

Current progress in ambient energy harvesting using piezoelectric materials and electroactive polymers

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Abstract- A review on current progress in energy harnessing micro-generators using active materials (ceramic and polymeric piezoelectric materials as well as electroactive polymers) is presented. A problem of effective electrostatic energy extraction from those capacitive-in-nature energy supplies is illustrated experimentally. It is shown that using Macro Fiber Composite (MFC) piezoelectric transducers working in resonant mode and matching the load to the MFC impedance it is possible to attain 10 % generation efficiency.

I. INTRODUCTION

Energy harvesting, scavenging, and harnessing – these are all almost analogous terms related to research and engineering activities aimed at extracting energy in electric form from various ambient energy reservoirs, which generally cannot be scaled up for full-size, power-plant energy generation schemes. There are many ambient energy pools that could be exploited by autonomous, low-power fuel-less generators: waste heat, electromagnetic hum, vibrations, localized air movement or human-generated power. In addition, traditional “renewable energy resources” like water flow, tidal and wind energy or sun radiation can also be exploited at the miniature scale by energy micro-harvesters. All environments are now being populated by miniaturized, micro-power electronic devices working in wireless sensor networks or just as mobile gadgets. A dream to power all those devices without batteries making them perpetual or at least to supplement mobile supply scheme is the driving force of the research oriented on ambient energy harnessing. Serious interest in those problems, partially motivated by climate change and global warming, is also reflected by several R&D organizations (e.g. DARPA, CEALITEN) and companies aiming at harnessing energy from ambient vibrations, leg and arm motion, shoe impacts, and blood pressure for self-powered systems.

II. KINETIC ENERGY HARVESTING

Different techniques are being proposed for powering up remote, unattended, implantable or wearable sensors, short-distance wireless communication stations, RFID tags or personal health monitors. Generating electricity from ambient vibrations or kinetic motion is one of those approaches applicable as a renewable substitute for batteries in micro-power electronic products making timed use of accumulated energy. Kinetic energy in the form of motion or vibrations is generally the most versatile and ever-present [1]. Operating principles of motion-driven ambient energy microscavengers relay on utilization of inertial forces acting on a proof mass

fitted with a damper which simultaneously serves as an electromechanical transducer converting kinetic into electrical energy. Vibration stimuli are extensively present but vary widely in amplitude and frequency thus micro-generators are designed as resonant systems matched to vibration spectrum of the source. Non-resonant or dynamically tunable devices are also being designed, as broadband operation is required for maximizing output power when the source has a complex or time-variable vibration spectrum [2].

A. Electrostatic generators

Although miniature human-powered electromagnetic dynamos has been used for a long time to supply flashlights and portable radios yet the electrostatic: capacitive, piezoelectric and electroactive polymer (EAP) generators possess a serious advantage over other competing electromagnetic generation schemes: electricity is generated “intrinsically” thus virtually all moving parts are eliminated so the mechanical complexity of the generator is seriously reduced which makes it lightweight, reliable and wear-proof.

In electrostatic generators, external mechanical force is engaged to do work against the attraction of charged electrodes of a variable capacitor. Two modes of such operation are applicable: switched and continuous. In the switched regime the capacitive transducer and the supplementary circuitry is reconfigured by a set of contactors at different stages of the generation cycle. Such electrostatic transducers require a pre-charging voltage source in order to operate. As the device capacitance is reduced against electrostatic attractive forces it produces current flow into the pre-charging source.

Most of the miniaturized electrostatic energy scavengers are being build as integrated micromachined chips using MEMS fabrication processes. Micromechanical vibration energy scavengers use pre-charged capacitors with capacitance-modulating variable air gap formed between comb electrodes [3]. In order to avoid pre-charging circuitry electret layer may be deposited on capacitor electrode - Arakawa *et al.* has designed a microseismic electrostatic generator using spin-coat-deposited polymeric electret capable of delivering 6 μ W of energy for 1 mm amplitude 10 Hz oscillation [4].

Recent years have brought in new concepts emerging on the rims of high voltage engineering and materials science. These are related to electroactive polymers (EAP) also described as artificial muscles. The last name comes from their ability to directly convert electrical energy into mechanical work and

motion (linear or bending) without any moving parts found in classical electrical drives. Electronic EAPs are one of the main sub-class in broad family of EAP material systems. These are dielectric polymeric materials that change shape or dimensions due to shift or limited migration of electrons in response to electric field stimuli. Dielectric EAP actuators (DEA) display also inverse effect – when working in so-called generator mode they generate electricity from mechanical deformation. In this mode DEA can be perceived as a variable capacitance device. The electrical capacitance is initially charged when the DEA transducer is in the stretched, high capacitance, state. When it is then mechanically contracted it goes back to its low capacitance state and the elastic stresses in the DEA material film works against the compressive Maxwell stress (electric field pressure resulting from opposite charges attraction), thus increasing electrical energy in form of voltage raise. Therefore, energy harvesting from ambient “reciprocating” power sources is also possible by means of dielectric EAP materials.

