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Piezoelectric Power Generation Under Quasistatic And Dynamic Conditions

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Abstract

In the case of the PPG(Piezoelectric Pulse Generator, the most commonly used method to generate electrical power), the piezoelectric crystalline material consists of a zirconia titanate material providing a method to convert mechanical energy into electrical energy. A pulse conditioning stage is also included in the generator. Although the energy density of the generator is not extremely high in comparison to batteries, its durability, compactness, and long shelf-life are advantageous in certain applications. The piezoelectric generator consists of commercially available piezoelectric elements arranged in a stack and electrically connected in parallel. The piezoelectric generator is, at most, 50% efficient due to its internal capacitance. In this study paper we shall review two methods of exciting a piezoelectric generator namely static and dynamic stress in both theoretical and practical applications.

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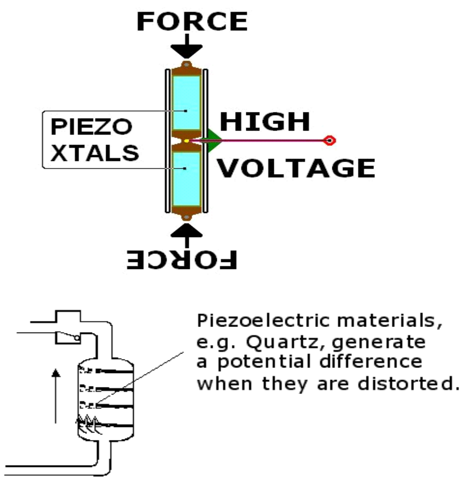
I. INTRODUCTION

The generation of an electric charge in certain non-conducting materials, such as quartz crystals and ceramics, when they are subjected to mechanical stress (such as pressure or vibration) is known as piezoelectric effect. Piezoelectric ceramics, when mechanically activated with pressure or vibration, have the capacity to generate electric voltages sufficient to spark across an electrode gap. This is the basic principle behind piezoelectric generators. The piezoelectric effect is found in a number of natural and man-made materials. Commonly used naturally-occurring crystals include quartz, topaz, tourmaline, Rochelle salts and cane sugar. Man-made crystals include the quartz-like langasite and gallium orthophosphate. Common piezoelectric man-made ceramics include barium titanate, lead titanate and lead zirconate titanate, the most common piezoelectric ceramic in use. Other naturally-occurring piezoelectric materials include dry bone, tendons, silk, some woods, enamel, dentin and collagen.



Piezoelectric generation of charge

Several recent studies have investigated piezoelectric power generation. One study used lead zirconate titanate(PZT) wafers and flexible, multilayer polyvinylidene fluoride (PVDF) films inside shoes to convert mechanical walking energy into usable electrical energy. This system has been proposed for mobile computing and was ultimately able to provide continuously 1.3 mW at 3 V. When walking at a rate of 0.8 Hz. Other projects have used piezoelectric films to extract electrical energy from mechanical vibration in machines to power MEMS devices. This work extracted a very small amount of power (<5uW) from the vibration and no attempt was made to condition or store the energy. Similar work has extracted slightly more energy (70uW) from machine and building vibrations. Piezoelectric materials have also been studied to generate electricity from pressure variations in micro hydraulic systems. The power would presumably be used for MEMS but this work is still in the conceptual phase. Other work has used piezoelectric materials to convert kinetic energy into a spark to detonate an explosive projectile on Impact. The above studies have all had some success in extracting electrical power from piezoelectric elements. However, many issues such as efficiency, conditioning and storage have not been fully addressed.

There are two types of piezoelectric generators namely, single layered and multilayered piezoelectric generators.Electrical energy in a rod-shaped single-layer piezo-generator is released very quickly, is very high voltage, and very low current. Piezoelectric ignition systems are small and simple, long lasting and require little maintenance. Generally, these generators are used.Multilayer piezo generators consist of a stack of very thin (sub-millimetre-thick) piezoelectric ceramics alternated with electrodes. The electrical energy produced by a multilayer piezo-generator is of a much lower voltage than is generated by a single-layer piezo-generator. On the other hand, the current produced by a multilayer generator is significantly higher than the current generated by a single-layer piezoelectric generator. Because they do not create electromagnetic interference, multilayer piezo-generators are excellent solid-state batteries for electronic circuits. Due to advancements in micro-electronic systems many consumer devices have decreased in size. Smaller electronic systems require less power to operate. As a result, solid-state multilayer piezoelectric generators have become a feasible power source for some applications. Current applications for multilayer piezo generators are energy sources for munitions and wireless sensors, such as sensors that monitor tire pressure in automobiles.

