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Polymer Based Piezoelectric Energy Microgenerator

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Abstract. The interest in application of all kinds of electronic devices and everyday's demand on implementation of microelectromechanical systems in the last decade has produced rapid progress in the efforts of miniaturizing sensors and actuators. This paper describes microsystem with integrated power source on piezoelectric principle with pressure sensor. It's meant to be implemented without any physical contact to the outside world. It is energy sufficient and easy to produce with printing technology. It uses the PVDF polymer material.

Key words

Polymer, generator, energy.

1. Introduction

Supplying these devices with conventional power supplies - such as batteries, could be used. But there are many applications, however, that require sensors to be completely embedded in the structure with no physical contact to the rest of the world. Supplying energy to such a system is difficult and the only possible solution is to make them so-called self-powered microsystems [Fig.1,2]. With integration of power supply unit on the same chip there are several advantages associated like noise reduction, elimination of crosstalk and reduction of power delivery control system complexity.

2. Self-powered microsystem concept

Integrated self-powered microsystem consists of four units:. power supply unit with an energy generator, energy storage block, signal data processing, transmission unit and sensor.

A. Power supply unit with energy generator

Nowadays conventional solution to supply power is to use some kind of batteries. However, some of the drawbacks associated with such a solution are that the energy inside batteries is limited, they have short effective life in comparison with the supposed sensor system lifetime, and contain dangerous chemicals that could cause a hazard, their dimensions are not suitable for "micro world" applications and they can fail at inconvenient times.

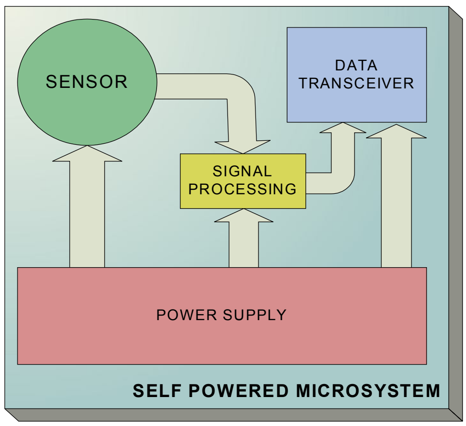

Fig. 1. Self-powered microsystem

This shortens the system maintenance cycle and increases the total costs. It is therefore recommendable to make arrangements for energy generation within the micro system. [Fig.3] as lightweight, flexibility and reasonably good force/displacement, they make good candidates for actuators.

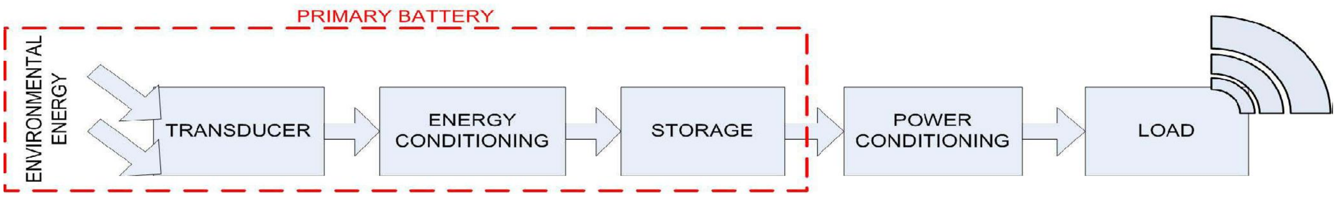

Fig.2 Block diagram of an autonomous system. [1]

An unconventional solution is to design a micro generator to convert mechanical vibrations into electrical energy with help of the piezoelectric effect. But today's most used piezoelectric material PZT was substituted by more flexible polymer material - Polyvinylidene fluoride (PVDF). They have excellent properties applicable for typical usage fields of such kinds of sensors. Piezoelectric polymers are a class of materials with great potential and promise for these applications. Because of their ideally suitable characteristics such as lightweight, flexibility and reasonably good force/displacement, they make good candidates for actuators.