A recent theoretical analysis indicates that typical human-motion-generated displacements available for inertial microgenerators (approx. 5 mm motion at 1 Hz) can provide energy density of up to $4 \mu\text{W}/\text{cm}^3$ and up to $800 \mu\text{W}/\text{cm}^3$ can be extracted from high-pitched machine-induced stimuli (approx. 2 nm motion at 2.5 kHz) [5]. As typical human applies over 100 % of his own weight across the shoes at every heel strike therefore, cushioned shoe soles can be significantly compressed even during normal walk. Assuming an average person weighting 75 kg, 5 mm sole compression, regular walking speed of 2 steps/s this indicates that roughly about 7 W of power could be available just from heel strikes. Company SRI Intl. has designed and tested a multilayer EAP shoe generator, schematically illustrated in fig. 1. When the device is compressed, the coupling liquid or gel medium contained in the bellows forces out and stretches a thin, elastic layer of electroded EAP through circular openings in the upper perforated plate sealing the bellows. In normal walking conditions such boot energy scavenger was delivering energy output of 0.8 J per every step with just 3 mm heel compression and provided 0.8 W of power [6]. The company Artificial Muscle Inc. has also presented plans to build switched EAP-based power supply units operating on wind or tidal energy. Flapping (flag- or string-like) power generators made of cyclic-distorted DEA fibers are proposed to populate windy locations and floats secured to the sea bottom on stretchable elastic strings made up of dielectric EAP fibers provide extensional motion by ridding on tidal or wind- generated waves [7].

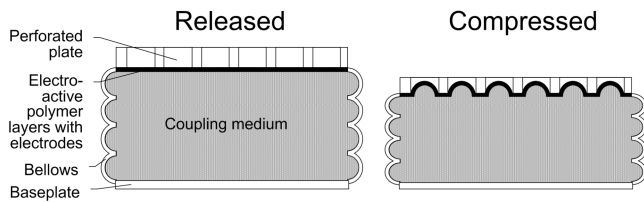


Figure 1. Schematic view of electroactive polymer heel energy harvester module developed by SRI Intl. (sketch based on [8]).

SRI Intl. has already started tests of a prototype buoy-mounted, ocean wave-powered DEA generator. The “Hyper Drive” generator utilizes sleeve-like EAP polymer transducers generating an average output power of more than 5 W under typical ocean wave conditions, which is enough to power up a buoy-mounted radio [9].

B. Piezoelectric continuous mode generators

Although theoretical modeling shows that EAP-based switched energy scavengers using highly compliant electroactive polymers and running at high voltages can provide energy density up to 1,5 J/g and much better performance figures than piezoelectric generators, the latter (despite their intrinsic material properties limiting efficiency due to low electromechanical conversion efficiency and high brittleness and thus low tolerance for high and abrupt mechanical stress) are extensively utilized in construction of continuous mode electrostatic generators. The advantage lays in no requirement for circuitry reconfiguration and no pre-charging source. In this case mechanical work is partially stored in the energy of the electric field associated with the induced polarization of the piezomaterial. Neutralization current flows if an external load is shorting the electrodes deposited on the piezoelement. Effective piezoelectric energy harvesting requires piezoelectric materials with elevated electromechanical coupling coefficients, thus ceramic (PZT) materials dominate those designs.

The company Adaptiv Energy is promoting its kinetic energy harvesting solutions based on Ruggedized Laminate Piezo (RLP) composite combined with efficient, very-low-loss MOSFET power extraction electronics. The RLP technology allows to compress piezoceramic material in order to increase the voltage per strained unit area. The RLP is a stainless steel flat spring double-side laminated with a piezoelectric ceramics and copper electroding layers. Appropriate thermal cycling during bonding process introduces initial compressive prestressing into the piezoelectric material, giving greater density and flexibility and thus provides added output voltage. RLP transducer uses calibrated mass to match the exploitable vibration spectrum [10]. Ocean Power Technologies company exploits strips of piezoelectric foil to harness the power of flowing water, in the form of 18-inch-long “eels” that flap in turbulent water flow like a weeds in the wind [11]. Energy scavenging by piezoelectric generators has also been recently perceived by automotive industry, especially car automation designers and manufacturers. Kim *et al.* discuss the use of a piezoelectric cymbal transducers to generate electricity to supply car remote onboard sensors from the vibration of a car engine [12]. Dynamic strain coupled from the rolling tire of a car has also been recently patented as a power source for a wireless tire condition monitoring system [13].

