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Impact-driven up-conversion in piezoelectric MEMS energy harvesters with pulsed excitation

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Impact-driven up-conversion in piezoelectric MEMS energy harvesters with pulsed excitation

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Abstract. The potential of impact-driven frequency up-conversion in a MEMS EH is evaluated using numerical simulations. The investigated design is compared to a conventional cantilever EH in terms of output power and loss rate. The upshifting can lead to significantly increased output power at a similar loss rate but as the time scale for the loss is long, the benefit is limited. This also requires an effective upshifting process. The design of the impact introduces a length scale that must be selected with excitation, gravity, and pre-stress taken into account. This makes this type of EH application-dependent as a non-optimal choice may result in low output power.

1. Introduction

One way to power sensors is with piezoelectric energy harvesters (PEHs), where PZT cantilevers is a common choice [1]. One alternative is a bridge configuration, which, due to its inherent nonlinearity, has been suggested as a way to adapt to an increasing excitation frequency [2]. Further benefits are the mechanical robustness and the uniform PZT strain, which is higher at a given deflection than in a comparable cantilever [3, 4]. Another concept is the use of impacts to obtain frequency upshifting.[1] One example is a scrape-through PEH [6], where a high-frequency PEH (PZT-H) was excited by impacts from a low-frequency PEH (PZT-L). The PZT-H, however, generated little power (30 nW) compared to the PZT-L (145 nW). This makes the approach questionable since the space needed for the PZT-H could be used to optimize the PZT-L. In a PEH by Gu and Livermore [7], power was mainly harvested *during* impact.

In this paper, impact-driven frequency up-conversion in a MEMS PEH is evaluated using numerical simulations. The discussion is kept as general as possible to assess the approach. Assuming a medical application, the use of magnets is not allowed and the excitation is pulsed.

2. Problem statement

For manufacturing simplicity, the structure is made of silicon with PZT deposited on top. With this method, the PZT is thin, 2 μm. The PZT material, modeled as PZT-5H, is operated in the 31 mode, i.e., the strain is orthogonal to the electric field. A tungsten proof mass is used to reach the energy target, which is > 1 μJ per excitation pulse. Large tungsten pieces can be attached to MEMS structures, but the drawback is mass production issues. We assume that the impact occurs between the device and the capping as this reduces the height and complexity

[1] Impacts can generate nonlinear effects somewhat comparable to those in a bridge, see, e.g., Ref. [5].

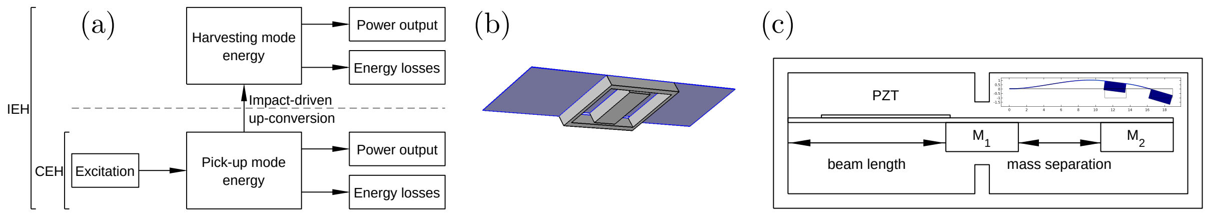

Figure 1. (a) The impact and cantilever EH approaches. (b) A conceptual double bridge IEH. (c) The double cantilever EH. The inset shows the harvester (second) mode.

compared to having multiple devices. Thus, the impact transfers energy between modes. We aim for a factor of 10 frequency up-conversion to clearly bring out the scaling effects.

A pulsed excitation is targeted. As the device velocity is bounded, the excitation pulse must have both positive and negative values and we model it as a single period of a sine wave. The maximum amplitude is $1g$. Thus, the EH is not operated in resonance, as is often assumed in the literature, and the output power is limited accordingly. A low-frequency application is targeted and the excitation single-period sine wave frequency is 40 Hz. As the excitation spectrum is wide, matching of the device to the excitation is facilitated.

The aim is to investigate if up-conversion can be effectively achieved and if the resulting EH can extract more energy than one without up-conversion. We compare with a traditional cantilever EH, and refer to this and the impact EH as the *CEH* and the *IEH*, respectively.

