Strain Energy Harvesting for Wireless Sensor Networks

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ABSTRACT

Our goal was to demonstrate a robust strain energy harvesting system for powering an embedded wireless sensor network without batteries.

A composite material specimen was laminated with unidirectional aligned piezoelectric fibers (PZT5A, 250 um, overall 13x10x.38 mm). The fibers were embedded within a resin matrix for damage tolerance (Advanced Cerametrics, Lambertville, NJ). A foil strain gauge (Micro-Measurements, Raleigh, NC) was bonded to the piezoelectric fiber and shunt calibrated. The specimen was loaded in three point cyclic bending (75 to 300 $\mu\varepsilon$ peak) using an electrodynamic actuator operating at 60,120, and 180 Hz.

Strain energy was stored by rectifying piezoelectric fiber output into a capacitor bank. When the capacitor voltage reached a preset threshold, charge was transferred to an integrated, embeddable wireless sensor node (StrainLink, MicroStrain, Inc., Williston, VT). Nodes include: 16 bit A/D converter w/ programmable gain and filter, 5 single ended or 3 differential sensor inputs, microcontroller w/16 bit address, on-board EEPROM, and 418 MHz FSK RF transmitter. Transmission range was 1/3 mile (LOS, 1/4 wavelength antennas, 12 milliamps at +3 VDC). The RF receiver included EEPROM, XML output, and Ethernet connectivity. Received data from network nodes are parsed according to their individual addresses.

The times required to accumulate sufficient charge to accomplish data transmission was evaluated. For peak strains of 150 $\mu\varepsilon$, the time to transmit was 30 to 160 seconds (for 180 to 60 Hz tests).

Keywords: strain, energy, harvesting, piezoelectric, sensors, RF, MEMs

1. INTRODUCTION

This work was aimed at developing a new class of sensing systems that can wirelessly report data without the need for batteries. Instead, they will rely on harvesting vibration or strain energy from the local environment for power. These will allow machines and structures to be monitored without the need for a battery maintenance schedule. Truly smart structures and machines will be able to autonomously report their conditions throughout their operating life.

Advanced sensing technology continues to evolve at a rapid pace, and the next generation of smart structures, machines, and materials can and will benefit from present and future developments[i]. Sensors, signal conditioners, processors, and digital wireless radio frequency (RF) links continue to become smaller, consume less power, and include higher levels of integration. The combination of these elements is key to providing sensing, acquisition, storage, and reporting functions. Wireless networks coupled with intelligent sensors and distributed computing enable a new paradigm of machine monitoring[ii].

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Wireless sensors have the advantage of eliminating wiring installation expense as well as connector reliability problems. However, wireless sensors still require system power in order to operate. If power outages occur, critical data may be lost. In some cases, sensors may be hardwired to an existing power system. Doing so, however, defeats the advantages of wireless sensors and may be unacceptable for many applications. Most prior wireless structural monitoring systems have relied on continuous power supplied by batteries. For example, in 1972, Weiss developed a battery powered inductive strain measurement system, which measured and counted strain levels for aircraft fatigue[iii]. The disadvantage of traditional batteries, however, is that they become depleted and must be periodically replaced or recharged. This constitutes an additional maintenance task that must be performed.

Given the limitations of battery power, there is a need for systems which can operate effectively using alternative power sources. In this work, we have begun to develop wireless sensing network systems which can harvest energy from the local environment to provide the power needed for operation. Such systems would be truly "wireless" in that they would not require traditional batteries.

There are several devices on the market which allow mechanical energy in the local environment to be converted into electrical energy, such as the Seiko "Kinetic" watch, and AM/FM mechanical wind-up radios ("Model ICF-B200", Sony Corp). These systems do not automatically record data from sensors. The MIT media laboratory is developing systems using PZT materials mounted in a shoe to harvest the energies of human activity. They reported on prototype development of radio frequency identification (RFID) tags which are self powered by a pair of sneakers[iv] (http://computer.org/micro/homepage/may_june/shenck/index.htm). A recent report by Meniger et al., entitled "Vibration-to-Energy Conversion", discloses a microelectromechanical system (MEMs) device for the conversion of ambient mechanical vibration into electrical energy through the use of a variable capacitor[v] http://www.kric.ac.kr:8080/pubs/articles/proceedings/dac/313817/p48-meninger/p48-meninger.pdf . However, these MEMs systems only demonstrated 8 microwatts of power. Transmission of RF data over distances of 20 feet or more requires milliwatt power levels.

