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Adrien Morel, David Gibus, Gael Pillonnet, Adrien Badel. Opportunities for electrically-based frequency tuning of piezoelectric vibration energy harvesters. 2021 IEEE 20th International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS), Dec 2021, Exeter, United Kingdom. pp.236-239, 10.1109/PowerMEMS54003.2021.9658360 . hal-03505561

HAL Id: hal-03505561

<https://hal.science/hal-03505561>

Submitted on 31 Dec 2021

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Opportunities for electrically-based frequency tuning of piezoelectric vibration energy harvesters

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Abstract—This paper focuses on electrically-based solutions for tuning the resonant frequency of piezoelectric vibrations energy harvesters in order to compensate for aging or vibration frequency shifts. We present the theory behind electrical frequency tuning, and show that a strong electromechanical coupling associated with two-tuning electrical interfaces allow to reach relatively large frequency tuning ranges. Such solution requires the design of strongly coupled harvesters as well as the design of self-adaptive self-powered electrical interfaces, but, compared to other design approaches, requires much less volume and energy.

Index Terms—Electromechanical dynamics, Vibration energy harvesting, Piezoelectricity, Nonlinear circuits, Frequency tuning.

I. INTRODUCTION

Piezoelectric vibration energy harvesters (PEH) have been widely investigated in order to complement or replace batteries for powering sensor nodes. Most PEH are made with a linear mechanical resonator. The harvested power with such PEH is maximized if the vibration frequency matches the PEH resonant frequency. However, in real environment, the vibration frequency as well as the PEH resonant frequency might vary with time (because of aging, environmental changes, temperature variations), leading to a drastic decrease of the harvested power. In order to face this issue, researchers propose various ways to in-situ adjust the PEH resonant frequency: mechanical tuning [1] [2], magnetic tuning [3] [4], piezoelectric tuning [5] [6] (Fig. 1). All those tuning techniques require the use of bulky components (motors, magnets) or high voltages, which might be a problem in real-case applications and require a relatively large power consumption. In this paper, we describe a recent family of tuning solutions based on the electrical interface, traditionally aimed at collecting and storing the energy from the PEH. Such solution combines compactness and low-power consumption, but requires a thorough design of both the mechanical part and electrical part of the PEH.

The second section of this paper reminds the theory behind electrical frequency tuning solutions. In the third section, we show that electrical frequency tuning solutions offer a trade-off between complexity (i.e. more tuning parameters) and tuning frequency range. Some power frequency-responses of well-known tunable interfaces such as the phase-shift synchronous electric charge extraction (PSSECE) and the frequency tuning synchronous electric charge extraction (FTSECE) are given. In the fourth section, we describe the design requirements on

the mechanical and electrical parts of the PEH in order to conceive an electrical frequency tuning solution.

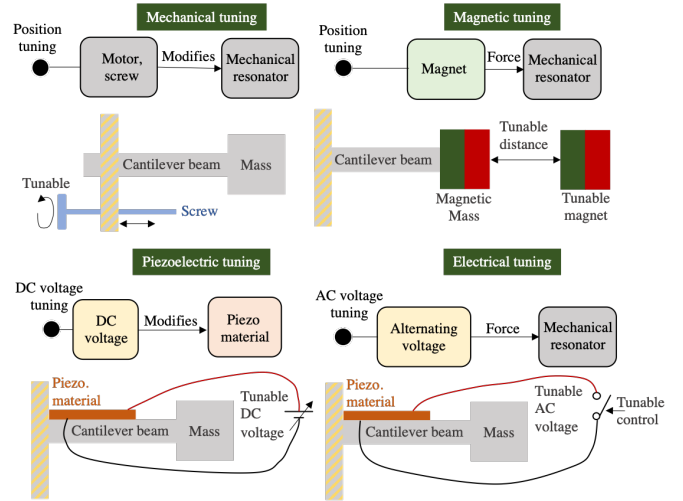


Fig. 1. Frequency tuning mechanisms in the literature.

II. ELECTRICALLY-BASED FREQUENCY TUNING

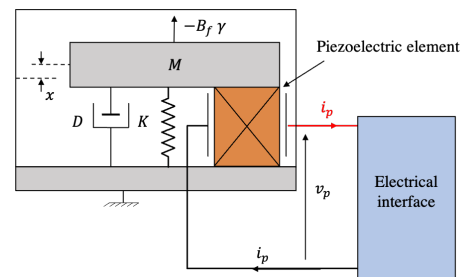


Fig. 2. Model of a linear piezoelectric energy harvester based on a cantilever beam structure.