Energy scavengers operating in continuous mode may also be used to extract energy from human motion. A heel strike may be used to flatten a piezoelectric (PZT) unimorph bender and toe-off action may bend a multilayer polymeric piezoelectric bimorph stave made of PVDF (polyvinylidene

fluoride) foil. Such combined system was shown to produce 1.3 to 8.3 mW during a standard walk depending on the location of transducer (toe/heel) and available displacement range [14]. The East Japan Railway Company has been testing an experimental system that produces electricity as people pass through subway ticket gates. The gates are fitted with floor-embedded energy-scavenging mats with series of piezo-element diaphragms that generate electricity as commuters walk over and compress the mat. 90 m² energy-scavenging floor was producing on average 0.14 kWh of energy a day with peak performance of 0.21 kWh on busy weekends [15].

C. Electric energy extraction from electrostatic scavengers

Another challenging issue is an effective extraction of electrical energy from capacitive-in-nature, high internal resistance piezoelectric and EAP elements. Electrostatic harvester cannot be simply load by ohmic resistor as it results in poor overall efficiency of the generator. Energy generated by piezoelectric and most EAP scavengers is available in form of high voltage peaks which are hazardous for low-voltage electronics if no appropriate conditioning circuitry is used. To demonstrate those problems an experiment, described in the following paragraph, was run using a simple model of the piezoelectric energy scavenger build of Macro Fiber Composite (MFC) transducers. MFC is a novel complex multilayer composite material consisting of PZT piezoceramic fibers laminated with epoxy resin and sheets of mechanically tough polyimide foil fitted with interdigitated electrodes.

III. EXPERIMENTAL

A piezoelectric energy scavenger model was build of two M-8557-P1 type MFC transducers (Smart Materials GmbH, Germany) fixed to a phosphor bronze flat beam (1 mm thick) using DP460 epoxy adhesive and connected in parallel to increase magnitude of the generated current. The assembly was permanently fixed at one end, its free tip was deflected by 3 mm and allowed to freely vibrate at its own resonant frequency until completely damped. The voltage produced over a variable low-inductance load resistor was recorded by means of a digital oscilloscope fitted with 1:10 10 M Ω passive probe. An exemplary voltage train recorded for 100 k Ω load resistance is illustrated in fig. 2. The maximal voltage amplitude registered in this case was exciding 150 V and even higher voltages were recorded for high resistive loads (252 V for 10 M Ω). The signal frequency spectrum contains a strong component related to the fundamental mode of the beam mechanical free vibration (approx. 54,5 Hz) as well as a number of higher harmonics, related to other modes of oscillations. The recorded voltage trains were then processed to calculate the mean total energy dissipated at the resistive load - the results obtained for different loads are illustrated in fig. 3.

IV. DISCUSSION

There is an optimal load which results in the maximal energy output of the MFC energy harvester. The harvester model is producing oscillatory voltage response, therefore the optimal load is equivalent to the impedance of MFC transducers which

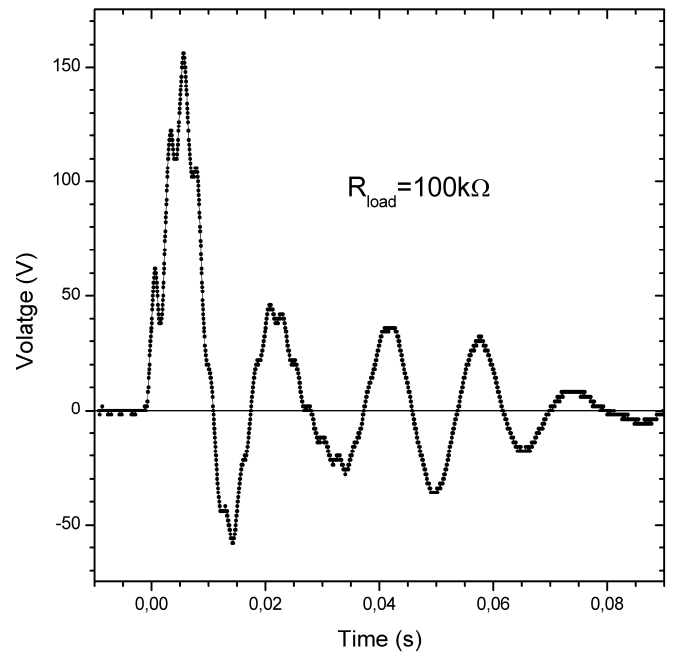


Figure 2. Exemplary voltage train generated over 100 k Ω resistive load by MFC energy scavenger model working in resonance mode.

form capacitive-in-nature alternating voltage source. Taking into account the mechanical resonant frequency of the model (54,5 Hz) and MFC stack capacitance (21.9 nF, measured for 50 Hz excitation) one obtains impedance of approx. 133 k Ω . The calculated value is somewhat higher than the optimal load determined experimentally (approx. 100 k Ω) and the discrepancy may be attributed to higher frequency components present in the real voltage response spectrum and to non-flat frequency-capacitance MFC characteristics. The obtained results are consistent with findings of Swallow *et al.* for resonant harvesters build using piezoelectric fiber composites (PFC) and polymeric piezoelectrics (PVDF) [16].