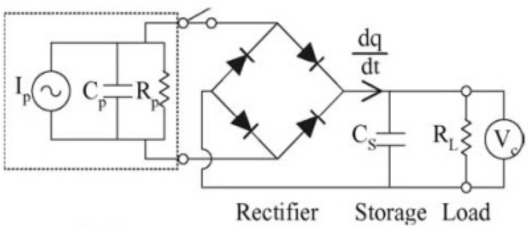

Fig. 3. Model of power supply block

B. Generated energy storage

For this purpose we would like to use a polymer based capacitors [2]. In the field of capacitors there has been done some new combination of irradiating PVDF and coating it with a thin, amorphous acrylate polymer film. This produces a single-layer capacitor of power density on the order of 5.0 joules per cubic centimeter (J/cm^2). Commercial capacitors on the market today provide about 2.0 to 2.5 J/cm^2. According to Sigma [3], optimizing the radiation curing process, polymer material, and electrode resistivity could in theory produce a single-layer capacitor with power density on the order of 20 J/cm^2. Coating PVDF with acrylate polymer also has a fringe benefit: it improves the melting point of the PVDF from 150°C to 300°C, enabling the capacitor to handle higher voltage. The coating also acts as a skin that helps a metalized capacitor self-heal. Therefore, there has been a third option investigated - a capacitor-battery combined system.

C. Output signal data processing and transmission unit

The system must be able to transmit the measured data to the outside world and it must be done while the sensor system is physically isolated. The objective is to use as small energy as possible to transmit the data. Then the power can be reduced to a low level by limiting the data rate. There are several communication media to be used. For this purpose very low power optical fiber communications can be used. Another possibility is usage of magnetic coupling resonant inductive circuits, where the transmission range is reasonably short. For longer transmission ranges, radio telemetry techniques should be investigated.

3. Principles and Devices

State-of-the-art MEMS generators and transducers can be such self-renewing sources, extracting energy e.g. from vibrations [4]. The energy extracted from these sources is stored in chip-compatible, rechargeable batteries such as thin-film lithium-ion types, which power the loading application (the sensor) via a power management circuit. Figure 3 shows a diagram of a cantilever beam with piezoelectric plates bonded on a substrate and a proof mass at the end; multilayer piezoelectric plates and equivalent lumped spring mass with external excitation. Cantilever structure with tip mass is the most widely used configuration for piezoelectric energy harvesting device. The source of vibration is shown with an arrow at the base of the contact point. The stiffness of the structure depends on the loading condition, material, and cross-sectional area perpendicular to the direction of vibration. The governing equation of motion for the system shown in Fig. 2(c) can be obtained from energy balance equation or D'Alembert's principle. This configuration applies to both the energy harvesting mechanisms shown in Fig. 2(a) and (b).

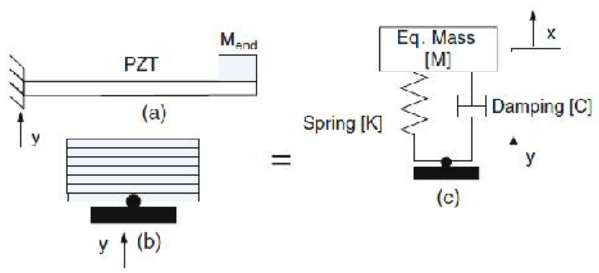

Fig. 3. Power supply block (a) Cantilever beam with tip mass, (b) multilayer PZT subjected to transverse vibration excited at the base, and (c) equivalent lumped spring mass system of a vibrating rigid body[2]

4. Modeling

The governing equation of motion of a lumped spring mass system can be written as[5] :

$$M\ddot{z} + C\dot{z} + Kz = -M\ddot{y} \tag{2}$$

where $z = x - y$ is the net displacement of mass. Equation (2) can also be written in terms of damping constant and natural frequency. A damping factor, ζ, is a dimensionless number defined as the ratio of system damping to critical damping as:

$$\zeta = \frac{c}{c_c} = c/2\sqrt{mK} \tag{3}$$

The natural frequency of a spring mass system is defined as:

$$\omega_n = \sqrt{K/M} \tag{4}$$

where the stiffness K for each loading condition should be initially calculated. For example, in case of a cantilever beam, the stiffness K is given by $K = 3E\ I/L^3$, where E is the modulus of elasticity, I is the moment of inertia, and L is the length of beam. The moment of inertia for a rectangular cross-sectional can be obtained from expression, $I = (1/12)bh^3$, where b and h are the width and thickness of the beam in transverse direction, respectively. For the other cross-sectional area and stiffness, formulas are available in standard mechanical engineering handbook (Blevins, 1979). The power output of piezoelectric system will be higher if system is operating at natural frequency which dictates the selection of material and dimensions. The terms "natural frequency" and "resonant frequency" are used alternatively in literature, where natural frequency of piezoelectric system should not be confused with natural frequency of mechanical system.

5. Piezoelectric Micro-actuators

The piezoelectric principle can be used in many applications, such as electric fans, microphones, inkjet printers, control valves, micro pumps, tactile sensor, acoustic control and micro motors, etc. Figure 4 shows a typical piezoelectric micro actuator. The main advantages of this actuation principle are its high precision, speed and mechanical power.

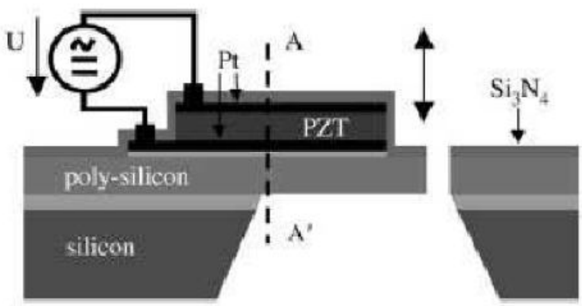

Fig. 4: Cross sectional view of a PZT micro actuator. (Manohara, 1999)

In these applications, piezoelectric ceramic materials such as zinc oxide and PZT are most commonly used, because they exhibit large piezoelectric coefficients. However, there are also some difficulties associated with their use. Piezoelectric ceramic materials require advanced deposition facilities and technologies to prepare thin films, they are usually brittle, and have a relatively large Young's modulus, thus limiting the achievable strain. Some composite active polymers (Friese *et al.*, 2003; Janos and Hagood, 2003) composed by piezoelectric ceramic materials and epoxy were fabricated to compensate for these disadvantages. Piezoelectric polymers such as PVDF and its copolymers can overcome some of these difficulties even though they have a relatively low piezoelectric coefficient. Low numerical Young's modulus values of these polymers have the potential for enabling relatively large strain piezoelectric actuators. There are two extreme cases of the high-energy density material[3], PVDF piezoelectric polymer (d_{33} = 33 pC/N, $\varepsilon_{33}/\varepsilon_o$ = 13, g_{33} = 286.7×10–^{3} m^2/C), and relaxor piezoelectric single crystals such as PZN – 7%PT (d_{33} = 2500 pC/N, $\varepsilon_{33}/\varepsilon_o$ = 6700, g_{33} = 42.1 × 10–^{3} m^2/C). It can be seen from this data that piezoelectric polymer has the highest piezoelectric voltage constant, g_{33}, of 286.7 × 10–^{3} m^2/C and relaxor-based single crystals have the highest product ($d_{33}.g_{33}$) of the order of 105, 250×10–^{15} m^2/N.

6. Used materials

Piezoelectric materials create electrical charge when mechanically stressed. The most widely used commercial piezoelectric material is various phases of lead zirconate titanate (PZT). Unfortunately, ceramic materials are fragile and it is very difficult to produce them in large sizes. Piezoelectric polymers are increasingly considered as favorable materials for MEMS applications due to their fast response, low operating voltages and greater efficiencies of operation.

The properties of polymers are so different in comparison to inorganic (Table I) that they are uniquely qualified to fill areas where single crystals and ceramics cannot be used effectively [6]. As shown in Table 1, the polymer piezoelectric strain constant (d_{31}) is lower than ceramic. However, piezoelectric polymers have much higher piezoelectric stress constants (g_{31}) indicating that they are much better sensors than ceramics.