Most linear piezoelectric energy harvesters (PEH) in the literature are made of piezoelectric plates bonded on a mechanical resonator [7]. When the resonator is under an external vibration, the piezoelectric material is strained, which generates electrical charges that can be collected by an electrical interface. An example of linear PEH is illustrated by Fig.2. The electromechanical dynamics of linear PEH can be expressed analytically by the system (1).

$$\begin{cases} M \frac{d^2 x}{dt^2}(t) + D \frac{dx}{dt}(t) + Kx(t) + \alpha v_p(t) = -B_f \gamma(t) \\ \alpha \frac{dx}{dt} = C_p \frac{dv_p}{dt} + i_p \end{cases} \quad (1)$$

With B_f , M , K , D , γ , and α being the PEH force factor, inertial mass, short-circuit stiffness, damping factor, input acceleration, and force factor, respectively. x represents the mechanical strain of the piezoelectric material, v_p the voltage across the electrodes of the piezoelectric material, C_p the capacitance of the piezoelectric plates, and i_p the current flowing in the electrical interface.

We will consider that the external vibration consists in a harmonic excitation of amplitude γ_m whose pulsation ω might slowly vary with time. In this case, the mechanical strain $x(t)$ can also be approximated as a cosine wave of amplitude X_m , such that $\gamma(t) = \gamma_m \cos(\omega t + \psi)$ and $x(t) = X_m \cos(\omega t)$, with ψ the phase difference between $\gamma(t)$ and $x(t)$. The piezoelectric voltage $v_p(t)$ is a periodic function and can be expressed as a Fourier series $v_p(t) = a_0 + \sum_{n=1}^{+\infty} [a_n \cos(n\omega t) + b_n \sin(n\omega t)]$, with a_n and b_n the n^{th} cosine and sine parameters of $v_p(t)$ Fourier series. Due to the filtering effect of the mechanical resonator (first equation of (1)), the higher frequency components of $v_p(t)$ share a negligible impact on the harvester dynamics (first harmonic assumption [8]). Hence, in order to compute the dynamics of the PEH as well as the extracted power, we only have to evaluate the fundamental of $v_p(t)$, $v_p|_1(t) = a_1 \cos(\omega t) + b_1 \sin(\omega t)$. The expression of $v_p|_1(t)$ can be rewritten as (2).

$$v_p|_1(t) = \frac{\alpha}{C_p} [\varepsilon_K x(t) + \frac{\varepsilon_D}{\omega} \frac{dx}{dt}(t)] \quad (2)$$

With $\varepsilon_K = \frac{a_1 C_p}{\alpha X_m}$ and $\varepsilon_D = \frac{-b_1 C_p}{\alpha X_m}$ the normalized electrically-induced stiffness and damping, respectively. By combining (2) with the first equation of (1) and rearranging the terms, we obtain (3).

$$\frac{1}{\omega_0^2} \frac{d^2 x}{dt^2} + \left[\frac{1}{\omega_0 Q} + k_m^2 \frac{\varepsilon_D}{\omega} \right] \frac{dx}{dt} + [1 + k_m^2 \varepsilon_K] x = -\frac{\gamma B_f}{\omega_0^2 M} \quad (3)$$

With $k_m^2 = \alpha^2 / (K C_p)$ the expedient electromechanical coupling of the PEH, $Q = \sqrt{KM}/D$ the quality factor of the mechanical resonator, and $\omega_0 = \sqrt{K/M}$ the short-circuit resonance pulsation of the resonator. From (3), we can observe that the electrical interface has an impact on both the damping of the system (ε_D) and the stiffness of the system (ε_K). This impact is proportional to k_m^2 , meaning that a larger electromechanical coupling leads to larger electrical-tuning capabilities. The mechanical displacement as well as the extracted power from the PEH can be derived from an analysis of (3) in the frequency domain.

$$\underline{x} = \frac{-(\gamma B_f) / (\omega_0^2 M)}{[1 - \Omega^2 + k_m^2 \varepsilon_K] + j[\Omega/Q + k_m^2 \varepsilon_D]} \quad (4)$$

$$P_{ext} = P_{lim} \frac{4k_m^2 \varepsilon_D \Omega / Q}{[1 - \Omega^2 + k_m^2 \varepsilon_K]^2 + [\Omega/Q + k_m^2 \varepsilon_D]^2} \quad (5)$$

