MULTIPHYSICS MODELING AND SIMULATION OF A DUAL FREQUENCY ENERGY HARVESTER

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Energy harvesting, Mechanical resonator, Finite element analysis, Multiphysics modeling, Piezoelectricity, Frequency tuning, Magnetic force.

ABSTRACT

Vibration based energy harvesting gained a lot of importance in the last two decades, due to the various potential vibration sources in industrial environments, where sensors have to be implemented in inaccessible environments. In this paper we present a concept of a dual frequency piezoelectric energy harvester with magnetic tuning capabilities together with characterization results. We subsequently investigate a potential gain in the electrical power output by implementing separated piezoelectric patches.

INTRODUCTION

Vibration based energy harvesting means converting vibrations present in the environment into electrical energy. It is particularly well suited for industrial condition monitoring applications where sensors need to be implemented in harsh, dark or dirty environments. During the last two decades, several energy harvesters and autonomous systems have been introduced. Further research has been devoted to the development of new resonator designs and to elaborate different strategies for performance optimization of these devices, e.g. by increasing the resonator bandwidth, or tuning the operating frequency of the device.
(Vinod, Prasad, Shi and Fisher, 2008) presented an approach using magnetic forces for tuning the energy harvester's frequency. (Neiss, Goldschmidtboeing, Kroener anf Woias, 2014) proposed a tuning mechanism that allows a compensation of the hysteresis as well as maintaining the optimal working point. A method has been proposed by (Upadrashta and Yang, 2016) to simplify modelling and simulation of the nonlinear magnetic tuning mechanism of a piezoelectric energy harvester using a nonlinear spring. (Hoffmann, Willmann, Hehn, Folkmer and Manoli, 2016) presented a self-adaptive energy harvesting system, which is able to adapt its operating frequency to the dominant vibration frequency of the environment. The energy harvester itself delivers the power required for frequency tuning. Finally, (Wu, Tang, Yang and Soh, 2013) developed a novel compact piezoelectric energy harvester with two resonant modes. (Bouhedma and Hohlfeld, 2017) presented a full experimental characterization of a single and dual frequency resonator with a potential use as an energy harvester.
In this paper, we study the behavior of a dual frequency piezoelectric energy harvester incorporating permanent magnets for frequency tuning. We calculated the magnetic forces to implement them as nonlinear springs. Finally, we investigated the potential gain in the power output of a simple harvester, by using segmented patches connected in series.

FREQUENCY TUNING

We investigate the magnetic tuning of a dual frequency mechanical resonator. A pair of fixed magnets exert forces on another permanent magnet which is mounted on the flexible beam. The net magnetic force superimposes with the restoring force of the deflected beam. Thereby, an effective spring constant arises. In other words, the magnetic forces will soften or harden the structure, depending on the magnets' orientation and their mounting configuration. This will result in a shift in resonance frequency. In order to experimentally investigate the frequency tuning performances, we consider a resonator fabricated from stainless steel. It features a so-called folded beam as shown in figure 1.

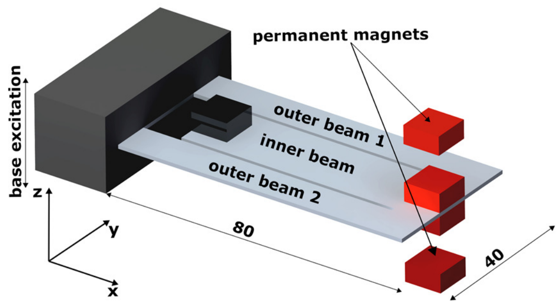

Figure 1: Descriptive scheme of the 1 mm thick folded beam mechanical resonator with the frequency tuning permanent magnets in the vertical configuration

The structure is subjected to a harmonic base acceleration with a magnitude of $a = 0.2$ g generated by a vibration test equipment. The tuning mechanism incorporates permanent magnets in attractive and repulsive orientations, mounted such that the force reaction is either collinear to the axis of the beam (referred as 'axial configuration') or perpendicular to the beam surface (referred as 'vertical configuration').

