

ENERGY HARVESTING SYSTEMS USING PIEZO-ELECTRIC MACRO FIBER COMPOSITES

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ABSTRACT

Harvesting energy from “waste” vibration present in the environment has seen an increasing interest during the past years as part of the general heightened awareness for alternative energy sources. Beside of typical electro mechanical methods, ferro electric devices have proven to be very effective to harvest energy for low power devices as often found in portable electronics, sensor controlled and condition monitoring systems due to the wide usable frequency range and adaptability.

Due to their excellent properties like flexibility, anisotropy and long term stability Macro Fiber Composites (MFC) fit most of the requirements to meet the specifications of energy harvesting systems based on the piezo electric effect. A test set up for the introduction of uniform strain into the MFCs as well as an electrical impedance matching will be presented based on a general consideration about energy transfer in electric dipoles and a comparison between soft and hard piezo electric materials (PZT). Test results outlining the differences between a PZT-5A1 and a PZT-SP4 material particularly with respect to power output, electrical mismatching and long term stability will be discussed. Finally examples of MFC based energy harvesting systems from different fields of application are presented, demonstrating the high potential of the MFC technology for the generation of electrical energy from mechanical vibrations. A short summary of the requirements for the electrical and mechanical subsystem concludes the presentation to help system engineers to design high performance energy harvesting systems.

Keywords: PZT, MFC, piezo composite, energy harvesting

1. INTRODUCTION

Energy recovery from waste or unused mechanical power has been the topic of discussion for a long time. Unused power exists in various forms such as machine vibration, flowing water, wind, human motion and shock wave. In recent years, industrial and academic research units have focused their attention on harvesting energy from vibrations using piezoelectric transducers. However, because the conventional device configuration was mostly a “bi- or trimorph” design working in resonance settings, the efforts clarified three main problems associated with piezoelectric transducers: (i) mechanical stability of the piezoelectric transducer under large ac stresses, (ii) electrical breakdown of the material under high fields, and (iii) reduction in efficiency due to dielectric losses and depolarization.

The development of piezoelectric composite material, like the MFC, helped to overcome some of the limitation of the monolithic piezo ceramic components, especially brittleness, lack of reliability and conformability. The recent advance in ultra low power electronic components has made a new type of electronic devices possible: battery free, autonomous devices functioning solely on harvesting mechanical vibrations with piezoelectric components.

The Macro Fiber Composite (MFC) is a planar piezoelectric device consisting of rectangular cross-section PZT fibers embedded in an epoxy matrix and sandwiched between Kapton®-clad copper interdigitated electrodes. Its lightweight, robust construction and increased actuation strain energy density have made it a popular choice for structural control in various applications in the aerospace, automotive, and consumer products industries¹⁻³. Developed at NASA Langley Research Center during the late 90's, the MFCs are manufactured by Smart Material Corp. in a full-scale production under a license agreement from the US government⁴.

2. COMMERCIALLY AVAILABLE MFC DEVICES

The MFC consist of rectangular, uni-axially aligned piezofibers sandwiched between layers of adhesive and electroded polyimide films. Using non-metalized PZT the electric field couples between neighboured finger electrodes of different polarity in the fiber direction (d_{33} effect, denoted by MFC P1 type), see Fig.1 (left). Recently, a contracting MFC has been developed with the advantage of reduced driving voltage of 360V (d_{31} effect, denoted by MFC P2 type). This device uses PZT fibers with top and bottom electrodes obtained by dicing metalized PZT wafers. All finger electrodes of each side connected together. Thus, the applied electric field is applied through the fiber thickness, see Fig.1 (right). The MFC assembly enables in-plane actuation and sensing in a sealed, durable, ready-to-use package.

