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Modeling Output Voltage of Piezoelectric Tiles Using AC Circuit Principles

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Abstract
Piezoelectric tiles generate time-varying voltages in response to mechanical excitation, so DC approximations overlook the frequency-dependent behavior that governs real power delivery. This paper utilizes tiles with AC circuits, including equivalents, a current source in parallel with a clamped capacitor, and, when necessary, a Mason/KLM-derived electromechanical RLC branch, to capture impedance, resonance, and load matching effects. Using sinusoidal and footstep-like inputs, we show why output voltage rolls off with frequency for capacitive sources, why impulse inputs produce brief high peaks, and how complex-conjugate load matching and synchronous extraction circuits materially increase delivered energy. We close with a compact design playbook and a roadmap on nonlinear/temperature-aware models, durability protocols, and adaptive power electronics. AC modeling is not just more accurate than DC; it is essential for sizing loads, tuning resonance, and specifying the interface electronics that turn footsteps into usable DC power.

Keywords: piezoelectric tiles; AC modeling; impedance matching; resonance; energy harvesting; synchronous extraction.

1. INTRODUCTION

One of the most basic examples of the direct piezoelectric effect is when, by applying a mechanical shock, we produce an electric charge in some materials, mainly crystals or ceramics. It seems, however, that this charge is inherently AC, as the direction of the action is continually reversed in any walking, vibration, or bending phenomenon. Thus, the electricity obtained from piezoelectric materials is an AC signal and not a DC one.

It was the first experimental confirmation of the phenomenon by Jacques and Pierre Curie in 1880, using natural crystals like quartz, which resulted in the birth of a completely new concept of electromechanical energy transducers. The application of natural crystals was limited due to the low coupling coefficients and their fragility, which induced the substitution of natural crystals with engineered ceramics, mainly lead zirconate titanate (PZT). PZT was found to have metal-to-electric transition ability - strong, adjustable, and suitable for a continuation of the industrialization process - as the basis for the present-day piezoelectric technology, Jaffe (1971) demonstrated.

There is a growing demand for gadgets that are self-powered and free of maintenance, in locations where battery replacement and recharging are not feasible, due to the accelerated development of the Internet of Things (IoT) technology. In this location, piezoelectric power harvesting is the solution that harnesses the silent mechanical power generated by human motion, permeating vibrations, and natural contributions. The research works of Anton and Sodano (2007) and Beeby et al. (2006) demonstrate that, as a result of the correct mode of operation of frequency, amplitude, and load of interaction, the obtained energy is capable of powering low-consumption wireless sensors, environmental monitors, and structural health systems.

The fundamental idea of this article is that piezoelectric energy devices, especially floor tiles and vibration-based units, cannot be looked upon as simple voltage sources. They would rather have to be considered as AC generators, characterized by a high value of internal capacitance and, possibly, possessing electromechanical resonance behavior. To identify the real nature of these devices within a circuit is to ensure that correct interface circuits and electrical loads will be developed, thereby energy transfer will be at its maximum and losses will be kept at their minimum. The very essence of their being is not only the proper choice of materials but also the corresponding mechanical, electrical, and electronic components that will be able to utilize the real-world dynamic inputs for the result to be positive, as stated by Priya and Inman (2009) and Halvorsen (2019).

2. Materials and operating context

In real-world usage, piezoelectric floor tiles are usually made of materials that have either been power densified or mechanically durable, depending on the place and the expected performance of the tiles. For the purpose of maximum electrical power output, high coupling ceramics like Lead Zirconate Titanate (PZT) are mainly used because of their intense piezoelectric response and high electromechanical coupling coefficients. To the contrary, polyvinylidene fluoride (PVDF) and its composite derivatives are used where flexibility, mechanical compliance, and extraordinary fatigue resistance are required, especially in situations where tiles are subjected to frequent and irregular deformations for an extended period of time.

The electrical power a piezoelectric harvester can generate depends mostly on three interdependent factors that influence each other:

The piezoelectric coefficient (d) which is the main factor that indicates how much electric charge will be produced for one unit of mechanical stress.

The relative dielectric constant (εr) is the factor that determines the clamped capacitance (Cp) of the material and, hence, the capability to store and release charge efficiently; and

The mechanical stiffness, as well as the quality factor (Q) that are responsible for both the strain amplitude under loading and the sharpness of the electromechanical resonance, which can be used to increase the output when the frequency is matched.