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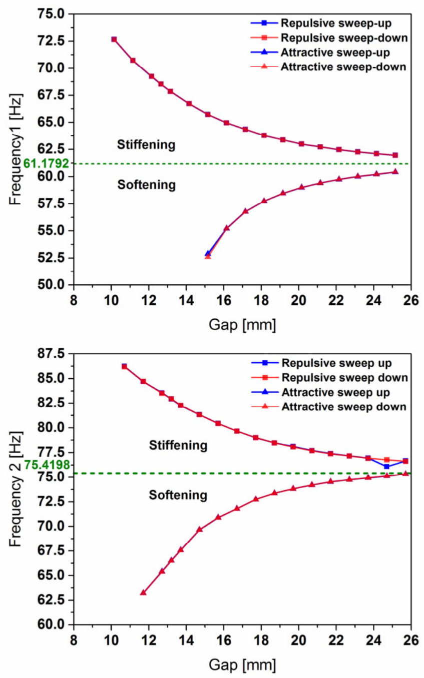

Figure 2: Frequency shift of the dual frequency resonator in the vertical configuration, considering both, outer part tuning (top) and the inner part (bottom). The magnetic forces enable tuning the operating frequencies by approximately 12% in both directions

The experimental results in figure 2 show natural frequency tuning of the dual frequency resonator by up to 20%. The tuning of the two frequencies can be achieved independently of each other; this open up the opportunity to reduce the frequency gap between the two resonances. Furthermore, achieving a frequency overlap is possible. However, we observed a drop in displacement amplitudes during tuning, which constitutes a limitation of using such a strategy (Bouhedma and Hohlfeld, 2017).

SIMULATION APPROACH

In order to understand the behavior and estimate the power output of the proposed energy harvester, we implemented the structure in ANSYS Multiphysics. We considered the mechanical resonator shown in figure 1 with two identical masses m = 7.6 g.

Mode shape comparison

A modal analysis yielded the mode shapes at the two resonance frequencies. We implemented a harmonic response simulation in ANSYS and verified its results via experimental data. We excited the structure with a harmonic base acceleration generated by a vibration test system with an amplitude of a = 0.5 g.

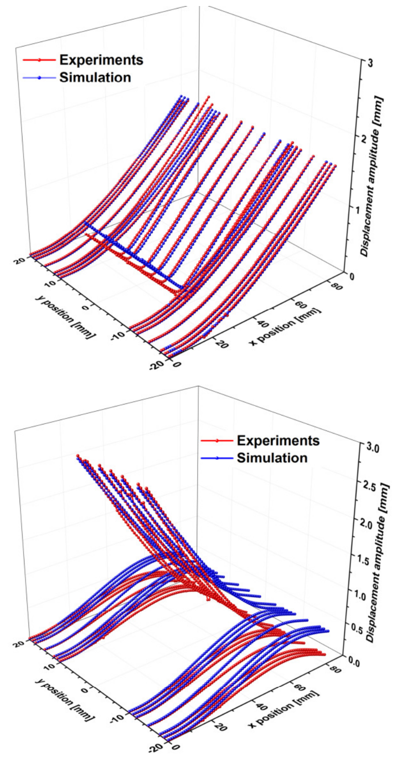

Figure 3: Comparison between the simulation and experimental first (top) and second (bottom) mode shapes of the mechanical resonator

The results on figure 3 show a good qualitative fit between simulation and experimental results. The slight discrepancy in the amplitude values is presumed to stem from measurement errors and the clamping system. Moreover, the positions of the magnets, which in this case are used only as tip masses, can also induce errors.

Piezoelectric model

Furthermore, we implemented the piezoelectric transducer elements in our ANSYS model. Patch dimensions are 60×10×0.2 mm^3 on the outer beam and 48×18×0.2 mm^3 for the inner beam. The material properties of the piezoelectric ceramic originate from PIC-255 supplied by PI Ceramic.

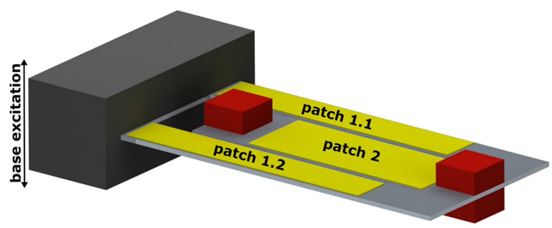

Figure 4: Arrangement of piezoelectric energy transducing patches on the flexible segments of the resonator