Table 1. – Material Properties

Property	Units	PVDF	PZT
Piezoelectric strain constant	$\frac{10^{-12}C}{N}$	$d_{31}=23$ $d_{33}=-33$	$d_{31}=-171$ $d_{33}=374$
Coupling constant	$\frac{CV}{Nm}$	$k_{31}=0.12$ $k_{33}=0.15$	$k_{31}=0.34$ $k_{33}=0.69$
Piezoelectric stress constant	$\frac{10^{-3}Vm}{N}$	$g_{31}=216$ $g_{33}=-330$	$g_{31}=-11$ $g_{33}=25$

The most efficient energy conversion, as indicated by the coupling constants in Table 1, comes from compressing PZT (d_{33}). Even so, the amount of effective power that could be transferred by this way is minimal since compression follows the formula:

$$\Delta H = \frac{FH}{AY} \tag{5}$$

where **F** is applied force, **H** is the unloaded height, **A** is the area over which the force is applied, and **Y** is the elastic modulus. The elastic modulus for PZT is 4.9e^{10} N/m^2. Thus, it would take an incredible force to compress the material a small amount. Since energy is defined as force through distance, the effective energy generated by compression of PZT would be vanishingly small, even with perfect conversion.

The coupling constant shown in Table I represent the mechanical to electrical energy conversion efficiency of the material. The g_{31} is much higher that by PZT thus the generated voltage reaches more usable values for rectifying.

A. Fabrication of PVDF cantilever

PVDF is material which can be used in many applications, especially all kinds of micromanipulators or microactuators. Therefore there is a significant effort to shape and form these kinds of polymers into a required shape and size. The most commonly used manufacturing process is laser micromachining, electroplating and punching (micro embossing).

7. Layout

The proposed electromechanical microgenerator is essentially a resonant mechanical structure based on cantilever modifications. The base PVDF layer is coated on both planar sides with a conductive metal layer (Fig.5),[7].

These layers act as electrodes. Serpentine cantilever (Fig. 6) has been designed to achieve a low resonant frequency structure as well as a low damping effect when it resonates. A small mass is attached to the free end of the beam [8].

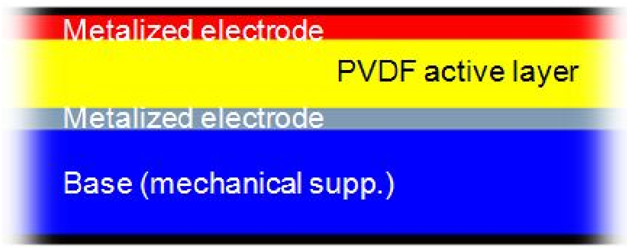

Fig. 5. Layers of the generator

For simulation was used CoventorWare software. Simulation results of electro-mechanical behavior of 1mm in diameter small serpentine are visible on Fig.8.

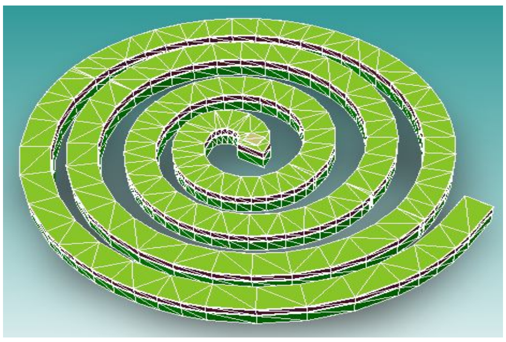

Fig.6. Layout of the serpentine cantilever

Generated charge in the PVDF layer is visible on Fig.7.