With $\Omega = \omega/\omega_0$ the normalized vibration frequency, and $P_{lim} = (B_f^2 \gamma^2 Q) / (8\omega_0 M)$ the maximum power that can be harvested with a linear PEH, as proved in [7]. Equation (5) demonstrates that the power-frequency function of any linear PEH can be adjusted thanks to an electrical interface: the system damping can be virtually tuned to any value thanks to $\varepsilon_D \in \mathbb{R}^+$, and the system resonance frequency can be virtually tuned to any value thanks to $\varepsilon_K \in \mathbb{R}$. Practically, the values that can be taken by ε_D and ε_K are limited by the choice of the electrical interface. Furthermore, the value of k_m^2 is also limited by the choice of piezoelectric material and the mechanical design of the PEH, which constraints the values of $k_m^2 \varepsilon_D$ and $k_m^2 \varepsilon_K$.

III. TUNABILITY VERSUS COMPLEXITY

As mentioned in the previous section, the tunability of a system {linear PEH + electrical interface} depends on the range of reachable ε_D and ε_K with the considered electrical interface. Since ε_D and ε_K depend on the fundamental of v_p (a_1 and b_1), we call an electrically-tunable parameter ψ a parameter that is electrically-controllable and exhibits a direct impact on the fundamental of v_p . A k -tuning interface is an interface that allows the control of k tuning parameters ψ_j , with $j \in \{1, k\}$. The vast majority of electrical interfaces that have been introduced in the literature prior to 2014 exhibited either no tuning (0-tuning interfaces: SECE, OSECE), or a single tuning parameter (1-tuning interfaces: SSHI, SEH, PSSECE, NSECE) [9] [10]. 0-tuning interfaces do not allow any control of the PEH dynamics, meaning that the electrically-induced damping and stiffness are fixed. 1-tuning interfaces allow to adjust the electrically-induced damping and stiffness ($\varepsilon_D(\psi_1)$ and $\varepsilon_K(\psi_1)$), but they cannot be tuned independently (meaning that adjusting the system stiffness cannot be done without modifying the system damping). In order to allow an independent control of both the electrically-induced stiffness and damping, 2-tuning interfaces have been introduced in the literature (SCSECE, PSSSHI, FTSECE) [8] [11] [12].

The choice of the tuning parameters is not trivial. Some tuning parameters, such as the voltage inversion ratio β in the tunable SECE [13], allow to explore large ranges of electrically-induced damping ε_D , while some other tuning parameters, such as the harvesting event phase-shift ϕ_s in the FTSECE [11], allow to explore large ranges of electrically-induced stiffness ε_K . The extracted power with three interfaces (SECE, PSSECE and FTSECE) are presented in Fig.3 for a PEH exhibiting a $Q = 50$ and for three electromechanical coupling ($k_m^2 = 0.01$, $k_m^2 = 0.1$, $k_m^2 = 0.5$). Their harvesting bandwidth (frequency range where the harvested power is greater than $0.5P_{lim}$) is shown in Fig.3.

As shown in Fig.3.a, for weak coupling PEH, adding tunability to the electrical interface brings little-to-no improvement in terms of power-frequency bandwidth (the frequency

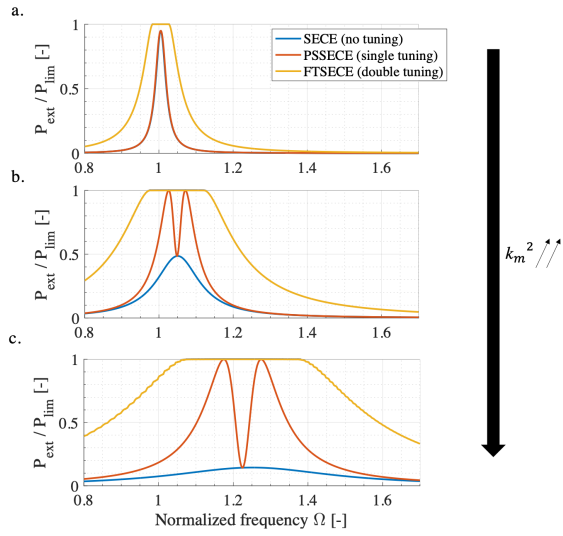


Fig. 3. Extracted power envelopes with three literature interfaces: SECE (0 tuning), PSSECE (1 tuning), FTSECE (2 tuning), for a PEH exhibiting $Q = 50$ and a. $k_m^2 = 0.01$, b. $k_m^2 = 0.1$, c. $k_m^2 = 0.5$.