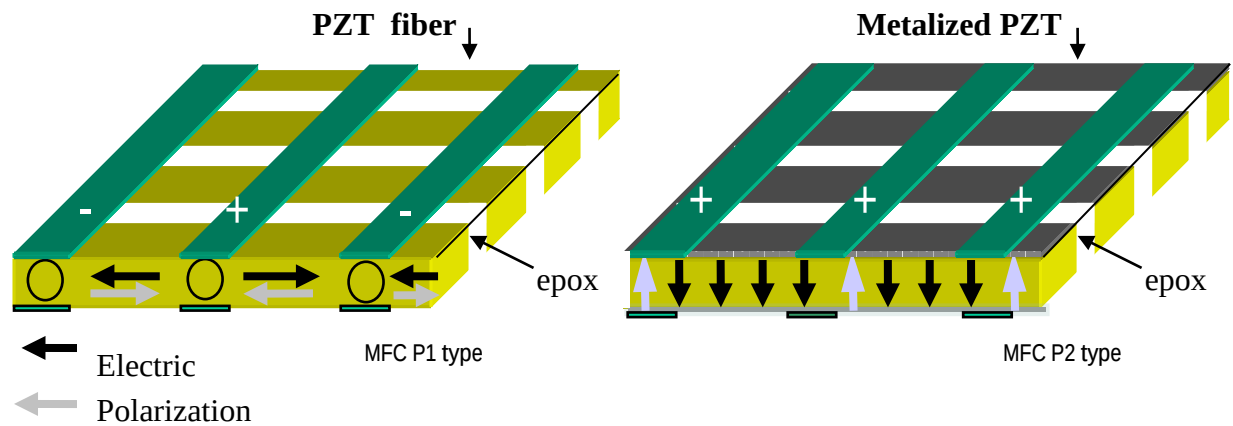


Figure 1: Explanation of the different drive modes of P1 MFC with IDE on non metalized PZT fibers (left) and P2 MFC with unipolar electrode structure on each side comprising a layered metallization on diced PZT fibers and unipolar finger electrodes

The P2 type MFC is especially suited for energy harvesting applications due its higher capacitance and increased charge generation at the same strain level compared with the P1 device (see also table 1).

Macro Fiber composites are still innovative devices and the performance is constantly improved. Components with new geometrical data, new PZT and interstitial materials are constantly added or improved. Table 1. gives essential engineering data. The linear elastic properties are $E_{1x}=30$ GPa, $E_{1y}=16$ GPa and $\nu=0,31$.

Many life tests, e.g. mechanical unloaded uniaxial cycling of MFCs with specified voltage at room temperature and 75°C, have been done showing no significant degradation until 10^{10} cycles. Further investigations are still necessary, especially under relevant load parameters, like mechanical load, bending stress and harsh environmental conditions.

MFC Device	Operation voltage		Capacity	Sensor characteristic		Actuator characteristic	Generator characteristic
	V_{op}^+ [V]	V_{op}^- [V]	C_{pol} / cm ² [nF]	d_{33}^{eff} / N [pC]	d_{31}^{eff} [pC / N]	Strain / Volt. [μstrain / V]	Charge/Strain [pC / ppm]
P1	1500	-500	0,42	460	-	0,7..0,9 [0 ... 1500V]	1670 [> 100V]
P2	360	-60	4,5	-	-170	- 2 [0 ... 360 V]	3250 [< 100 V]

Table 1. showing specific capacity C_{pol} (after poling, 1 kHz, at room temperature), effective piezoelectric constant $d_{33/31}^{eff}$, strain response per voltage and charge response per strain for P1- and P2- type MFC. Updated performance data are always available from the website of Smart Material ⁴.

MFC have been also successfully tested in array structures, i.e. combining several MFC devices to a larger device with the necessary interconnect already on the device, thus allowing force coupling into larger areas and implantation of different force vectors.

3. DESIGN RULES FOR ENERGY HARVESTING SYSTEMS

Since every energy harvesting system combines two different sub-systems, a mechanical one and electrical one, both have to be designed very carefully. Only if both interfaces match their direct connected environment – the mechanical load conditions as well as the charge electronics input characteristics – a high degree and efficient harvesting of energy from environmental “waste” vibrations can be observed.

Starting with the electric part of such a harvester the question of maximum energy transfer has to be answered. Figure 2 shows the basic dipole model which is used in general to characterize electric power sources. The source with the potential U_q drives a current I through the in series connected resistors R_{in} , for the inner resistance of the power source, and R_{out} for the electric load.