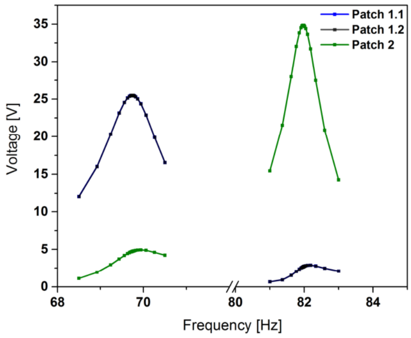

Figure 5: Estimated voltage output of the dual frequency energy harvester

The power output can be given by the following expression:

$$P_{ij} = \frac{1}{4} V_{0\,j}^{2}\, 2\pi\, f_j\, C_i \qquad (1)$$

Where: $V_{0\,j}$ is the open-circuit output voltage amplitude at mode j, f_j is the mode frequency and C_i is the capacitance of the piezoelectric patch i. The total power output, as represented in figure 6, is then the sum of all powers delivered by each patch at every mode.

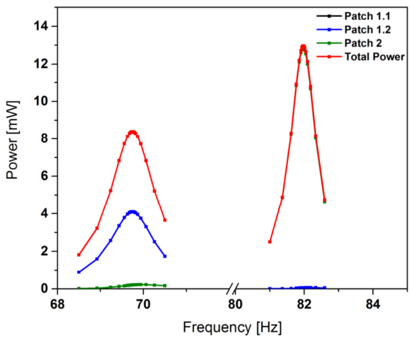

Figure 6: Estimated power output of the dual frequency energy harvester

These results illustrate the possibility of harvesting energy from the first two resonance frequencies. Power generation, as shown on figure 6, occurs mostly at the patches located at the inner respectively outer beams. Only one patch is mechanically stressed at each of the two operational frequencies.

Magnetic forces simulation

We also investigate the magnetic forces for later implementation in our ANSYS model. This will enable us to simulate the frequency tuning effect in different configurations and orientations. We considered a pair of neodymium permanent magnets in COMSOL Multiphysics, with N42 magnetization and with the geometry showed in figure 7. The magnet's dimensions are 10×10×5 mm^3. For simplification purposes, we ignore the rotation of the magnet as the beam deflects.

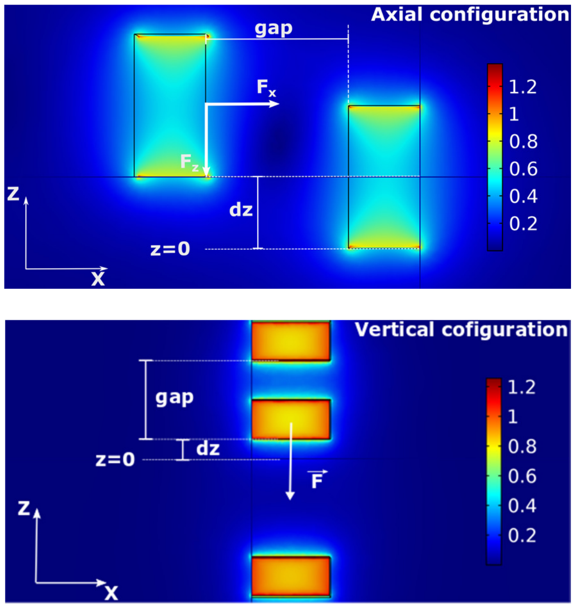

Figure 7: Axial (top) and vertical (bottom) magnet configuration; the color scale corresponds to the magnetic flux density

The simulation considered different orientations (attractive and repulsive) and different configurations (axial and vertical). It has been performed for different gap values and for different vertical displacements as depicted in figures 8 and 9.

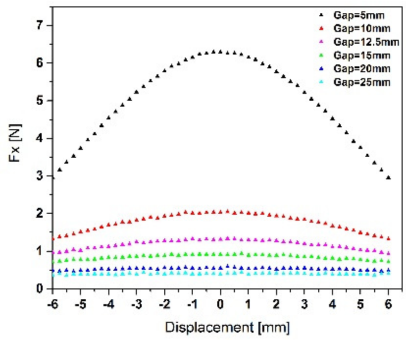

Figure 8: Axial component F_x of the attractive force in axial configuration

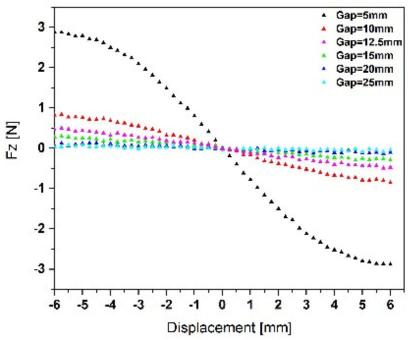

Figure 9: Vertical component F_z of the attractive magnetic force in axial configuration

These results show a nonlinear force-displacement relationship between the force components and the vertical displacement of the magnet, which in our case represents the beam respective magnet displacement amplitude.