range where the power is greater than $0.5P_{max}$). As the PEH electromechanical coupling gets stronger (Fig.3.b.), the power-frequency bandwidth becomes larger, and the improvement brought by two-tuning interfaces become significant. For strong coupling PEH (Fig.3.c.), the power-frequency bandwidth of the FTSECE (two-tuning interface) is around three times larger than the bandwidth of the PSSECE (single-tuning interface), which illustrates how such two-tuning interfaces exploit the PEH strong coupling to enlarge the PEH power-frequency bandwidth.

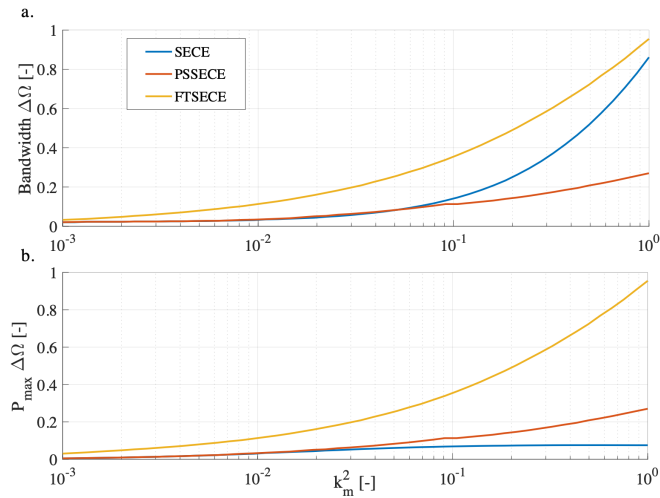


Fig. 4. a. Frequency bandwidth and b. P_{max} -bandwidth product as a function of k_m^2 with three literature interfaces: SECE (0 tuning), PSSECE (1 tuning), FTSECE (2 tuning), for a PEH exhibiting $Q = 50$.

Figure 4.a shows the evolution of the power-frequency bandwidth for these three electrical interfaces, as a function of the electromechanical coupling of the PEH. Thanks to

its two-tuning, the bandwidth of the FTSECE is the largest. The bandwidth of the SECE is particularly large because the maximum power of the SECE decreases with a stronger k_m^2 (leading to an increase of the frequency band where the power is larger than $0.5P_{max}$). Indeed, Fig. 4.b shows that the product of the maximum power times the bandwidth of the SECE decrease with a larger coupling.

Figure 4 illustrates the strong correlation between the PEH harvesting power and bandwidth and the PEH electromechanical coupling k_m^2 , and shows that adding two tuning parameters to the electrical interface becomes particularly relevant when the PEH is strongly coupled. A thorough quantitative comparison of tunable interfaces is an on-going work, and should help the scientist to choose the best harvesting interface for a dedicated application and for a particular vibration energy harvester.

IV. COMBINING HARVESTING AND TUNING CAPABILITIES

Contrarily to mechanical or magnetic frequency tuning solutions, electrical tuning does not require an additional (consequent) volume and power consumption. Such interface can be combined with the harvesting circuit in an ASIC of a few mm^2 consuming less than a few μW [14]. However, electrical tuning solutions require a thorough optimization of the whole electromechanical generator, going from mechanical design, piezoelectric material choice, to circuit design and self-convergent low-power algorithms. Figure 5 shows the various design requirements of an optimized electrically-tunable solution.

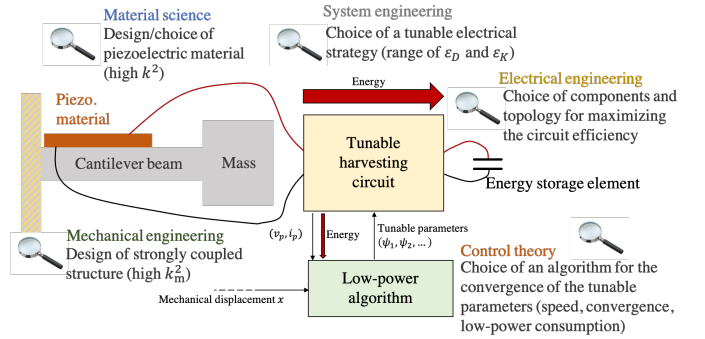


Fig. 5. Design of an electrically tunable vibration energy harvester: from mechanical design to control theory.