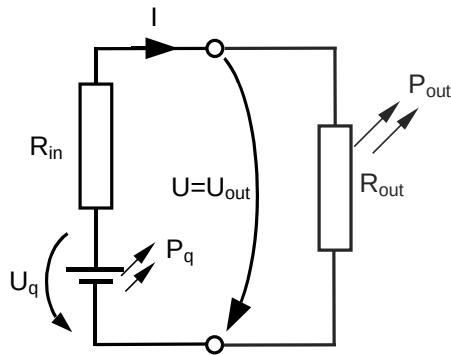


Figure 2: Dipole model for electric power sources

Based on this model the general relations for the efficiency and power transfer can be deviated. The efficiency, an expression for the power transferred into the electric load related to the total power in the source, is given in equation 1 as a function of the resistors.

$$\eta = \frac{P_{out}}{P_q} = \frac{R_{out}}{R_{in} + R_{out}} \quad \text{Eq. 1}$$

It becomes clear that by increasing the resistance of the load resistor the efficiency converges to a value of $\eta=1$. Of course real input impedances of current state-of-the-art systems for electronic charge control and collection do not meet the perfect value for a load resistor, so efficiency will be always below 1.

Another interesting point is the optimization of the power transfer from the power source into the electric load. The power which can be transferred to the load is given with equation 2, depending on the values of the resistors.

$$P_{out} = U_q^2 * \frac{R_{out}}{(R_{in} + R_{out})^2} \quad \text{Eq. 2}$$

In most cases the inner impedance of a power source is fixed so the only way to optimize the power transfer is the adaptation of the load impedance. The best energy transfer can be reached if the outer resistor has the same value like the inner one has $R_{out}=R_{in}$. A typical and well known example for power matching is the impedance of loudspeakers which has to be closely the same as the output impedance of the power amplifier.

As a second important part of energy harvester the mechanical sub-system has to be designed in a way that a high amount of the offered environmental vibrations can be used to strain the piezoelectric MFC patch. A typical and often used configuration for energy harvesting is a simple cantilever oscillator. Cantilever oscillators have a disadvantage of a non-uniform strain distribution over the length, as shown in figure 3.

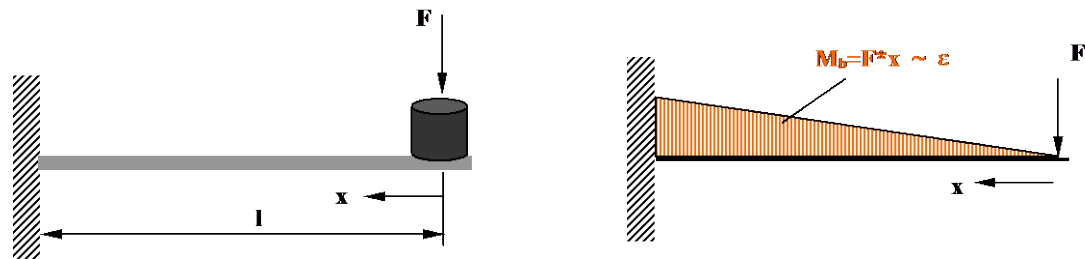


Figure 3: strain distribution of cantilevers with constant thickness

While the bending moment rises with shorter distances to the clamp the bending stiffness of the beam is constant due to the uniform thickness. As a result the strain along the top and bottom surface will increase and any attached harvester module can not use its whole potential since only a small area near to the clamp is under the full strain load.

A better performance can be achieved if one succeeds to induce strain into the MFC more uniformly. Two different ways are shown in figure 4. On the left hand side the thickness for the beam was adapted. With an increasing bending moment the structure becomes stiffer and the surface strain is closely the same along the length. A typical set-up for a four point bending test is shown on the right side. The big advantage for that type of test is a constant bending moment which leads finally to a uniform strain load for the MFC harvester patch.