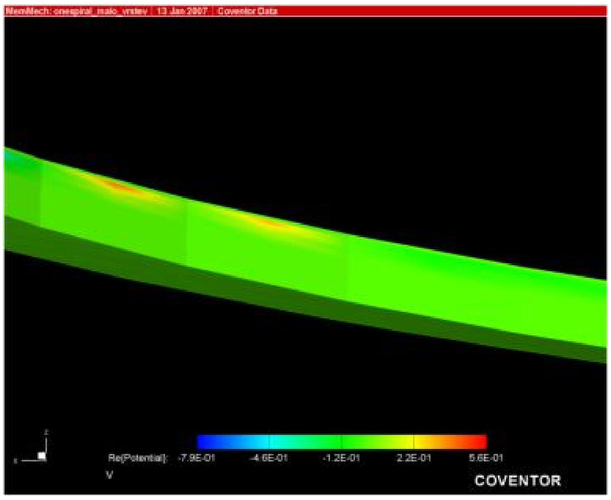

Fig. 7. Detail of generated charge (simulation)

There has been already published concepts of microgenerators [8], which use a magnet and coil arrangement to generate the electrical power.

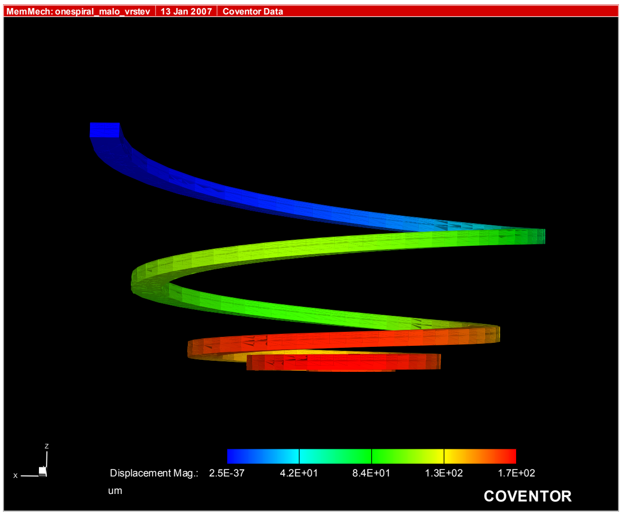

Fig. 8. PVDF based microgenerator – mechanical serpentine in motion under pressure

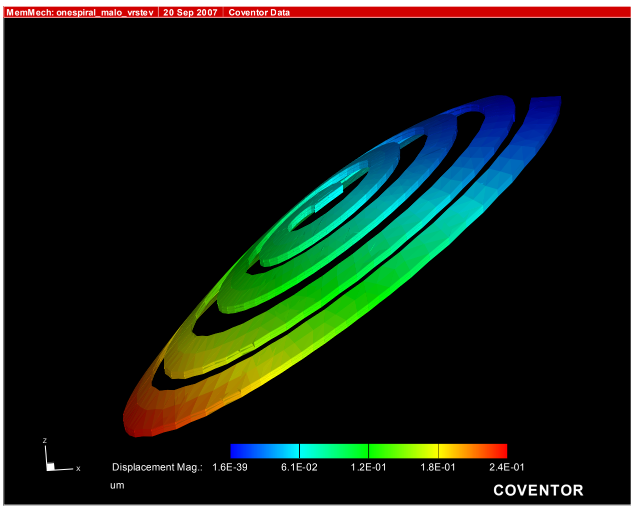

Fig. 9. Reverse mode

One of the factors affecting output power delivered is the resonant frequency of the beam; the higher the frequency the more power will be available. The application areas envisaged for our system include vibrating machinery and vehicles, where the frequencies of interest do not generally exceed a few hundred Hertz, and are often restricted to below 100 Hz.

There is also a reverse reaction of the structure on the applied voltage. Hereby we get a miniaturized micro manipulator that can be used for precision positioning. The bending reaction is visible on Fig.9.

8. Power Efficiency Optimization

The most important aspect is the power generation efficiency to surface ratio [9]. To minimize the microsystem area and to maximize the energy efficiency of the layout there has been designed a field of hexagonal shaped serpentine cantilever (Fig. 10). Higher output can be achieved by building "sandwich" structure – multiple multiple PVDF layers on each other. There has been designed several generations (Fig.11) of cantilevers from the simplest circular structure over the serpentine cantilever to the most effective field of hexagonal shaped serpentine cantilever. PVDF layers on each other.