3. Design considerations

The impact approach is visualized in Fig. 1a. The excitation generates *pick-up mode* motion, which transfers to the *harvesting mode* via the impact(s) and results in a certain fraction of energy transfer.[2] For the CEH, these are the same mode. Due to the thin PZT, the mechanical and electrical processes are weakly coupled (as confirmed below) and there (approximately) is an *excitation phase*, with a certain energy input, and a *harvesting phase*, with power output and energy reduction due to losses. The IEH should obtain maximum output energy per pulse by reducing the energy output time scale and/or increasing the loss time scale, without reducing the energy input.

First, a double bridge as in Fig. 1b was considered. The PZT is on the inner bridge and power is output after the frame impacts the capping, which has an indentation for unimpaired proof mass motion. This, however, reduces the input energy dramatically. With reasonable dimensions, a 1 g proof mass, and a 40 Hz pick-up mode, the beam thickness is ∼10 µm. This is incompatible with the excitation as it puts the bridge in the strongly nonlinear regime. (The nonlinear potential term becomes important at deflections comparable to the beam thickness [8, Eq. (1)].) In words, as the excitation increases the deflection, the spring force increases superlinearly. The proof mass velocity changes signs, and then a deceleration occurs although the pick-up mode is linearly matched to the excitation. Thus, in this application, a linear pick-up structure should be used and we instead consider the double cantilever EH in Fig. 1c, where M_1 impacts the capping and M_2 corresponds to the inner bridge proof mass.

4. Numerical simulations

To assess the IEH, the potential for output power increase, loss reduction, and efficient conversion, respectively, must be estimated. In all cases, the EH width is 10 mm and the beam thickness is 80 µm.

[2] There may also be "leakage" to other modes, which is neglected here.

4.1. Output power

For comparison, a traditional CEH with a 5 mm $\times$ 10 mm $\times$ 1 mm tungsten proof mass (weighing 0.97 g) and a 12.7 mm beam (cf. Fig. 1c) has the first resonance at 40 Hz. Directly after the excitation, the EH energy is $W = 7.1$ μJ. (With no output power, $W = 7.3$ μJ, confirming the weak coupling.) The PZT and the load resistance are optimized for maximum output power [9]. Thus, the PZT is at the CEH base (maximum strain) and is 10.4 mm long. With a load resistance of 4.5 kΩ, the optimal maximum output power is $P = 23$ μW. Based on average power, the time scale is $\tau_{\mathrm{el}} = 2W/P = 620$ ms. (The excitation occurs over 25 ms.)

A 400 Hz CEH is obtained by shortening the beam to 1.0 mm. Using a 400 Hz excitation with $11g$ amplitude, the energy after excitation is the same as before.[3] An optimal maximum output power of 240 μW ($\tau_{\mathrm{el}} = 58$ ms) is reached with a 1.0 mm PZT and a 4.6 kΩ load resistance. Thus, the 400 Hz CEH can have significantly increased output power.

To investigate if an IEH can achieve similar output power, the EH in Fig. 1c is simulated. The proof mass is now split in two equal pieces. The pick-up (first) mode (at 40 Hz) and the harvesting (second) mode (at 400 Hz) have been designed by optimizing the beam length (18.8 mm) and the mass separation (2.8 mm). Placing the PZT from 6.8 mm to 11.1 mm, using a load resistance of 1.1 kΩ, and exciting the harvesting mode with the same energy as before, the maximum output power is $P = 110$ μW ($\tau_{\mathrm{el}} = 130$ ms). While lower than the power for the 400 Hz CEH, this is still almost five times higher than for the 40 Hz CEH.

4.2. Energy losses

It has been found for comparable CEHs [10] that squeeze film damping is the dominating loss mechanism. For the IEH pick-up and harvesting modes, the proof masses move normal to the capping. The deflection is not small compared to the capping distance, but we nevertheless use analytical estimates for this regime for a general discussion. The drag coefficient, c_d, is known [11, Eq. (3.17)][4], and this can be used to calculate the Q-value.[5] For a harmonic oscillator, the power decay with time is proportional to $\exp(-2\zeta\omega_0 t)$, i.e., the characteristic time $\tau_{\mathrm{sf}} = 1/(2\zeta\omega_0) = Q/\omega_0$. Since the Q-value is proportional to ω_0, the time scale is independent of which mode is oscillating and nothing is gained from frequency upshifting in this respect.