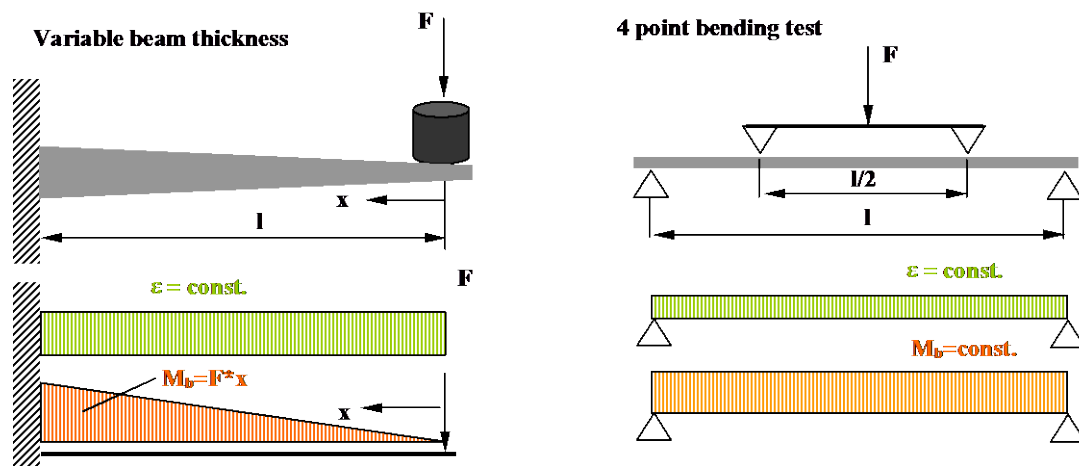


Figure 4: optimized harvester designs with uniform strain load for the generator patch

All these types of harvesters are working in a resonance mode which requires a well tuned mass/stiffness system for a high efficiency. However fact is that most mechanical vibration sources for energy generators show a broadband behaviour. Thus several harvester systems with different resonance frequencies are required to improve the total system efficacy which increase the costs for such a “multi-channel” system and probably make it economically unattractive.

A suitable and good way for a lot of real industrial energy harvesting scenarios is using an off-resonance approach utilizing MFC patches directly attached to the area of maximum strain. The MFC’s flexibility, conformability and anisotropic force coupling is making it the perfect component for such an approach. From our experience one can find always strained areas or nodes on a structure, machine or vehicle that are oscillating in a bending mode. Attaching the MFC directly to these areas or nodes allows for picking up *all* the available vibration from the structure independently of certain resonance restrictions. Applying the MFC directly to the structure requires locating the area on the structure with the highest strain first. Typical ways to achieve that is using a strain gauge or a laser vibrometer. Table 2 gives a comparison between resonator systems and directly applied MFC patches.

Table 2: Comparison resonant harvesters vs. direct working MFC patches

	resonant harvester	direct attached, non resonant MFC
Single frequency efficiency	extremely good	good
Broad band signal efficiency	low	very good
Mechanical design	complex	simple, only strain check
Packaging	large especially for low frequencies	small and thin
Cost	medium (mechanic system)	low (only MFC patch)

4. LONG TERM STABILITY RESULTS

Beside the electrical and mechanical design the selection of a suitable piezoelectric material becomes a key task in the development process for high efficient and long term stable energy harvesting systems. It is known from many experiments that mechanical overloading of PZT may cause partly or total depolarization effects. As shown in figure 6 there are major differences in the behavior of Soft and Hard PZT materials.

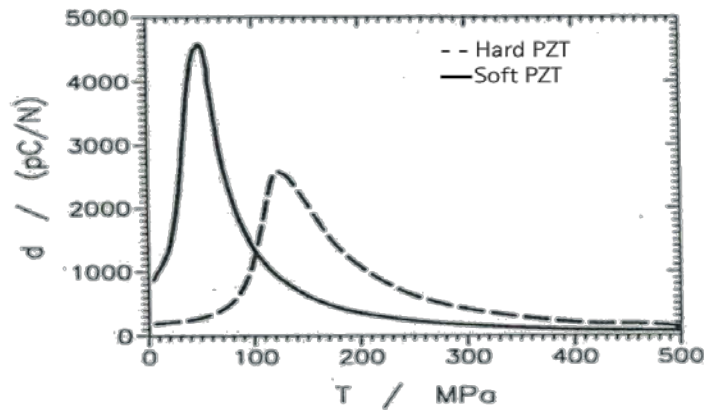


Figure 6: mechanical depolarization of Hard and Soft PZT

While the softer PZT materials offer a more than 2-times higher charge output the stability against higher mechanical loads is lower than for a hard PZT. On the other hand the diagram shows that soft PZT allows to produce output charges in the range of hard PZT with a mechanical load which is about half of the required hard PZT load and without any risk of depolarization. Against that background we conducted tests with MFCs assembled with a 5A1 material (Soft PZT) and a SP4 (Hard PZT).

