A PZT Modeling for Energy Harvesting Circuits

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Abstract— **This work presents the modeling of PZT (Lead Zirconate Titanate) intended for using in low frequency mechanical movement applications such as prosthetic legs. This includes the simplified PZT electromechanical modeling based on PSCAD/PSPICE, simulation and experiment. The model can emulate the behavior of the PZT in variety conditions. The simulation and experimental results well agree with each other. The benefits of the model are the easiness of analyzing and studying the behavior of PZT when the conditions or applications of use are changed such as in the case of using full-bridge diode rectifier, buck/boost converter, bridgeless rectifier, and series or parallel PZT modules.**

Keywords-Piezoelectric; PZT; Smart Material; Boost converter; Buck converter; Bridgeless rectifier

I. INTRODUCTION

Piezoelectric devices are capable of converting mechanical energy to electrical energy and vice visa. Recently, many researchers are paying attention to harvest ambient vibration energy by using piezoelectric devices for micro power applications. Since the output voltage of the piezoelectric devices is ac voltage, therefore, a power converter is necessary for converting the ac voltage to a dc voltage for supplying the electrical energy to loads those are usually electronic circuits. Due to the output power of the piezoelectric devices is relatively low, the applications for applying the piezoelectric devices as power source are generally low power electronic equipment such as wireless sensor [1].

The major limitations of harvesting the energy from piezoelectric devices are not only providing low power, but also the difficulty to investigate their behavior when applying to some applications such as prosthetic legs. Moreover, the behavior of the piezoelectric devices would change when the operating conditions such as in the cases of connecting directly to a resistive load and using full-bridge diode rectifier, the piezoelectric devices will perform differently. This will cause the utilization of the piezoelectric devices less efficiency that means high cost per Watt.

This work presents a modeling method based on PSCAD/PSPICE, which emulates the behavior of the PZT by investigating the actual open-circuit output voltage at no load operation together with measuring the output parameters (resistance and capacitance) of the PZT by RLC meter. Then, complete the modeling by PSCAD/PSPICE. The model is able to operate in variety conditions. It is, therefore, would be useful for energy management circuit analysis and design.

This paper is organized as follows: Section II describes the basic structure and open-circuit output voltage waveforms of the PZT. Its simplified mechanical, electrical, and electromechanical are also described. Section III presents the simulation and experimental results of the PZT. Then, Section IV discusses the energy harvesting circuits for efficiently harvesting energy from the PZT. Finally, Section V concludes the paper.

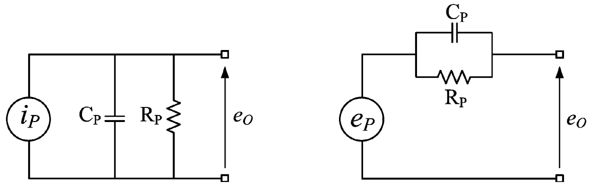
II. PZT (LEAD ZIRCONATE TITANATE) AND ITS MODEL

The actual picture of the PZT and its basic structure are shown in Fig. 1. It comprises two piezo-ceramic plates and two arms formed a single metal substrate [2]. The piezo-ceramic is a high performance commercial grade Lead Zirconate Titanate formed. In the case of ignoring energy loss, when applying mechanical force on the upper arm, some energy is directly applied into the piezo-ceramic and converted to electrical energy, while the rest is stored in the metal substrate in the form of potential energy. When stop applying the mechanical force, the upper arm is free and the stored potential energy converts to kinetic energy with a resonant frequency. This results in the metal substrate and piezo-ceramic being continuously shake until the resonant period ends. The electrical energy is continuously produced after stop applying the mechanical force in the resonant period.

Fig. 2 shows the general output characteristic of the PZT. It can be either current source or voltage model, however, in this

(a) (b)

Figure 1. (a) The PZT module (b) Basic structure of the PZT.