Relevant to our study, Elfrink et al. [10] found that in vacuum-packaged devices, the squeeze film damping was comparable to the intrinsic damping. For the "Type 5" CEH with 5 mm$\times$5 mm silicon proof mass and 600 Hz resonance frequency, the Q-value was 1000, cf. [10, Table 2]. Using this value, we find that $\tau_{\mathrm{sf}} \gg \tau_{\mathrm{el}}$ for both the CEHs discussed above.

4.3. Mode conversion efficiency

Simulation of the mode coupling requires impact modeling and a simple lumped IEH model, where the capping acts as a stiff linear spring, has been used. This causes an ideal impact on a very short time scale. Using the same masses, resonance frequencies, and excitation as above, the energy at the end of the excitation is 7.3 μJ at a maximum deflection of 490 μm. After placing the capping at a selected distance, the average energy in the two springs can be found.

One important complication is that the static deflection due to gravity is 160 μm and if the device orientation is not known, then the equilibrium position uncertainty is 33 % of the maximum deflection. With in-plane (or no) gravity, a capping distance of 300 μm leads to a high impact velocity, shortly before the end of the excitation. This distributes the energy effectively between the modes but the system energy is reduced by the impact to 5.4 μJ. However, when

[3] We here, temporarily, assume that the energy can be ideally transfered to the 400 Hz CEH.
[4] Note that Eq. (3.17) of [11] has incorrect dimensions as a factor $1/\omega$ is missing.
[5] For an assumed proof mass motion, the energy is known. Calculating the energy loss in one period using c_d, the Q-value can be obtained from its definition.

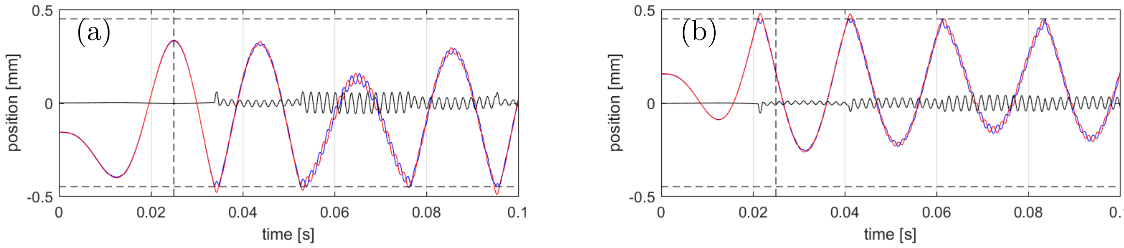

Figure 2. The position of M_1 (blue), M_2 (red), and their separation (black). The dashed lines indicate the position of the capping and the end of the excitation. (a) Gravity acts downwards and impact occurs after the end of the excitation. (b) Gravity acts upwards. The earlier impact reduces the system energy.

aligning gravity with the up or down directions, the system energy is significantly reduced to about 3 µJ due to the early impact. Increasing the capping distance to 450 µm gives the results in Fig. 2. In Fig. 2a, the first impact occurs after the excitation while in Fig. 2b, the energy is 5.3 µJ due to the impact. The impact velocity is here reduced and more impacts are needed to effectively distribute the energy between the modes. Thus, the optimal capping distance is both excitation- and orientation-dependent and it is expected that any device pre-stress changes the optimal capping distance.

5. Conclusion

The potential of impact-driven frequency up-conversion in a MEMS PEH has been studied. It was found that the upshifting can lead to significantly increased output power at a similar loss rate, implying that a higher fraction of the available energy is obtained as useful output. However, the time scale for the loss is long and the benefit is therefore limited. An IEH, however, requires an effective upshifting process. The capping distance introduces a length scale that must be selected with both the maximum deflection due to excitation and the static deflection due to gravity and pre-stress taken into account. If information about this is not present during the IEH design process, then the impact may reduce the total system energy considerably or the mode conversion may be ineffective.

Acknowledgments

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