Figure 7 gives the set-up for these tests. A large MFC M8557-P1 was used as actuator to realize a uniform and controllable strain level for the entire six assembled generator MFC's of the type M2814-P2.

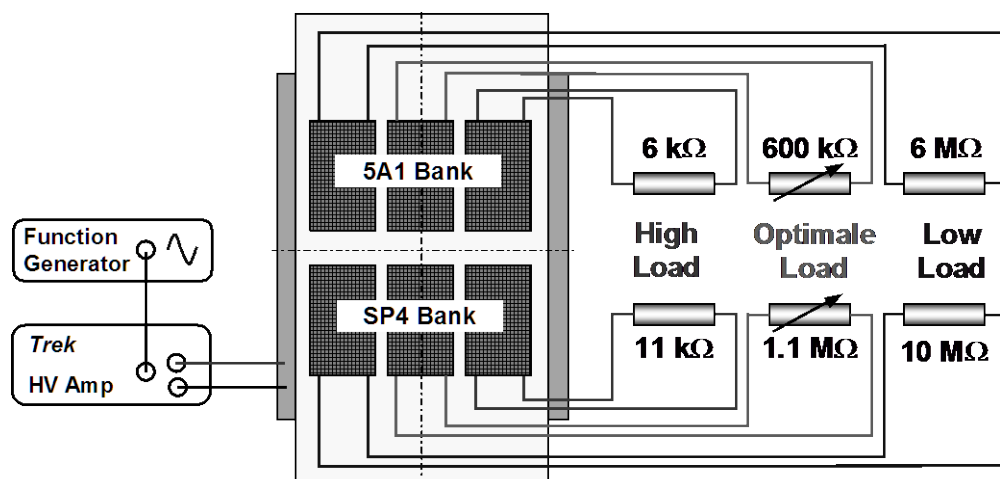


Figure 7: set-up for long term stability tests

The actuator MFC was driven with a frequency of 10 Hz. For this frequency the generator impedance was calculated from the capacity and matched with an optimal load for both PZT materials. Furthermore a higher electrical load, which was a

hundredth of the optimal load and a load resistor 10-times higher than the optimal value was added to simulate an electrical under- and overload. During the tests the strain level was increased in several steps. The results are outlined in figure 8. The RMS power output using the optimal electrical matching is extremely higher for the Soft PZT 5A1 compared with the hard SP4.

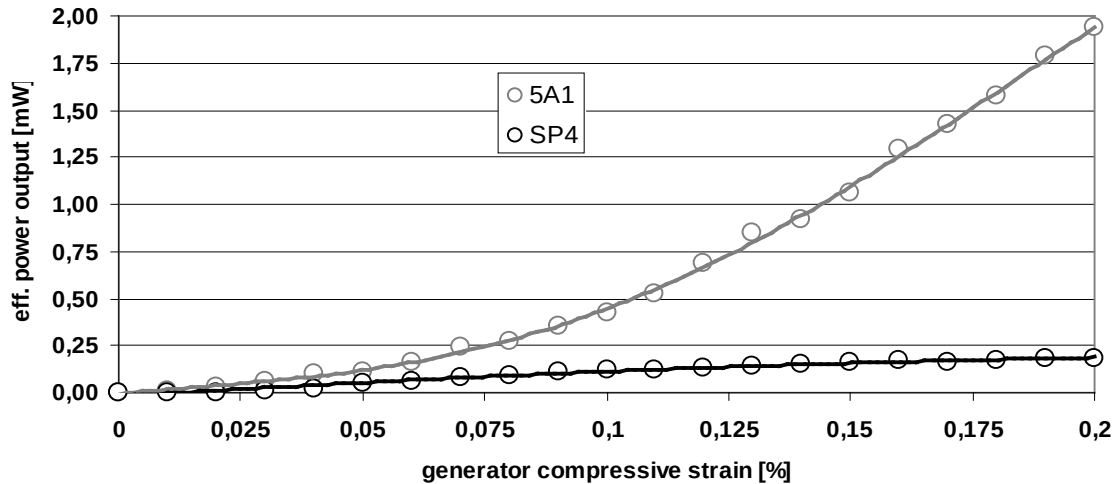


Figure 8: Power output vs. strain level (optimal electrical matching)

