequencies as well.

In terms of maximal power output, this suggests that the attractive arrangement should be slightly inferior in terms of impedance matching, due to the differences in frequencies during the catch and release phases. However, this was not demonstrated in an experiment, where both arrangements delivered around 1.4 µW at 2 Hz and 2.7 m/s^2 acceleration. This might be due to limitations of the measurement set-up, making it difficult to adjust the gap to the same value after changing the magnets.

The influence of the gap between the magnets and the driving velocity has been shown as well. The gap size should be kept as small as possible for a good plucking of the beam.

The effects of the initial force and whether stronger magnets could ease the constraint of the small gap will be studied in the future. Replacing the mass-spring-damper system by an actual model of the piezoelectric bimorph is a work in progress.

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