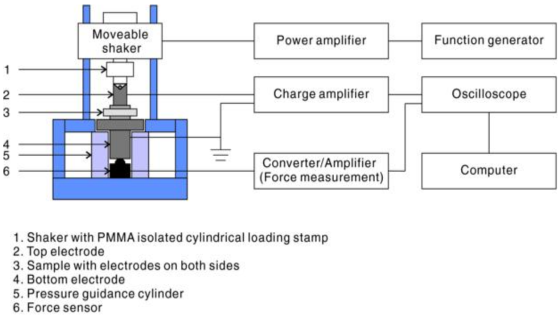
There is a large array of applications for piezoelectric materials, particularly quartz, which can generate thousands of volts of electricity. One of the most common applications of piezoelectricity is in the electric cigarette lighter. Other common applications include sensors on electric guitars like pick-ups and contact microphones, ultrasound machines, sonar wave detection and generation devices, engine management systems in cars, loudspeakers, fuel injectors for diesel engines and quartz clocks.In this case of the PPG, the main concept is to convert mechanical energy into electrical energy gaining higher electrical generation. The PPG is constructed from commercially available materials and the conversion of mechanical energy into electrical energy is accomplished by storing energy in the internal capacitance of the piezoelectric material. The energy storage discussed and developed in this exploration is an order of magnitude greater than in the previous studies discussed. In this analysis the Piezoelectric Pulse Generator, PPG is piezoelectrically charged to a maximum of 1400 volts. The PPG can be represented as a simple RC circuit with the internal capacitance charged to 0.15 µF and the external capacitance to 0.1 µF, thus storing nearly one joule of total output energy for a minimum of 5 seconds. The PPG also produces close to 0.3 J of energy. The large internal capacitance in the high energy PPG is created by stacking 30 single-element piezoelectric devices and electrically charging them in parallel; this is also referred to as the pz stack. The piezoelectric materials used in this research are leaded zirconia titanates PZT 5H. The single piezoelectric elements act as a mechanical converter and storage of electrical energy when it is impacted by a compressive force. The piezoelectric material eliminates the use of battery power or power grids which are heavy and stationary.

II. DESCRIPTION

In that investigation, the PZ material was subjected to a slowly applied (i.e., quasi-static) stress and a fast impact (i.e., dynamic) stress, both of equal magnitude. The results showed that the quasi-static stress produced a bidirectional voltage pulse, the dynamic stress produced a unidirectional voltage pulse, and the output voltage magnitudes were practically identical, regardless of stress. This investigation applies quasi-static and dynamic stresses to a PZ material and uses the electromechanical model to explain its behaviour under the different stress conditions. A computer model of the PZ material also is developed and used to predict its behaviour. The PZ materials used in this investigation are the leaded zirconia titanates PZT 5H and PZT 5A (Morgan-Matroc, Inc., New Bedford, MA02745). The results show that, although the quasi-static output voltage produces a bidirectional output and the dynamic output voltage produces a unidirectional voltage. This investigation finding that the dynamic stress produces an output voltage that is always higher in magnitude than the quasi- static stress. This proves that for generation purposes, the application of dynamic force will always be preferred than the standard static stress.

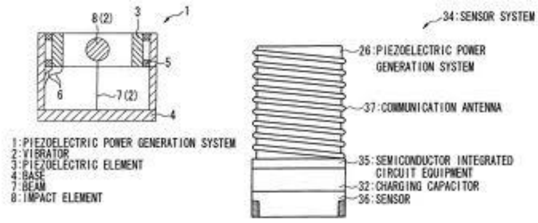
III. PIEZOELECTRIC POWER GENERATOR MODEL

The piezoelectric power generator model consists of two parts: the mechanical model and the electrical model. The mechanical configuration of the piezoelectric power generator consists of one or more PZ elements between two masses, in this investigation made from steel. The force is applied to the generator in parallel with the poled direction of the PZ material.