High strain levels will lead to high power generation but it holds the risk of increasing depolarization effects. While both materials are long term stable at 0.025% strain (over 60 million cycles) the 5A1 material starts to depolarize at 0.15% strain after 3 Mill. cycles. The SP4 acts stable in this load case for more than 30 Mill. cycles. The final test was done with a strain level of 0.2% which corresponds to a three times higher strain compared with the nominal value for that MFC type. Figure 9 shows the generator behaviour during mechanical overload. It can be shown that especially for the Soft PZT 5A1 a high mechanical load lead to a high degradation of the generated charge during the first 0.1 Mill. cycles. The reason for this finding is the depolarization of the material which was measured using an electric impedance spectroscopy after every 0.1 Mill. cycles. The SP 4 shows long term stability for the set mechanical load but the power output is with approx. 700 μ W in the same range as the softer 5A1 after the initial degradation of 0.5 Mill. cycles.

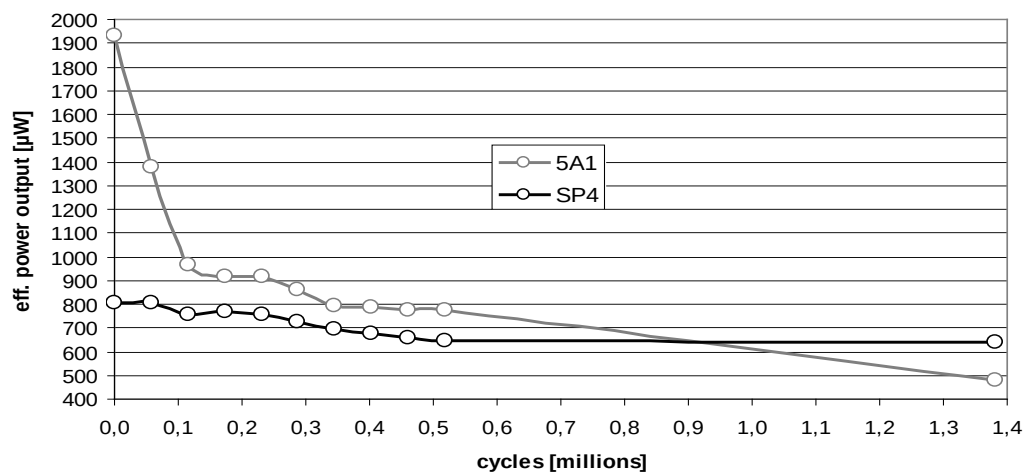


Figure 9: Power output at 0.2% strain

Looking at the total power generation at a moderate strain of 0.15% it becomes evident that even with a high initial depolarization of the softer PZT material during the first 20 Mill. cycles the total output remains still higher than a hard PZT material, as shown in figure 10. Both materials show a stable output after a period of initial depolarization.