There are numerous sources of ambient energy that could be exploited for energy scavenging or energy harvesting systems. Candidates include solar energy, wind energy, thermoelectric energy, water/wave/tide energy, and strain energy. For many applications, especially those indoors and in industrial environments, the best option is strain energy harvesting. Such energy would be present wherever machinery or structures are exposed to cyclic strains. Piezoelectric elements bonded to the surfaces of such structures would convert the strain energy to electrical energy which can be collected and stored.

Recent developments in single crystal Piezoelectric materials have led to significant improvements in the mechanical-to-electrical conversion coefficients (coupling coefficients), from 0.6 (60% efficiency) to 0.9 (90% efficiency). Single crystals also exhibit higher operating strain capabilities than conventional PZT materials (.2% vs. 1.4 %) . These materials are available through TRS Ceramics (State College, PA http://trsceramics.com/Single_Crystal.pdf). Furthermore, PZT fibers have recently been made commercially available at low cost for active damping of sporting equipment, such as baseball bats, tennis rackets, and skis (Advanced Cerametrics, Lambertville, NJ, http://www.advancedcerametrics.com/piezo_fiber.html). These fibers may be directly bonded to a straining element or structure to generate electrical energy that can be harvested. Major advantages of these fiber piezoelectric materials is that they can tolerate the loss of many individual fibers in a bundle and still function well. Since they are in mass production, they may be obtained readily and at relatively low cost. For these reasons, we focused our efforts in this work towards the use of these PZT materials for energy harvesting wireless sensor networks.

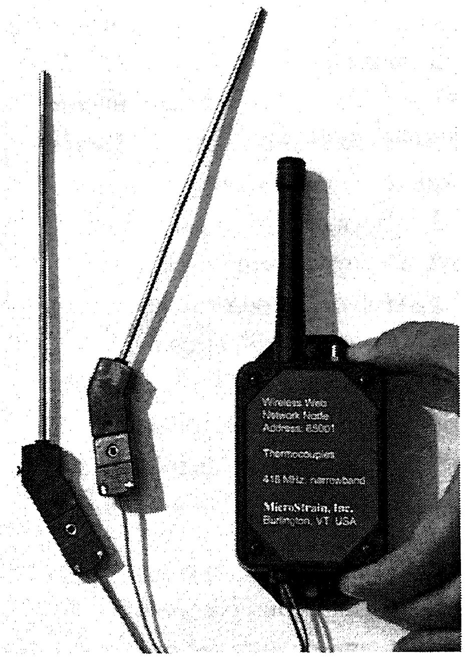


Figure 1 MicroStrain's WWSN sensor node shown with two thermocouple sensors as inputs.

In order to perfect a sensing solution which exploits energy harvesting, the entire system must be considered. The power consumed by all of the system's components (sensor, conditioner, processor, data storage, and data transmission) must be compatible with the energy harvesting strategy and the available power levels. Obviously, minimizing the power required to collect and transmit data correspondingly reduces the demand on the power source. Therefore, minimizing power consumption is as important a goal as maximizing power generation.

Many techniques are available for minimizing the power consumed by sensors. For example, we have previously reported on micro-miniature differential variable reluctance transducers (DVRT's) capable of completely passive (i.e., no power) peak strain detection to 25 $\mu\varepsilon$ resolution[vi]. These sensors can be embedded in a material, for example, and will continuously monitor for the existence of a damaging strain state[vii]. Recent improvements allow the sensors to withstand harsh environmental conditions (moisture, salt, and vibration), and to be reset remotely using shape memory alloys and (remotely applied) magnetic field energy. We have also recently developed totally passive strain accumulation sensors, which can be used to monitor fatigue. Furthermore, we have demonstrated novel radio frequency identification (RFID) circuits with the capability of interrogating these sensors in under 50 microseconds using less than 5 microamperes of current.