(a) (b)

Figure 2. General model of the PZT (a) current source model (b) voltage source model.

paper, the voltage source model is preferable. Fig. 3 shows the experiment set up for investigating the output voltage waveforms: (a) when hitting the upper arm of the PZT and (b) when pulling the upper arm of the PZT. Whereas, Fig. 4 shows the output voltage waveforms from the experiment in Fig. 3. By investigating the output voltage waveforms together with the general output characteristic of the PZT from Fig. 2, the simplified mechanical model [3] and mechanical-to-electrical models of the PZT can be written as shown in Fig. 5. Finally, the electromechanical model that includes mechanical-to-electrical and electrical models can be obtained by Fig. 6.

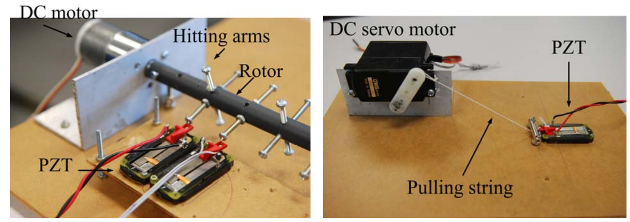
In Fig. 6, the output parameters: C_P and R_P can be measured by a RLC meter. The mechanical-to-electrical parameters: C_M, L_M, and R_{M1} can be defined by investigating the open-circuit output voltage waveform at the resonant period and assumingly is a second order resonant voltage waveform. Therefore, the damping factor of the resonant voltage waveform is

$$\xi = \frac{1}{2R_M}\sqrt{\frac{L_M}{C_M}}\,. \tag{1}$$

In the case of hitting, the damping factor can be as low as 0.06. On the other hand, in the case of pulling, the damping factor is as high as 1.5. The resonant frequency is defined by

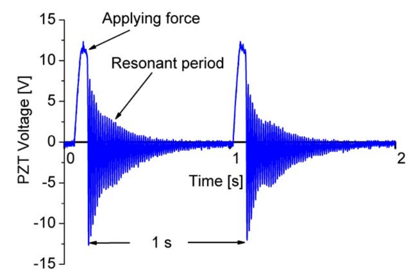
$$f_0 = \frac{1}{2\pi\sqrt{L_M C_M}}\,. \tag{2}$$

The resonant frequency from the measurement is approximately 80 Hz. R_{M2} is the representative of mechanical energy loss and set at 5 Ohm. C and R are for coupling the energy form input side to the output side of the PZT, they can be defined by the ramping down time of the output voltage during the period of being hit or pulled. SW1 and SW2 are complementary. SW1 closes the circuit when the PZT's arm

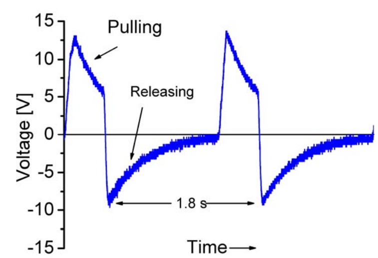


(a) With hitting force (b) With pulling force

Figure 3. Experimental setup for open-circuit voltage measurement.



(a) Hitting



(b) Pulling

Figure 4. Experimental open-circuit output voltage of the PZT.

is hit or pulled and opens the circuit when stop hitting or releasing the PZT's arm. e_F is the representative of mechanical force. Its value can be approximately set a bit higher than the peak of the open-circuit output voltage. There are two parameters those must be changed when the type of mechanical force changes as follows: R_{M1} = 5 for hitting force and = 0.2 for pulling force, e_M is a rectangular voltage waveform that has the pulse width of 0.1s and the period of 1s for hitting force and the pulse width of 0.5s and the period of 1.8s for pulling force. The resonant frequency is set by L_M and C_M from (2).

III. Simulation and Experimental Results

A. *The PZT Basic Operating Waveforms*

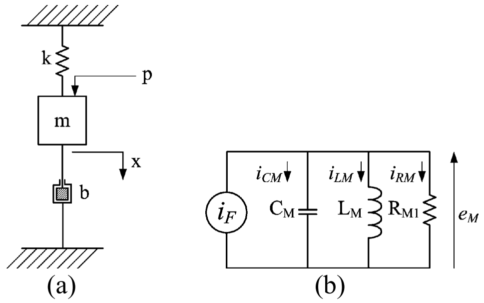


Figure 5. (a) Simplified machanical model (b) Machanical-to-electrical model.