Many piezoelectric materials fulfill the requirements for electrical tuning solutions. For instance single crystals materials such as PZN-PT and PMN-PT materials might exhibit very large coupling coefficient ($k > 80\%$). Even ceramic-based materials such as PZT materials might exhibit very strong coupling, up to 30% or 40% [15]. In order to fully exploit these strong coupling materials, it is important to design an optimized mechanical structure (note that the coupling of the harvester is always smaller or equal than the coupling of the piezoelectric material, because of the elastic energy stored in the mechanical structure). Such strongly coupled realization has been proposed in [16], with k_m^2 larger than 0.3. Then, a

tunable electronic interface has to be carefully designed. As shown in Fig. 5, the tunable parameters should be adjusted and optimized in real-time thanks to a low-power algorithm. Such tunable interfaces and low-power algorithms have already been proposed in the literature, based on look-up tables [17] or perturb-and-observe algorithm [14].

V. OPPORTUNITIES FOR ELECTRICAL FREQUENCY TUNING: COMPARISON WITH OTHER TUNING METHODS

In order to compare the electrical tuning approach with other tuning in the literature (mechanical tuning, piezoelectric tuning and magnetic tuning), we propose to use the figure of merit $SFoM_{BW}$ introduced in [18] :

$$SFoM_{BW} = u_{PD} v_{BW} = E_{HW} Q \rho_{eff} \frac{\Delta\Omega}{\Omega_c} \quad (6)$$

With $u_{PD} = E_{HW} Q \rho_{eff}$ and $v_{BW} = \frac{\Delta\Omega}{\Omega_c}$ the harvester power density factor and bandwidth factor, respectively. As detailed in [18], E_{HW} corresponds to the averaged harvesting power in the power-frequency bandwidth, ρ_{eff} the power density (harvested power divided by the total volume of the solution harvester+circuit+tuning system, $\Delta\Omega$ corresponds to the normalized power-frequency bandwidth and Ω_c corresponds to the bandwidth central frequency.

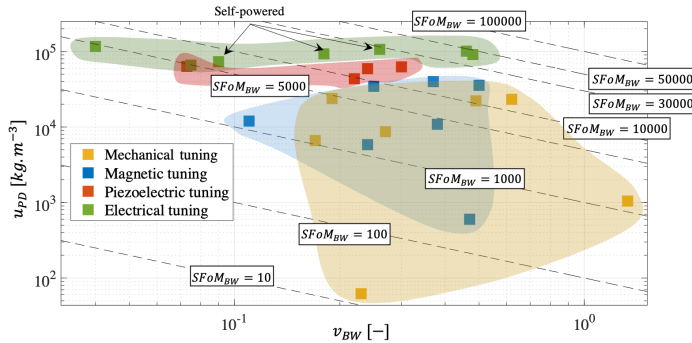


Fig. 6. Comparison of tuning approaches in the literature in the (v_{BW}, u_{PD}) plane, with v_{BW} being the bandwidth factor and u_{PD} the power density factor (6).

As shown in Fig.6, mechanical and magnetic tuning solutions allow to reach large frequency tuning ranges (v_{BW}), at the cost of power density (u_{PD}). Furthermore, most mechanical and magnetic solutions among the literature are not self-powered because the frequency tuning action consumes a relatively large quantity of energy. In the one hand, electrical tuning solutions allow to reach large power density (u_{PD}) and can easily be self-powered since the frequency tuning system (i.e. the harvesting circuit) occupies a very small volume and consumes a small percentage of the total harvested power. However, the frequency tuning ranges (v_{BW}) of electrical tuning approaches are inherently limited by the PEH electromechanical coupling. Indeed, the value of v_{BW} that can be obtained with electrical tuning solutions is always smaller than 0.5. With stronger coupling PEH (thanks to optimal

mechanical design and the use of single crystals materials for instance), such v_{BW} could reach larger values (0.6-1), leading to frequency tuning solutions combining large power density with large frequency tuning ranges.

VI. CONCLUSION

Electrically-based frequency tuning of piezoelectric energy harvesters requires an optimization at multiple levels: mechanical design, materials, electrical design, and system. However, it enables the elaboration of compact solutions that consume only a few micro watt to monitor in real-time the PEH resonant frequency. Such electrical tuning could lead to new self-powered harvesting solutions that could combine compactness and self-adaptability to their environment. Such solution would pave the way toward industrialization of robust PEH.

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