The mechanical energy stored in the harvester model beam displaced by 3 mm equals to 12.9 mJ (the elastic modulus of the model composite beam has been determined as 2.88 kN/m). Therefore, even for the optimal electric load, only slightly over 10 % of the stored mechanical energy may be extracted from oscillating MFC electromechanical transducer model. The reason for that is a fact that only a portion of the total mechanical energy “pumped” into the beam (when it is bent) is stored in the electric field associated with the piezoelectric effect due to low electromechanical coupling factor of the material. Also, some energy fraction is dissipated as the Joule heat over the MFC internal resistance.

The above simple experiment shows, that it is not only necessary to transform open-circuit high voltages generated by piezoelectric transducers into low voltages accepted by interdigitated circuits. Advanced power converters for use with piezoelectric and EAP generators are essential in order to maximize the power harvested as the circuitry needs to present an optimal load resistance to the piezoelectric/EAP generating

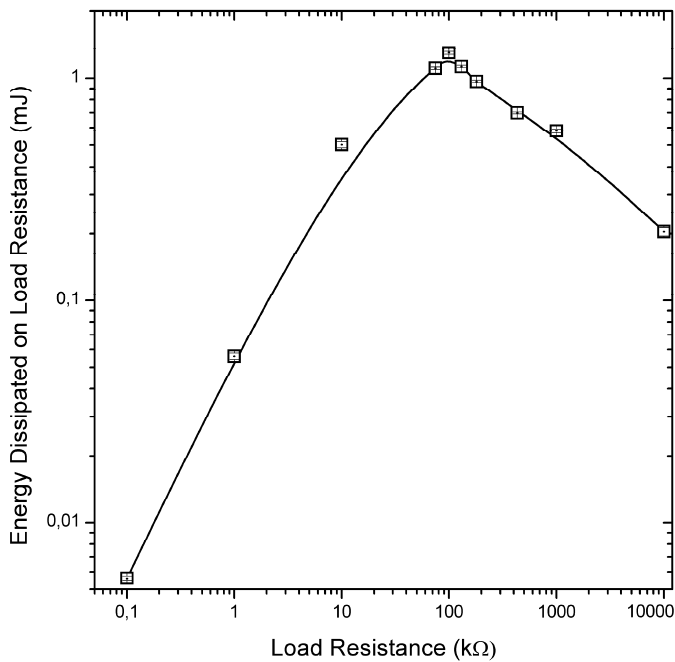


Figure 3. Energy dissipated at the resistive load by MFC energy scavenger model working in resonance mode.

element. Most of the recent work on power electronics intended for kinetic harvesters has been done for piezoelectric transducers: adaptive control voltage converters, synchronous half-wave voltage doublers and synchronous rectifiers [17] as well as new energy storage like supercapacitors or solid state thin-film batteries has been proposed and tested. Ren *et al.* have also shown that combining active energy harvesting control system (i.e. varying elastic properties of the transducer between the opposite generation phases by imposing an external electric field to zero a strain change in the active material or by imposing other electric boundary conditions to modify the energy harvesting cycle) together with high electromechanical yield electrostrictive polymer can provide harvested electric energy density of approx. 40 mJ/cm^3 at 10 % efficiency [18]. Similar approach is also required in case of EAP harvesters as they are capacitive voltage sources too.

V. CLOSING REMARKS

MP3 player powered by build-in yoyo energy harvester has been recently nominated as the best human powered device design during Core77 Design Challenge 2008 – it will provide round-the-clock listening to music everywhere without a risk of running out of batteries. And this is just one example of numerous new gadgets which are just about to come. There is no doubt that ambient energy harnessing using motion- or vibration-driven low-power generators is a topic of substantial and increasing research and engineering attention. Although there are many different techniques available to harvest raw energy from ambient “energy pools”, it seems to be justified to state that devices using electroactive polymers and piezo-

materials are now the most promising as they allow to put away most of movable and wearable parts and require very moderated maintenance efforts. It is expected that the time in which this technology will be demonstrated for military applications (so-called smart soldier concept) extends from 2-5 years and 3-7 years is needed in case of domestic appliances (e.g. mentioned MP3 players) [19].

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