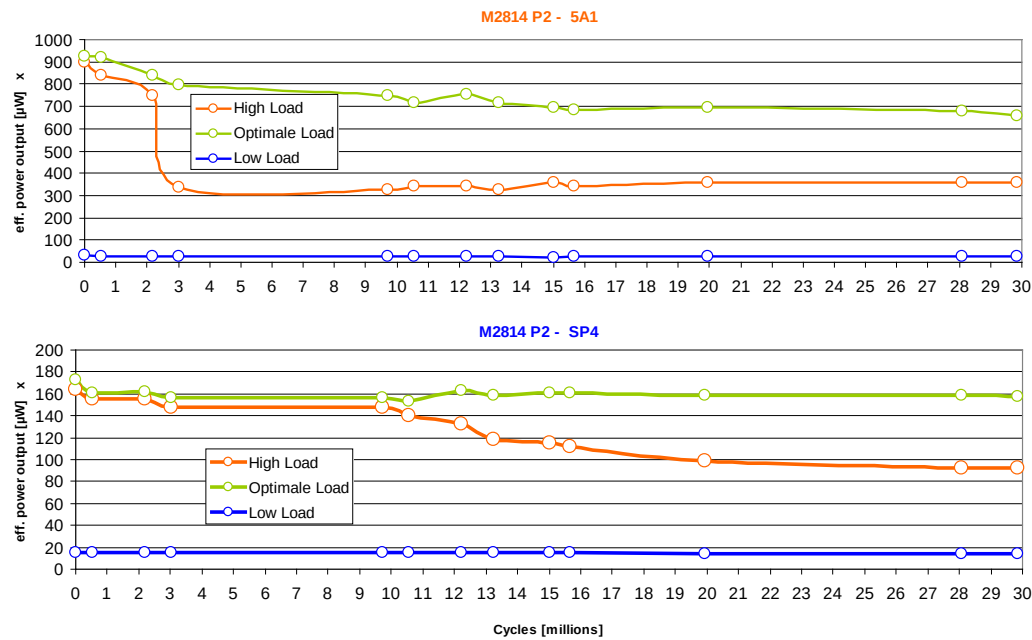


Figure 10: Power output comparison at 0.15% strain over extended number of cycles

As a conclusion both materials are suitable for high efficiency energy harvesters. The soft PZT tends to depolarize more than the hard SP4 PZT material. On the other hand the total power generated even including depolarization is higher for the softer PZT material and makes the 5A1 an excellent material for energy harvesting applications. The design-in process has to ensure that the applied strains will be within the safe range as derived from the experiments above.

5. USING MFCs FOR ENERGY HARVESTING VS. BATTERIES

Low power electronics with a consumption of less than 1 Ws have been a major application area for vibration based energy harvesting devices using piezo ceramics for some time. Monolithic piezo ceramic bi- or tri-morphs were normally used for these applications. Piezo ceramic fiber composites improve lifetime, reliability over standard piezo ceramics and allow direct attachment to the vibration source thus allowing for new cost/benefit calculations of energy harvesting devices. The P2 type MFCs have been tested for up to $> 10^{10}$ cycles at 0.1 ppm without observed failures. Assuming a structural vibration of 10Hz for harvesting the MFC would provide electric power for more than 30 years. Table 3 compares the advantages of using batteries and a complete vibration power harvester comprised of a MFC with a standard commercially available harvester electronic as provided by Advanced Linear Devices¹³ or Ambio Systems, Inc.

	MFC P2 type with EH301	Battery Li-Manganese
Lifetime 5 years +	++	+
Lifetime 10 years +	++	-
Maintenance Free	++	+
Acquisition cost	-	++
Cost incl. Maintenance	++	-
System integration	-/+	++
Wide temperature range	++	-
Self sufficient	- (vibration must be present)	++
Green Product	(+)	-
Weight	++	+

- only batteries are considered, not re-chargeable batteries due to their high discharge ratio
- temperature range for MFC -40 to 100C
- EH300 is a energy harvesting electronic, 3V output up to 200mW
- Battery is CR123
- Green product is referencing amount of non-degradable wastewaste, toxicity
- Maintenance references exchange of parts

Table 3: Comparison MFC214P2 + EH301 energy harvesting vs. standard battery

Vibration harvesters have a clear advantage over standard batteries if life time and maintenance costs are critical factors. The higher costs for the design-in and acquisition costs of an energy harvester can be offset by a longer lifetime as the overview in table 4 shows, comparing the MFC M2814P2 with the harvesting electronic against two widely available batteries. A constant power generation of 100μWs at 3V is assumed.

100μWs, 3V output 10Hz, 0.05ppm	M2814P2 MFC + EH300	CR123 1500mA/h	CR2032 230mA/h
Acquisition Cost (> 1Mill. units)	\$ 19.00	\$ 2.00	\$ 1.50
Lifetime years, calculated	30	5	0.79
cost per year	\$ 0.63	\$ 0.40	\$ 1.90
<i>Energy Harvesting is economical</i>	-	> 5 years	> 1 years
10 years with change of battery ¹ , cost per year	\$ 1.90	\$ 1.40	\$ 14.56

¹ change cost of \$10.- assumed, calculation based on 2008 costs, not accounting for battery voltage decrease with depletion, room temperature assumed

Table 4: Energy Harvester/Battery cost comparison over life time

7. BASIC DESIGN RULES FOR ENERGY HARVESTER USING THE MFC

The following check list is based on some of the results of the prior chapters and is intended to be used by design engineers for a quick assessment if an energy harvesting approach for a given vibration source is feasible.