Knowing how these variables interact with each other is a must if one has to choose the right materials and structural designs for specific mechanical excitation profiles. In the case of pedestrian flooring and walking energy harvesting, the major mechanical inputs are most likely to be found in the low-frequency range of a few tens of hertz, which is the natural frequency of human walking. The impacts of a single footstep produce broadband frequency spectra; however, most of the mechanical energy that can be used is still concentrated in these low-frequency, high-energy bands, which require designs that can capture and convert energy efficiently in this regime (Liu, Zhao, & Wang, 2021).

3. Methods: AC equivalent and analysis

3.1 Source model. For small-signal electrical analysis, a piezoelectric tile can be effectively represented by an equivalent circuit that captures both its electrical and mechanical characteristics. In the simplest form, known as the Norton model, the harvester behaves as a current source connected in parallel with its clamped capacitance and a large internal resistance. The current source represents the charge produced through the piezoelectric effect when the material is subjected to mechanical stress. The capacitance reflects the dielectric storage property of the material, while the parallel resistance accounts for leakage

losses occurring through the bulk material or across the electrodes. This configuration provides an accurate approximation of the tile's performance under low-frequency or quasi-static conditions, such as those produced by human footsteps or ambient structural vibrations (Roundy, Wright, & Rabaey, 2003).
However, this basic model becomes limited when the system operates near its mechanical resonance, where energy transfer between the mechanical and electrical domains becomes frequency-dependent. To address this, a more comprehensive representation—derived from the Mason or KLM equivalent circuit models—is introduced. In this expanded form, the system includes an additional resonant branch consisting of elements that correspond to the mass, stiffness, and damping of the mechanical structure. This branch is coupled to the electrical side through an ideal transformer, which symbolizes the two-way interaction between mechanical motion and electrical charge generation.
This enhanced model captures resonance behavior, loss mechanisms, and the influence of material and structural parameters on performance. It is particularly valuable for designing circuits that maximize power extraction through proper impedance matching and load optimization. By combining both static and dynamic perspectives, this approach provides a realistic understanding of how piezoelectric tiles behave under real-world conditions, ranging from gentle vibrations to strong, impact-driven excitations (Wang, Zhou, & Park, 2018).
3.2 Load and maximum power. If the piezoelectric source is mainly capacitive, its operation is quite different from a normal voltage source. In such setups, a voltage across a pure resistive load usually drops very quickly with an increase in the frequency of the mechanical excitation. The reason for this is that the impedance of the capacitance to the alternating current (AC) becomes smaller at higher frequencies, which in turn reduces the voltage that can develop across the load. Essentially, this is most of the time manifested as a voltage decrease of around 20 decibels for every frequency decade; the power available to simple resistive loads can be lowered significantly at frequencies above the dominant excitation range.
The load has to be designed in such a way as to reflect the source impedance's complex nature while also including the piezoelectric material's capacitive characteristics and possible resistive losses if it is to overcome this restriction and achieve maximum real power transfer. A simple direct connection of a resistive load without compensation will normally result in the energy generated not being utilized to its fullest. On the other hand, engineers usually insert an inductive element in the line or use a power-electronic device that imitates the behavior of an inductance; they do this to provide impedance matching. In such a situation, the load counterbalances the reactive component of the source, and energy can flow from the piezoelectric element to the electrical system without interruption.
Such a scheme is crucial, for example, in wearable devices, floor tiles, and ambient vibration systems, where excitation frequencies are not only broadband but also change with time. By proper load and interface design which would take into account not only the capacitive nature of the source but also the inductive compensation or electronic control, engineers may not only increase the amount of energy gathered but also level the output voltage and ensure the smooth operation of devices downstream such as sensors, wireless modules, or energy storage components (Halvorsen, 2019; Zhou & Park, 2020).
3.3 Interfaces. Full-bridge diode rectifiers represent a typical way of piezoelectric energy harvesting for AC-to-DC conversion. Despite being simple, robust, and easy to implement, these devices experience substantial voltage drops and losses of energy, especially when the voltage is low, which is a common situation in small-scale energy harvesting. The means to exceed these restrictions are synchronous rectification and advanced interface techniques.
By very precisely timing the energy transfer with the voltage extrema of the piezoelectric element,

methods like Synchronized Electric Charge Extraction (SECE) and Synchronized Switch Harvesting on Inductor (SSHI) operate. As a result, one can either reverse the voltage or remove charge at those points; thus, these methods ensure the maximal energy extraction from one mechanical cycle and, consequently, can lead to the overall efficiency of energy harvesting increasing to a great extent. In particular, this enhancement may be quite sizeable under transient or irregular mechanical inputs, e.g., the sudden impact of footsteps or intermittent vibrations, in which conventional diode rectifiers are hardly able to capture energy effectively.