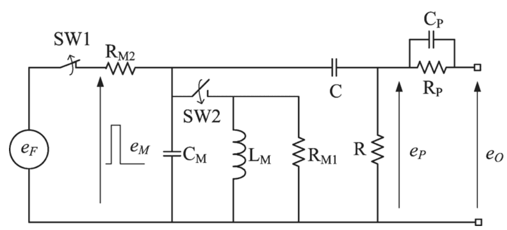
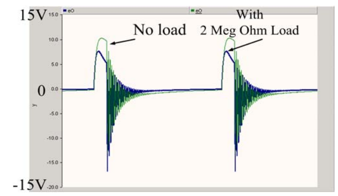
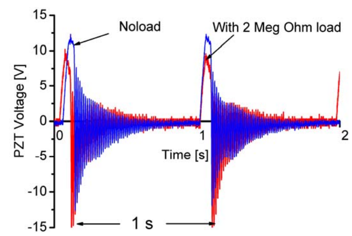


Figure 6. The proposed electromechanical model of the PZT.

In this paper, the simulation can be obtained by PSCAD or PSPICE simulation software. Fig. 7 shows the simulation and experimental operating voltage waveforms of the PZT with hitting force at the frequency of hitting at 1 Hz (nearly the frequency of walking) when directly connecting a 2-MΩ resistive load and at no load. Whereas, Fig. 8 shows the results of applying pulling force at the frequency of 0.6 Hz. It is clear that the simulation results agree well with the experimental results from Fig. 4. It should be noted that the open-circuit voltage waveform of the PZT with pulling force seems to have higher rms voltage. However, with a resistive load connection, the voltage is much reduced than the case of hitting force. Consequence, the PZT output power with the pulling force is much lower than the hitting force. Therefore, in the next sections only the case of hitting force will be mentioned.

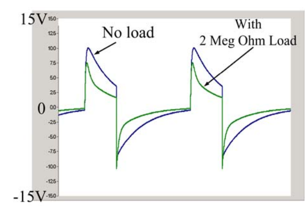


(a) Simulation

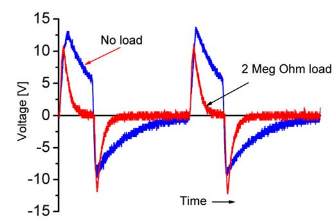


(b) Experimental

Figure 7. PZT voltage waveforms with hitting force.



(a) Simulation



(b) Experimental

Figure 8. PZT voltage waveforms with pulling force.

B. Comparision of Simulation and Experimental Results

Fig. 9 shows the power and the rms output voltage curves of the PZT when the resistive load is directly connected to it. It can be seen that the behavior of the PZT from the simulation and experimental results agree well with each other. The maximum power point is approximately 27 µW at 50 kΩ and 1.2 Vrms. Fig. 10 is the simplest energy harvesting circuit, full-bridge diode rectifier, that has fours diodes and one capacitor. Fig. 11 shows the power and the dc output voltage e_L by using the full-bridge diode rectifier as an energy harvesting circuit. From the simulation and experimental results, it can be seen that the maximum power point is much lower than the maximum power point from Fig. 9. The reason of losing power is the maximum power point of the PZT occurs at low voltage (1.2 Vrms), which is close to the forward voltage drop of the diode rectifier. Moreover, during the resonant period, the resonant voltage which has instantaneous voltage level lower than the average output voltage of the diode rectifier cannot deliver the energy to the output. Therefore, utilizing full-bridge diode rectifier is not an effective way for harvesting the energy from the PZT.

IV. Power Convetrters Consideration for Energy Harvesting Circuits

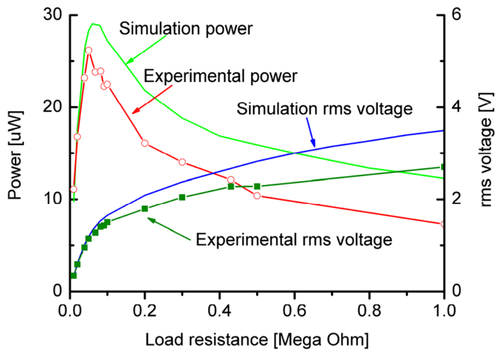


Figure 9. rms voltage and power curves of the PZT with hittng force (1 Hz) when directly connected to resistive load.