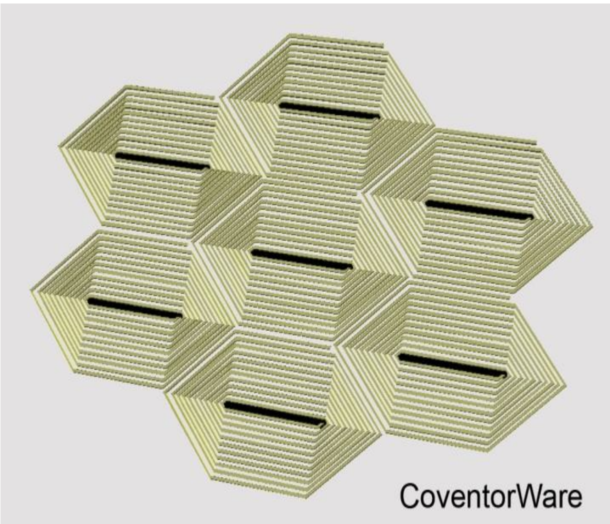

Fig. 10. Hexagonal shaped serpentine cantilever

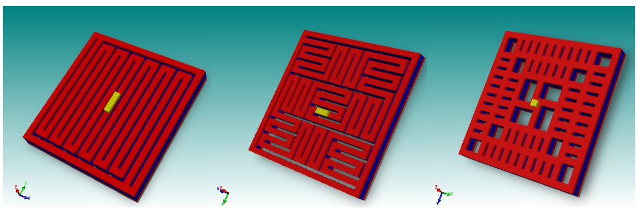

Fig. 11. Different generator layouts

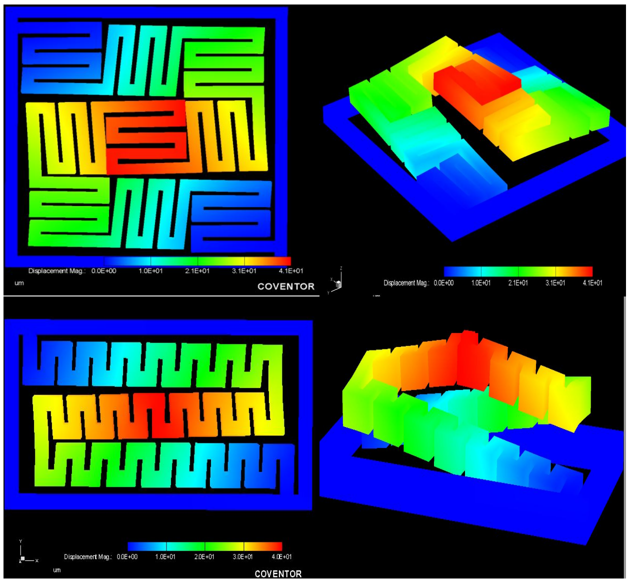

Fig.12 – Simulated generator movement on resonant frequency

Vibration energy harvesters can be employed to harvest energy from vibrations and vibrating structures, a general requirement independent of the energy transfer mechanism is that the vibration energy harvesting device operates in resonance at the excitation frequency [10]. Most energy harvesting devices are single resonance frequency based. To obtain the lowest possible resonant frequency it is necessary to design layout with long cantilevers. But this condition is limiting the resulting area occupied by the generator. There have been designed several different layouts of the micro generator with different resonant frequency. Each of these layouts are usable in different environments.

9. Conclusion

The electro-mechanical model of the piezoelectric power generator is presented and used to predict and understand the behavior of the generator under quasi-static and dynamic stress conditions. Under quasi-static stress, the piezoelectric power generator produces a bidirectional (i.e., positive and negative peak) output voltage. In contrast to the quasi-static stress condition, the dynamic stress condition produces a unidirectional output voltage ca.10 times larger than the quasi-static case. This difference is caused by loading time of the capacitance created by the active piezo-material layer. This capacitance doesn't have enough time to charge and subsequently recharge the generated voltage during the dynamic conditions and therefore it doesn't decrease.
Resonant frequency of micro-generator is crucial parameter to obtain the maximum energy out from the design. There are tunable layouts in development which can be used in applications with broad frequency range.

Acknowledgement

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