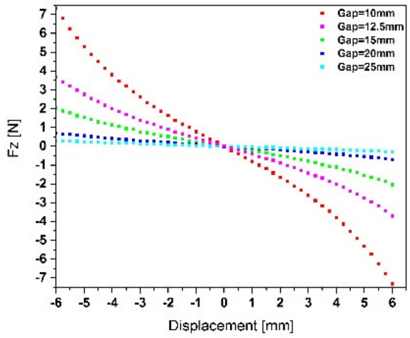

Figure 10: Repulsive magnetic force components in the axial configuration

We intend to implement the effect of the magnetic forces in our dual frequency resonator model by either considering springs elements with nonlinear stiffness or by a position-dependent force. Therefore, we identify fitting functions represented in figures 11 and 12.

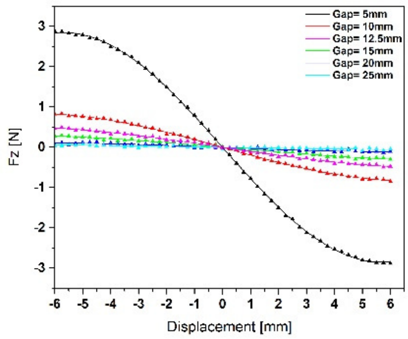

Figure 11: Fitting function for the attractive magnetic force component F_Z in the axial configuration

In both configurations, we mainly focus on F_Z, and this is due to the approach similarities used for both components (Fx and Fz).

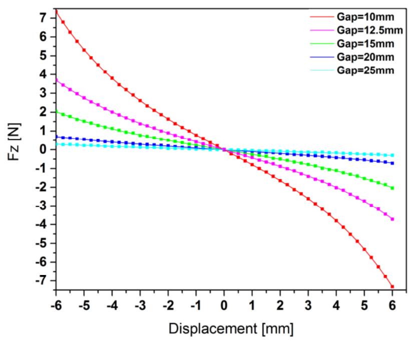

Figure 12: Fitting function for the repulsive magnetic force component F_Z in the vertical configuration

The defined functions in all configurations show an excellent match with the simulation results. As an example, the fitting functions Fz_a and Fz_v corresponding to the minimum gap values (5 mm in the axial configuration and 10 mm in the vertical one) are given as follows:

$$Fz_a = -0.002 + 2.85 \sin\left(\pi \frac{z - 11.46}{11.46}\right) \tag{2}$$

$$Fz_v = \sum_{i=0}^{5} a_i z^i \tag{3}$$

where: a_1 = -0.006, a_2 = -0.782, a_3 = 4.11×10^{-4}, a_4 = -0.009, a_5 = 1.65×10^{-7} and a_6 = 9.02×10^{-5}. These force-displacement functions can be directly implemented into our ANSYS model. Alternatively, we implement their derivatives, which give the nonlinear stiffness of the lumped springs.

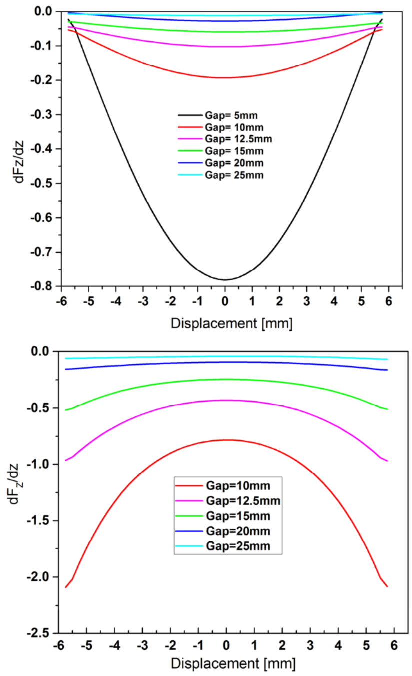

Figure 13: Derivatives of the fitting functions, which give the nonlinear stiffness of the spring elements in the axial configuration (top) and in the vertical configuration (bottom)

The fitting functions are valid for a specific gap. Therefore, we will compose fitting functions with two variables, which will enable us and to parameterize the problem and run the model for different gaps.