3.1 Electrical Model

The electrical model of the piezoelectric power genera- tor is represented as an RC circuit consisting of a stack capacitance, Cstack , loss resistance, Rloss , and leakage resistance, Rleakage. Experimentally, the values of Rloss , Rleakage , and k33 are measured using a HP 4277A LCZ meter (Agilent Technologies, Palo Alto, CA).



3.2.Characteristics of Piezoelectric Power Generator

A. Quasi-Static Force Case

The quasi-static force of this investigation has a rise time, fall time, and pulse length on the order of 100 ms each. The quasi-static stress produces an output voltage having two opposite-polarity peaks: one peak when the force is applied and one peak when the force is removed. This behaviour is expected and is attributed to the charge force is investigated. Typically, the open circuit voltage generated by the compression force can be modelled as a ramp pulse where tr is the rise-time, th is the pulse length, and tf is the fall-time of the out- put pulse. In the quasi-static case, the applied force pulse length is in the order of 100 ms, and the dynamic case has duration on the order of 10 ms. Mathematically, the open circuit voltage of is expressed as:

$$V_a(t)= atu(t)-a(t-t_1)u(t-t_1)-b(t-t_2)u(t-t_2)+ b(t-t_3)u(t-t_3)$$

where a and b are the slope of the rise-time and can be rep- resented as a = Va,max /tr and b = Va,max /tf . The output voltage, Vstack , of the piezoelectric power generator can be solved analytically using Laplace transforms. Initially, the PZ capacitance is in the uncharged state and, with an application of force, Va will increase and immediately appear across the load. As time progresses and with the force held constant, Va charges the PZ capacitance. Because the PZ capacitance charges in opposite polarity to Va , the load voltage decreases. Removal of the applied force after the PZ capacitance is completely charged causes Va to decrease to zero. However, the output voltage will reflect the voltage of the charged PZ capacitance and is negative.

3.3.B. Dynamic Force Case

For dynamic force application, the time duration of the applied force is on the order of 10 ms. The PZ capacitance does not have sufficient time to charge in this case, and the majority of the output voltage is due to Va . In addition, because the PZ capacitance cannot charge, removal of the force does not produce a negative peak in the output voltage. the decay of output voltage is very small, a direct result of the short stress- pulse length. Additionally, the peak of the output voltage:

$$V_a(s)=a(1-e^{-st_1})s^2-b(e^{-st_2}+e^{-st_3})s^2$$

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IV. EXPERIMENTAL AND SIMULATION RESULTS

In that investigation, the piezoelectric power generator is tested using both quasi-static and dynamic load stress conditions to confirm the previous theoretical results.

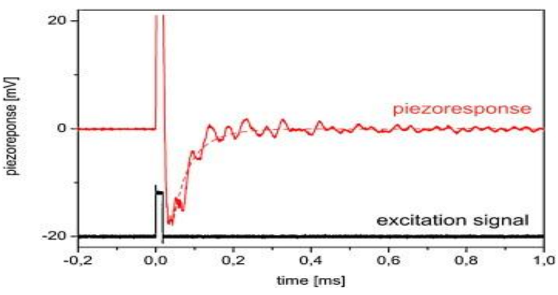
A. Quasi-Static Force Case

In the quasi-static case, the piezoelectric power generator is placed in an arbour press. the experimental setup. A 3.6 kg steel mass is momentarily hung from the end of the press handle. With the handle's length of 55.5 cm and the gear radius of 4 cm, the compression force can be calculated using the moment of force equation as $F=(3.6 \times 9.8 \times 55.5)/4$, approximately 490 N.