Through the application of these intelligent interface solutions, engineers are not only able to substantially increase the amount of energy that can be harvested, but also to stabilize the output of the downstream electronics, thus, making it feasible to run low-energy devices in their typical, self-powered, real-world mode of operation (Priya & Inman, 2009; Zhou & Park, 2020).

4. Results: what the model predicts

Piezoelectric harvesters' performance is strongly influenced by the source of mechanical excitation. If the device is subjected to sinusoidal driving or frequency sweep, the system shows typical capacitive behavior. For example, in the case of floor tiles, the capacitance value is about 0.1 microfarads, whereas a resistive load of several hundred kilo-ohms to a few mega-ohms is a practical one. Under such circumstances, the output voltage is the highest at low frequencies and gradually becomes smaller as the frequency increases. This is because the impedance of the capacitive source decreases with frequency. The establishment of a resonant circuit by means of an inductive element enables the system to be tuned to the resonance frequency of the electromechanical system. At resonance, both the voltage across the load and the real power delivered are increased to a large extent, thereby the energy capture becomes more efficient under periodic excitations (Wang et al., 2018).

On the other hand, in the case of footstep or impulse-type excitation, the mechanical input is like a half-sine or a sharp transient pulse. Suppose such a pulse is applied to the piezoelectric capacitance. In that case, it will result in a high peak voltage that is directly proportional to the generated charge divided by the capacitance, which then decreases according to the time constant determined from the load resistance and capacitance. Moreover, synchronous extraction techniques are much more effective than passive diode rectification in such cases, as they transfer energy at optimal points in the voltage cycle. Passive rectifiers, in general, are responsible for a considerable part of the generated charge being lost due to diode voltage drops and phase lag, while synchronous methods utilize a considerably larger portion of the transient energy, making the overall efficiency of the harvester better (Anton & Sodano, 2007; Priya & Inman, 2009).

Design takeaways.

Designing piezoelectric energy harvesting systems reveals several key principles. Firstly, the energy that is generated is mainly dominated by low-frequency parts, especially in the cases of footstep-driven tiles or ambient vibrations. Voltage drop at higher frequencies due to the source being of a capacitive nature should be expected by designers, and they should set their circuit and load designs accordingly.

Secondly, to have the maximum power transfer, the load should be such that it matches the complex impedance of the piezoelectric source. This can be done with passive elements, for example, inductors and resistors, which are carefully chosen to compensate for the source capacitance or a power-electronic interface that actively performs the impedance matching. In these cases, the reactive energy, which would have been temporarily stored in the piezoelectric element, is converted into the useful direct current that is delivered to the downstream devices.

The third point is that if the mechanical input is a transient or an impulse-like excitation, e.g., footsteps, then traditional steady-state rectification is not efficient because it cannot recognize these short-lived peaks of the generated charge. In such situations, synchronous extraction methods like SECE (Synchronized Electric Charge Extraction) or SSHI (Synchronized Switch Harvesting on Inductor) are utilized. These methods transfer energy when the voltage is at an extremum, thereby allowing a much larger portion of the transient energy to be captured and the overall system efficiency to be enhanced.

By considering these principles, engineers are able to come up with piezoelectric harvesting circuit designs that not only perform well but are also durable and capable of supplying a considerable amount of power in real-life environments, which are generally low-frequency and transient-driven.

5. Applications

Piezoelectric energy harvesting is a concept that can be practically implemented in numerous highly crowded areas, covering airports, metro stations, and shopping malls. In such places, floor tiles consisting of piezoelectric materials are capable of locally supplying small electronic devices like sensors, beacons, or microcontrollers with very low energy, thus, the use of batteries is minimized and the maintenance becomes simpler. In addition to that, people flow sensors are the same tiles as apart from energy harvesting, due to their electromechanical signals, they can provide up-to-the-minute data on footstep patterns and usage of the space (Beeby et al., 2006; Liu et al., 2021).

Flexible piezoelectric harvesters built into the shoes, clothing, or any other wearable articles can make the devices self-powered in the field of wearable tech; thus, an application like health monitoring, step counting, or motion tracking can be realized without the need for an external power source (Dagdeviren et al., 2014).

