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Energy harvester device for charging capacitors and low capacity NiMH batteries

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ABSTRACT

Piezoelectric energy harvester devices have attracted much attention recently mainly because they present a realistic opportunity to power wireless sensors and low power sensor devices. The harvested energy has to be stored either in a capacitor or a low capacity rechargeable battery before it is availed to the sensor or the device to be powered. Presented in this work is the fabrication of PZT energy harvesting device that was used to experimentally investigate the storage of harvested energy in electrolytic capacitors and in low capacity rechargeable batteries. Other than the work of a few researchers, there is little published work on the demonstrated potential of charging batteries using piezoelectric devices. This research gives experimental results that show the feasibility of charging capacitors using PZT energy harvesters. Specifically, it gives some insight into the variations of harvested voltage, energy, and power as functions of charging time.

KEYWORDS

Energy harvesting;
Piezoelectric;
Energy storage;
Charging;
Wireless sensor.

INTRODUCTION

There has been a recent surge in the research of energy harvesting using piezoelectric devices mainly for powering wireless sensor devices[1-3]. When the energy is harvested by the piezoelectric device the challenge is the storage of the harvested energy. Typically the electrical energy is stored in a capacitor or a low capacity rechargeable battery. Much of the present research in energy harvesting has concentrated on modeling of energy harvester performance[4-6], and conditioning circuits to maximize power output of piezoelectric harvester devices. Unfortunately, there has been little or no experimental investigation into the basic storage of the energy harvested in electrolytic capacitors and in low capacity rechargeable batteries. Other than the work by Sodano[1,2] there is not much published work on the demonstrated potential of charging batteries using piezoelectric devices.

Storage in capacitors

Capacitors offer the most direct and literal way of storing electrical energy. The amount of energy stored depends on the value of the voltage across the capacitor, the area of the plates, distance between the plates and the permittivity of the dielectric material used. For a fixed capacitance, increasing the voltage across the capacitor increases the energy stored by the capacitor.

For most practical purposes, ordinary electrolytic capacitors dominate energy storage mainly because of their simplicity and easy availability.

Storage in NiMH batteries

The most commonly available rechargeable batteries are Nickel Metal Hydride (NiMH) and varieties. For the most application, NiMH batteries have virtually replaced Nickel Cadmium (NiCd) batteries in rechargeable applications. This is attributed to the fact that NiMH batteries are not potentially harmful to the environment like their NiCd cousins. In addition, NiMH do not exhibit signs of the so-called "memory effect" associated with the NiCd variety. The most common charging method for NiMH batteries is a constant-current charge, but with the current limited, to avoid too great an increase of battery temperature or to avoid exceeding the rate of the oxygen-recombination reaction[7]. The NiMH battery is being replaced at a rapid rate by Lithium Ion batteries, which have an even greater specific energy and energy density[8]. Lithium ion batteries have a much lower self-discharge rate than that of NiCd and NiMH, and do not exhibit any memory effects[8,9]. In comparison to nickel metal hydride batteries, lithium ion charging requires additional circuitry to ensure that the cell is neither overcharged nor over discharged. It is for this reason that NiMH was preferred to Li-ion batteries in this research.

MATERIALS AND METHODS

Materials

Piezoelectric ceramic sheets model number PSI-5A4E manufactured by Piezo Systems Inc. (USA) was used to fabricate the energy harvester device. The piezoelectric layers were attached to an aluminum substrate beam using two-part epoxy glue (Figure 1).The dimensions and properties of the materials are shown in TABLE 1. It should be noted that the aluminum was made longer to ensure enough material was available for secure clamping. The actual clamped length of the aluminium and the PZT are 150 mm and 72.4 mm respectively. The width of the PZT and aluminium was 25 mm. All the NiMH batteries and capacitors used were high quality, commercially available samples.

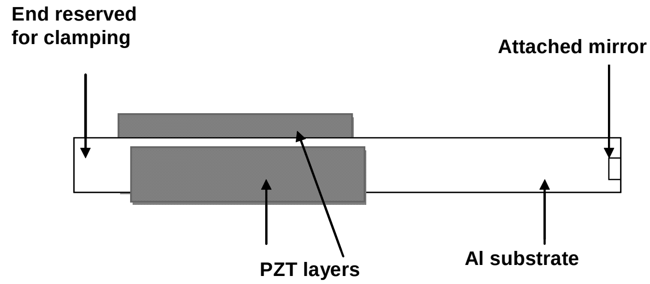

Figure 1: Finished piezoelectric harvester beam device

TABLE 1 : Dimensions and properties of PZT & aluminium

	Parameter	Value
PZT	length, L_p	72.4 mm
	width, w	25 mm
	thickness, t_p	0.267 mm
	Young modulus, E_p	66 GPa
	Piezo-strain constant	190 E-12 C/N
	permitivity ε_{33}	320E-12 m/V
Al	length, L	185 mm
	width, w	25 mm
	thickness	1.57 mm
	Young modulus, E	70 GPa

Methods

The fabricated energy harvester device was driven by an electromagnetic shaker, which acted as the vibration source. It is the DC output from the rectifier which was used for capacitor and battery charging. Throughout the experimental investigations frequency of vibration was set at about 60Hz, which corresponded to the first resonance frequency of the device[10].