1. Check for typical strain and frequency using strain gauge and/or laser vibrometer, locate nodes of high strain best suited to attach MFCs

2. For long life (> 10 years) best strain range for a P2 MFC is 500ppm to 1000ppm. Strain up to 1500ppm is permissible at reduced life expectancy. Maximum tensile strength is 4000ppm.
3. Best frequency range of the vibration source for low dynamic impedance (R_{in}) and life time is 5Hz to 200Hz.
4. Adjust MFC size and PZT material according to required charge generation. Due to the complex relations, we have compiled some basic charge generation estimates for the MFC
 - At 500 ppm, 10Hz, 5A1 approx. $25\mu\text{W}/\text{cm}^2$, charge generation is proportional with frequency
 - At 500 ppm, 10Hz, SP4 approx. $12\mu\text{W}/\text{cm}^2$, charge generation is proportional with frequency
5. Adjust rectifier/load balancing electronic for optimal load impedance, use of intelligent rectifier electronics like Advanced Linear Device's EH 300 series will increase the overall efficiency.

At 2008 costs, energy harvester solutions are in general a viable economical solution based on the following basic parameters:

- Applications are requiring < 10 mWs,
- Long life time is required, typical > 5 years
- Must work in a wide temperature range, i.e. -20C to +100C
- Vibration is present with deflections between approx. 50 μstrain up to 1500 μstrain and > 5Hz
- Applications with difficult access or high costs to change batteries
- Fully sealed systems

8. TYPICAL APPLICATIONS

In general all low power electronic applications with access to a sufficient environmental vibration source are suitable for energy harvesting applications. The current market trends especially in the developed countries to use alternative energy sources have fuelled a new and broad interest in energy harvesting from environmental vibrations. The new buzz word is "Cleantech", describing the use of sustainable energy sources and limiting the use of energy in general. One of the emerging large markets for piezo ceramic based energy harvesting are autonomous health monitoring or structural condition monitoring systems. Monitoring vibrations in building and aerospace structures, vehicles and many more is a known method to predict failure. The present vibration is not only used to discriminate critical structural health data but also to generate the required power for data acquisition and transmitting the data to a central computer.

Typical autonomous condition health monitoring systems including the telemetry part are consuming between 100 to 1000 μWs and are meeting all the mentioned requirements for cost effective and efficient energy harvesting system. Typical applications are health monitoring of

- airplanes, helicopters
- ships
- wind generator blades
- bridges and other high rise structure with “vibrations”
- medical devices used by patients



One of the newest application using the MFC as an energy harvesting device has been introduced by Microstrain, Inc.¹² Several MFCs are attached to the pitch link of a helicopter and are harvesting sufficient electric power during normal flight operation of the helicopter to support an attached electronic circuit which transmit important vibration information to the main on-board computer to predict failure of structural components. The complete unit, MFC with the integrated electronics and RF transmitter is fully autonomous, does not require batteries and is maintenance free.

Other important applications for MFC based energy harvesting circuits are

- Backup chargers for applications using rechargeable batteries, typical power requirements are 500 μ Ws to 1mWs for
 - Buoys
 - Active RFIDs
- “wake-up” circuits for dormant electronic circuits, typical < 100 μ Ws
 - Sealed and/or submersed Alarm systems
 - Door entries

9. CONCLUSION

The Macro Fiber Composite is highly suited to harvest energy directly from waste vibration present in the environment without additional mechanical fixtures due to its flexibility, robustness and long life time. It overcomes the disadvantages of monolithic piezo ceramic energy harvester requiring additional mechanical fixtures to transfer vibrations in a resonant and controlled setup. This allows completely new and cost effective applications for energy harvesting from structural vibration sources. The design of PZT energy harvesters requires specific and careful adaptation to each targeted vibration source for maximum efficacy. PZT energy harvester can compete with batteries in terms of overall costs in low power applications if these applications are requiring long life time and/or with difficult or impossible maintenance access, an increased operational temperature range.

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