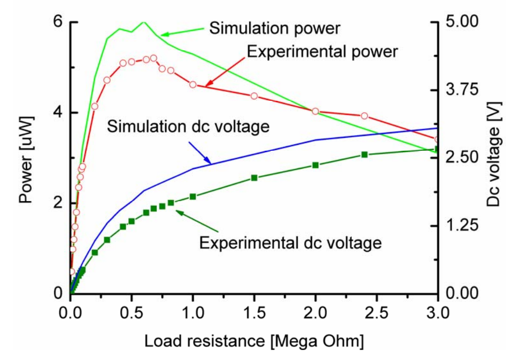


Figure 11. DC output voltage and output power curves of the PZT with hittng force (1 Hz) when connected with the full-bridge diode rectifier.

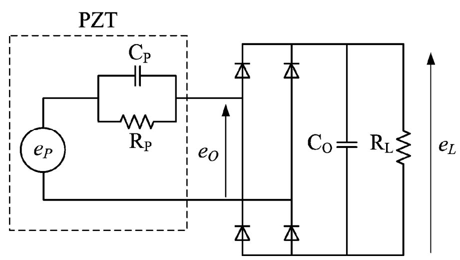


Figure 10. Full-bridge diode rectifier for a simple energy harverting.

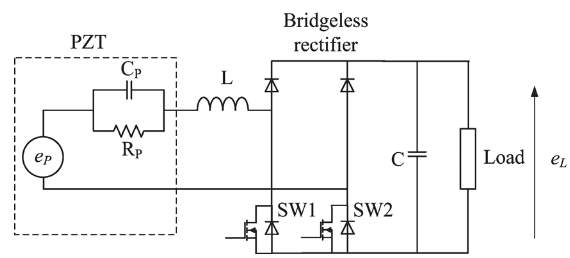


Figure 12. Basic bridgeless rectifier as an energy harvesting circuit.

The basic power converters, buck and boost converters, are widely used in widely applications [4] for converting a dc voltage level to another level of the dc voltage (and regulated). Their output is dc voltage that is suitable for general electronics control circuits. Basically, they require their input as a dc voltage. Generally, in the case of input power source is an ac voltage, connecting the full-bridge diode rectifier for converting an ac voltage to a dc voltage is an acceptable solution for using with the buck and boost converters. However, in the case of the PZT, using the full-bride diode rectifier is not an effective way for harvesting the energy, as mentioned in the previous section. Resulting in the buck and boost converters are not suitable for using as the energy harvesting circuits for the PZT.

The bridgeless rectifier [5] can rectify an ac voltage from its input to a dc voltage at its output. It also can regulate the output voltage. The basic bridgeless rectifier is shown in Fig. 12. It consists of an inductor, two switching devices, two diodes, and one output capacitor. When a switching device turns on, the energy from the PZT can be directly stored in the inductor, then, delivered to the output via a diode when the switching device turns off. It can be noticed that during the turn on period of a switching device the voltage drop in the circuit is low, especially in the case of using MOSFET as the switching devices. Even the energy is delivered to the output via a diode during the turn off period; the forward voltage drop of the diode does not affect the maximum power point of the PZT because the diode is at the output side of the circuit. This makes the bridgeless rectifier is more suitable for energy harvesting circuits of the PZT because it would exact higher power from the PZT.

V. CONCLUSION

This paper describes the modeling of the PZT by investigating the output voltage of the PZT and using simplified mechanical, mechanical-to-electrical, and electromechanical models. The simulation and experimental results are obtained by low frequency mechanical force which near to the human walking frequency. From the results, the model can emulate the behavior of the PZT in various conditions. Moreover, from the results, this paper also discusses the maximum power point of the PZT for designing a suitable energy management circuit to achieve the maximum power from the PZT.

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