Capacitor charging

To investigate the energy storage characteristics of capacitors, different capacitors shown in TABLE 2 were chosen for experimentation.

TABLE 2 : Capacitance values for charging experimentation

Printed Capacitance (μF)	Measured (μF)
220	242
470	483
1000	1070
2200	2260

The excitation level to the device was increased to a level where the energy harvester device produced an output of 20V r.m.s. The output from the device was fed into the standard full wave rectifier circuit constructed on a breadboard using Si diodes; and the DC output from the bridge was fed to the capacitor to be charged. The voltage and charging time of the capacitors were obtained and the results presented in Figures 3-5.

Battery charging

The experimental setup to investigate the ability of the harvester device to charge batteries is shown in Figure 2. The batteries used in the experimentation were two identical 550 mAh GP (trade mark) batteries and two identical 2200 mAh Energizer batteries. These batteries were of nickel metal hydride (NiMH) variety, and have a nominal full charge voltage of 1.2 V. NiMH batteries were chosen for use in the experiments because they have a high charge density and they do not require a charge controller or voltage regulator to be incorporated into the circuitry. As shown in figure 5, the charging circuit consisted of a full wave rectifier circuit, a reservoir capacitor of 100 μF, and the battery to be charged. The energy generated by the harvester device is accumulated in the reservoir capacitor (C). The battery to be charged is connected in parallel to the capacitor. The charging circuit is very simple, compact and does not include additional active components that can result in increased consumption of the generated output power from the harvester device.

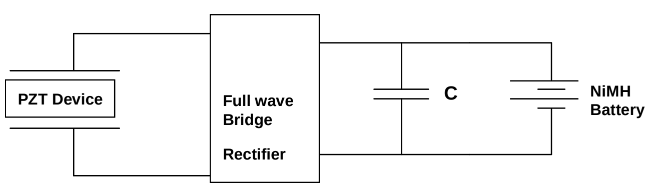

Figure 2 : Schematic of battery charging circuit[1]

The two GP 550 mAh batteries used were designated GP1 and GP2. Similarly the two Energizer 2200 mAh batteries were designated Energizer 1 and Energizer 2. With the function generator set at first resonance frequency and at optimum excitation level, the time to charge each battery to the highest voltage possible (the nominal full voltage is about 1.2 V) was measured. The Energizer batteries were charged overnight. The resulting charging time for each battery and the final voltage is shown in TABLE 3.