The experiment is performed on the leaded zirconia titanate PZT 5H and PZT 5A materials. To create a quasi-static force, the steel mass is mo- mentarily hung from the press handle. After a short time period, the steel mass is removed from the press handle. The results show that the output voltage of the piezo-electric generator, Vstack , has a bidirectional peak voltage as theoretically predicted. The results also show that the magnitude of the negative and positive peak voltage are almost identical. The small amount of error between the experimental and simulated results is small oscillations in the measured output voltage between the time of force application and force removal. Those oscillations are presumably caused by mechanical bounce of the steel mass and support structure. The results show good agreement between the experimental and simulated results. In the first experiment using PZT 5H material, the positive and negative peaks measured at 4.2 V and −4.5 V, respectively. The output power density is calculated to be 10.71 μW/cm3 and 12.30 μW/cm3 , respectively. In the second experiment using PZT 5A material, the peak volt- ages are 3.50 V and −2.44 V with an output power density of 33.88 μW/cm3 and 16.46 μW/cm3 , respectively.

B. Dynamic Force Case

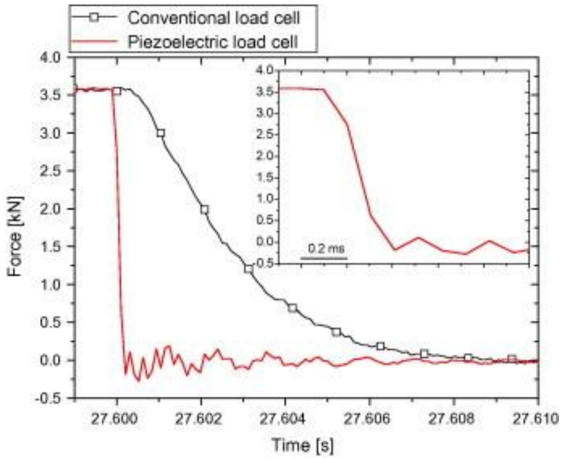
To produce a dynamic force, the piezoelectric power generator is placed in a PVC tube. A 0.25 kg mass is dropped from 10 cm. A computer model that simulates the dropping mass has been constructed. The output volt- age is experimentally measured and used in the model to calculate the impact force. The data show that brief peak impact forces of approximately 500 N are produced when the mass is dropped. The output voltage of the generator is measured with oscilloscope leads connected to the steel masses that sandwich the PZ material. Fig. 10 illustrates the experimental setup of the dynamic force test. The PZT 5A and PZT 5H are also used in this experimental series. The simulated and experimental results of the dynamic stress condition show that the output voltage has only one positive peak that slowly decays. . In the fist experiment using PZT 5H, the peak output voltage is 58.40 V with a power density of 2.07 mW/cm3 . The experimental results are in good agreement with the simulated results. In the second experiment using PZT 5A, the peak output voltage is 70.00 V with a power density of 13.55 mW/cm3 . Comparing the quasi-static and dynamic stress tests shows a significant difference between the relative magnitudes of the output voltage. The dynamic stress test produces approximately 10 times higher output voltage than the quasi-static test. The impact time of the dynamic stress test (i.e., < 10 ms) is faster than the RC time constant (i.e., approximately 15 ms) of the piezoelectric material. The PZ capacitance does not have time to charge, resulting in a higher output voltage.



V. CONCLUSION

In that investigation, the output voltage of a piezoelectric power generator is theoretically and experimentally characterized under quasi-static and dynamic stress conditions. The electro-mechanical model of the piezoelectric power generator is presented and used to predict and understand the behaviour of the generator under these two stress conditions. Under quasi-static stress, the piezoelectric power generator produces a bidirectional (i.e., positive and negative peak) output voltage. The bidirectional output voltage is produced because the PZ capacitance charges and reduces the magnitude of the PZ output volt- age.

The reduction in output voltage is especially evident when the rise time of the force is larger than or equal to the RC time constant. In contrast to the quasi-static stress condition, the dynamic stress condition produces a unidirectional output voltage and, in this investigation, is 10 times larger than the quasi-static case. The dynamic case produces a higher output voltage because the PZ capacitance does not have time to charge and subsequently reduce the PZ voltage. The results of this investigation are in disagreement with results reported by other investigators. The results also show that to produce high piezoelectric generator voltages, the RC time constant of the generator circuit must be much greater than the duration of the applied force.



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