Power optimization

Subsequently, a simulation using ANSYS Multiphysics has shown the potential to increase the power output of a piezoelectric harvester by considering two segmented patches electrically connected in series; instead of using a single patch. We considered a simple tip loaded (m = 3.8 g) energy harvester with the geometry shown in figures 14 and 15 subjected to a harmonic base excitation amplitude of d = 6 µm.

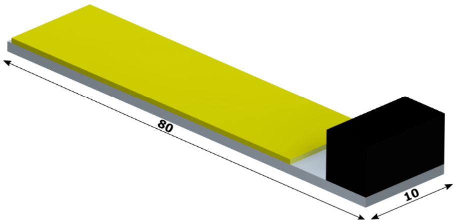

Figure 14: Simple tip loaded energy harvester with a full piezoelectric patch

By implementing PIC-255 as a piezoelectric material we observed that the power can be increased by up to 13% compared to a full patch (see figure 16, the full patch configuration corresponds to L_p = 60 mm). The simulations have been executed with unrealistically low damping coefficients, which explains the high power output values.

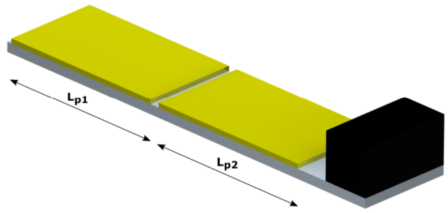

Figure 15: Simple tip loaded energy harvester with two-segmented piezoelectric patches electrically connected in series

The results indicate that optimum power delivery is achieved if the single patch is segmented into two patches of approximately equal sizes. This gain in power is due to the superposition of the voltage generation of the individual patches. Simultaneously, the total capacitance decreases due to the series connection, leading to a higher optimum load. As described in equation (1), the power output scales quadratically with available voltage and only linear with the capacitance. Only a minor gain in total power output is achievable if three or more patches are used.

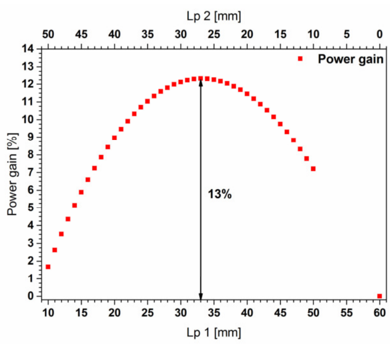

Figure 16: Normalized power output of a tip-loaded simple energy harvester for various piezoelectric patch dimensions, compared to a full patch configuration

The power gain is limited to 13% in the present case (tip masses). Cantilevers without additional masses show a different strain distribution and bear the potential of up to 30% of power gain (Bouhedma and Hohlfeld, 2017).

CONCLUSION AND OUTLOOK

In this work, we experimentally investigated the magnetic frequency tuning of a dual frequency resonator. The mechanical resonator was characterized in two configurations of different magnet arrangements (axial and vertical) with different magnets orientations (attractive and repulsive). It has been shown that the frequency can be tuned by up to 20% for both parts (inner and outer). As the tuning of one mode does not affect the other mode, the approach can also be used for reducing the frequency gap between the two modes.

On the other hand, we simulated the behavior of the mechanical resonator incorporating the piezoelectric energy transducer. We demonstrated the dual frequency operation and that energy can be harvested at two different frequencies. In order to simulate the behavior of the resonator under the influence of the magnetic forces, a static simulation of the magnetic forces between two permanent magnets, in the axial and the vertical configurations has been performed. The results of these simulations enabled us to define fitting functions giving the force-displacement relationships and their derivatives. The latter functions give the nonlinear stiffness of the magnetic spring elements. These data still needs to be thoroughly investigated and extended to define a more general gap-displacement-force relationship, since the magnetic forces are gap-dependent as well.

Subsequently, we investigated the possibility of increasing the power output of a tip-loaded simple piezoelectric energy harvester, by using an array of segmented piezoelectric patches, connected in series, instead of a full patch. The simulation results revealed that the gain in power can reach 13%. These results still need to be validated by an experimental work and will be generalized for the presented energy harvester.

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