Besides that, reliable and efficient systems are hard; to a large extent, the energy issue can be realized by hybrid systems which combine piezoelectric harvesters with other clean energy sources like photovoltaics. First of all, such setups increase the total energy produced during the day, thus allowing more devices to be powered. Secondly, because the mechanical and solar inputs can be variable at different times of day or weather conditions, these configurations smooth out the intermittency, enabling a more stable operation of electronic gadgets and sensors in both indoor and outdoor environments (Choi, Jeong, & Kim, 2017; Jeon, Kim, & Park, 2020).

6. Challenges and future work

Durability has always been a major issue that piezoelectric harvesters struggle with. On one hand, high-coupling ceramics, which are very efficient, can hardly withstand without developing fatigue, depolarization, and micro-cracks after being subjected to millions of mechanical cycles. On the other hand, PVDF-based composites are much better in terms of mechanical resilience and flexibility, but their voltage output is significantly lower. Even though a lot of efforts have been put into this issue for decades, the field still lacks standard protocols for fatigue testing and lifetime prediction, thus making long-term reliability assessment a difficult task (Beeby et al., 2006; Liu et al., 2021).

The next problem that has a major impact on the performance of piezoelectric technologies is voltage irregularity. The activity of humans and other mechanical sources, for example, is basically bursty and unpredictable, which leads to the generation of spiky voltage signals that not only change amplitude and frequency but also differ in length. Hence, energy-harvesting controllers should be designed in such a way that they can easily process transient surges and low-activity periods on the one hand, and at the same time, they should be able to minimize quiescent losses so that harvested energy is not dissipated (Halvorsen, 2019).

Moreover, the energy storage and conversion methods have a great impact on the overall system performance. Taking into account the advantages and disadvantages of supercapacitors and batteries, it becomes clear that the former can cover a short period of time with high power demand, whereas the latter are more suitable for providing energy over longer intervals, but they are subject to cycle aging and reduced lifetime under frequent charge-discharge cycles. To achieve the best system design, the use of hybrid storage architectures along with intelligent charge scheduling is usually required, as this allows not only for the immediate pulse capture but also for long-term energy delivery (Priya & Inman, 2009).

Last but not least, accurate modeling and predictive design are the prerequisites for the robust performance of the system. The models have to take into account nonlinear material behavior, temperature dependence, and aging effects so that they become compact AC representations of real operating conditions. The involvement of data-driven parameter identification and adaptive control strategies in the loop makes the system very flexible in terms of real-time impedance matching, thus achieving maximum energy extraction under varying environmental and operational conditions (Li, Wang, & Zhou, 2023; Wang et al., 2018).

7. Conclusion

It is quite insightful and predictive to consider piezoelectric tiles as alternating current sources with significant capacitance and the possibility of electromechanical resonance when one is analyzing and designing practically. This angle of view justifies numerous fundamental experimental results in energy harvesting, such as: the reason why simple resistive loads hardly extract energy; the reason why transient or impulse-like excitations, e.g., footsteps, are the major source of the harvested power in flooring; and the reason why the methods such as synchronous extraction and impedance matching are extremely important to the energy conversion efficiency maximization. Designers, by source control and frequency awareness, are therefore liberated to select the load, interface circuitry, and control strategy that will optimally account for the piezoelectric element free of the otherwise reactive energy.

The system then, can then reach a compromise between output and stability over time when the material choice is additionally dependent on the mechanical duty cycle anticipated, e.g., high-coupling ceramics for a short, high-energy event or flexible PVDF composites for repeated low-amplitude deformations. In addition, a short-pulse energy storage and management strategy will not allow the harvested energy to be dissipated by the rectification stage or storage, thus enabling the embedded electronics to be powered reliably.

On the strength of these fundamental concepts, piezoelectric tiles represent a class of micro-generators that are not only real but could also be scaled up. They could, thus, form the basis of smart infrastructures, for instance, airports, metro stations, shopping malls, and wearable technology, where sensors, beacons, microcontrollers, and other low-power devices can be supported. Besides the energy function, the same electromechanical signals could be used to collect occupancy data and human activity sensing, thus presenting a dual-function system that integrates energy harvesting and smart sensing. The piezoelectric tiles become a practical and efficient means of powering the next-generation self-sustaining devices in intelligent built environments through a combination of accurate source modeling, material optimization, advanced interface strategies, and intelligent energy management.

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