RESULTS

Capacitor charging

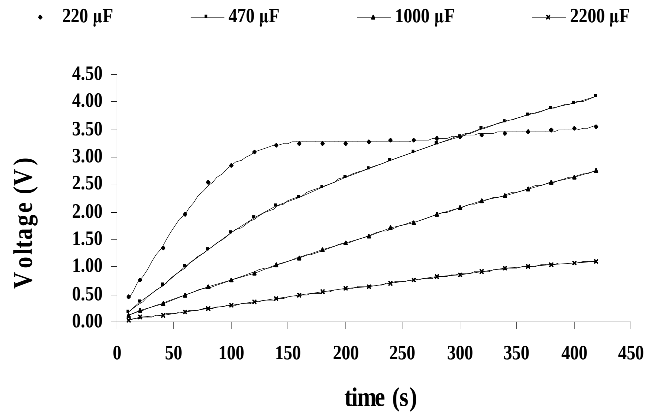

Figure 3 : Plot of capacitor voltage as a function of time

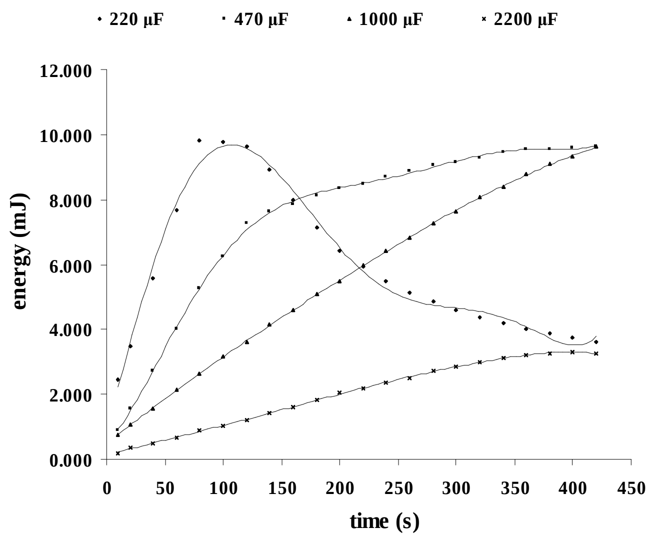

Figure 4 : Plots of stored energy versus time for different capacitances

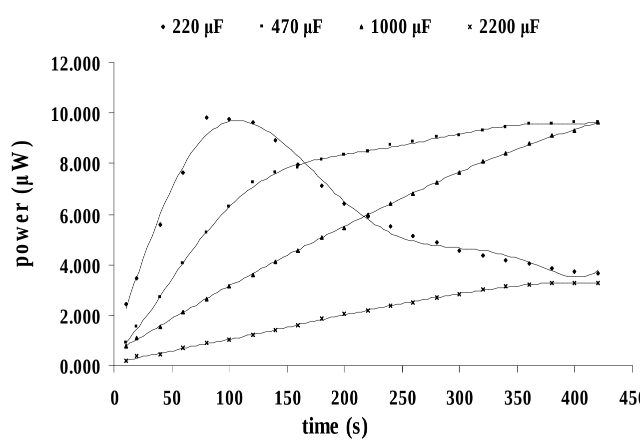

Figure 5 : Plots of power (Rate of energy storage) in various capacitors versus time.

Battery charging

TABLE 3 : Results of battery charging experimentation

Battery NiMH	Capacity (mAh)	Full charge voltage achieved (V)	Total charging time (Hours)
GP1	550	1.21	6.8
GP2	550	1.23	6.6
Energizer 1	2200	0.98	26
Energizer 2	2200	0.97	27

DISCUSSION

Capacitor charging

According to the plots shown in figures 4 & 5, if one wanted to harvest the maximum amount of energy in a 150 second interval, then a 220 μF would be the best suited for the application. If the time interval is increased to 400 seconds, then the 470 μF becomes the best choice. It can be observed from the plots that, the bigger the maximum energy harvesting interval, the bigger the value of the capacitor to be employed. For a specified duty cycle of the electronic device to be powered, the optimum capacitance for the application can be precisely chosen. It is evident from figure 5 that as the capacitance increases, the rate of energy storage increases asymptotically towards some upper limit value. From these plots, it can be seen that given a specified amount of time, a specific capacitor value can be selected to maximize the rate of energy storage (power). As a general pattern the longer the amount of time available to harvest the available ambient energy, the larger the storage capacitor that should be used. It can be seen from the figure that as the energy on the capacitor increases beyond some point, the amount of energy stored in a capacitor levels off and starts to decrease. This can be explained by the fact that energy lost through leakage increase as the voltage on the capacitor increases, countering the energy being input into the capacitor. The energy dissipation from the capacitor is given by:

$$E_{loss} = \frac{1}{2}C(V_i^2 - V_f^2) \quad (1)$$

where E_{loss} is the energy lost, C is the capacitance, V_i is the initial voltage on the capacitor and V_f is the final voltage on the capacitor. From equation (1), it is clear that - as the capacitor voltage increases; the amount of energy lost through leakage increases also, countering the energy being input into the capacitor. The results of the capacitor charging experimentation confirm that the electrical energy harvested from ambient vibrations can be successfully stored in electrolytic capacitors of various capacities. However, the non-ideal nature of capacitors as storage devices leads to some leakages that cannot be neglected in real world applications

Battery charging

The energy-harvesting device managed to charge 550 mAh batteries to full voltage in under seven hours when operating at resonance and driven by ambient vibrations corresponding to a generator output of 2.0 V r.m.s. The harvester device could not charge the 2200 mAh batteries to a full voltage value of 1.2 V. This may be attributed to the low output current of the device.

However, the results confirm that it is feasible to charge batteries using piezoelectric energy harvesting devices. The results from battery experimentation can be extrapolated to mean that this device has the capability of charging standard low capacity batteries namely the 40 mAh and the 80 mAh batteries. Other than the work of Sodano[1], experimental investigations that demonstrate the feasibility of charging batteries using piezoelectric materials is seldom reported in published literature. TABLE 4 shows the battery charging results obtained in this research compared to those reported in literature.

TABLE 4 : Comparison of research results with those reported literature

Battery capacity (mAh)	Charging Time (Hours)	
	Sodano[1]	This research
300	6	-
550	-	6.7
750	7	-
1000	22	-
2200	-	25.5

While the capacity of the NiMH batteries investigated in this research had a different capacity to those investigated by Sodano[1] there is an agreement of trend of the average charging times.

FINDINGS AND CONCLUSIONS

In this research, we have demonstrated that the energy harvested by a PZT- device can be successfully stored in capacitors and NiMH rechargeable batteries. The experimental results suggested exponential variations of energy and power delivered to a capacitor as a function of charging time. The results show that piezoelectric energy harvesting systems have the potential to deliver enough power to be used to charge capacitors and low capacity battery units.

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