The power required by the network system must also be minimized. One strategy for accomplishing this is demonstrated by MicroStrain's WWSN network architecture (Fig 1). This is an "ad hoc" network that allows thousands of multichannel, microprocessor controlled, uniquely addressed sensing nodes to communicate to a central, Ethernet enabled receiver with extensible markup language (XML) data output format[viii] (http://www.microstrain.com/WWSN.html). A time division multiple access (TDMA) technique is used to control communications. This saves power because the nodes are in sleep mode most of the time. Individual nodes wake up at intervals determined by a randomization timer, and transmit bursts of data. By conserving power in this manner, a single Lithium Ion AA battery can be employed to report temperature from five thermocouples every 30 minutes for a period of five years. The XML data format has the advantage of allowing any user on the local area network (LAN) to view data using a standard Internet browser, such as Netscape or Internet Explorer. Furthermore, a standard 802.11b wireless local area network (WLAN) may be employed at the receiver(s) end in order to boost range and to provide bi-directional communications and digital data bridging from multiple local sensing networks that may be distributed over a relatively large area (miles).

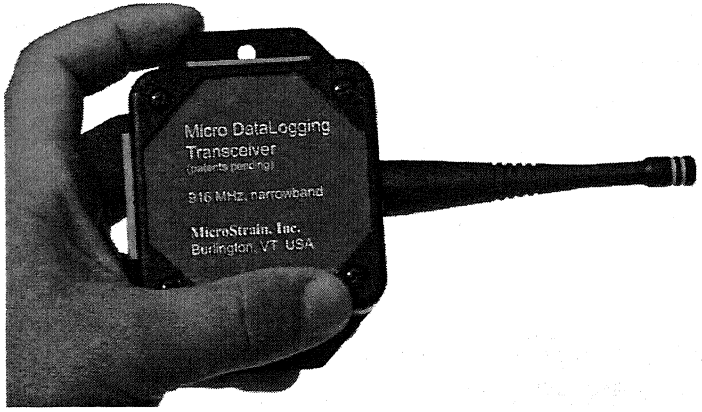


Figure 2. MicroStrain's DataLogging Transeiver node.

Another strategy for creating low power wireless sensor networks is demonstrated by MicroStrain's DataLogging Transeiver network (http://www.microstrain.com/DataLoggingTransceiver.html) (Fig 2). This system employs addressable sensing nodes which incorporate datalogging capabilities, and a bi-directional RF transceiver communications links.[ix] A central host orchestrates sample triggering and high speed logging to each node or to all nodes. Data may be processed locally (such as frequency analysis) then uploaded when polled from the central host. By providing each sensor node with a 16 bit address, as many as 65,000 multichannel nodes may be hosted by a single computer. Since each node only transmits data when specifically requested, the power usage can be carefully managed by the central host.

Our long term goal is to combine energy harvesting capability with low power sensors and low power network systems to produce a completely wireless sensor network which can be deployed easily in the field, and which can operate completely unattended for long periods (Fig 3).

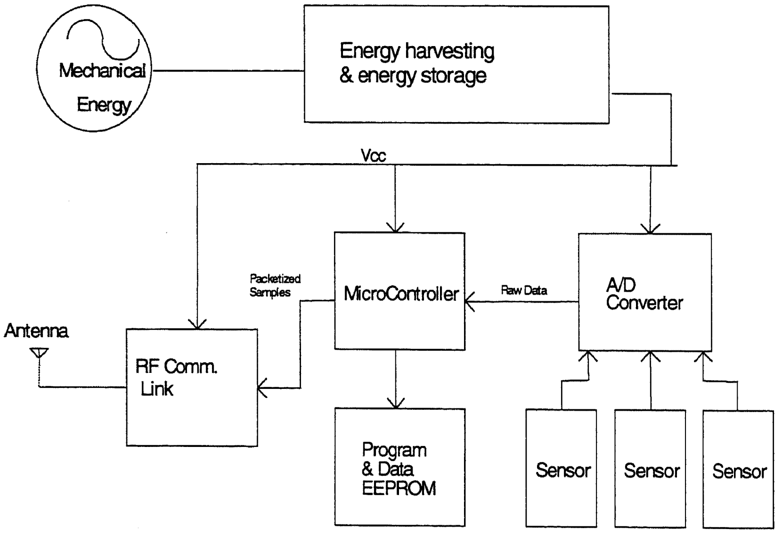


Figure 3 Functional diagram of proposed energy harvesting, sensing, data conversion, processing, & wireless communications system.

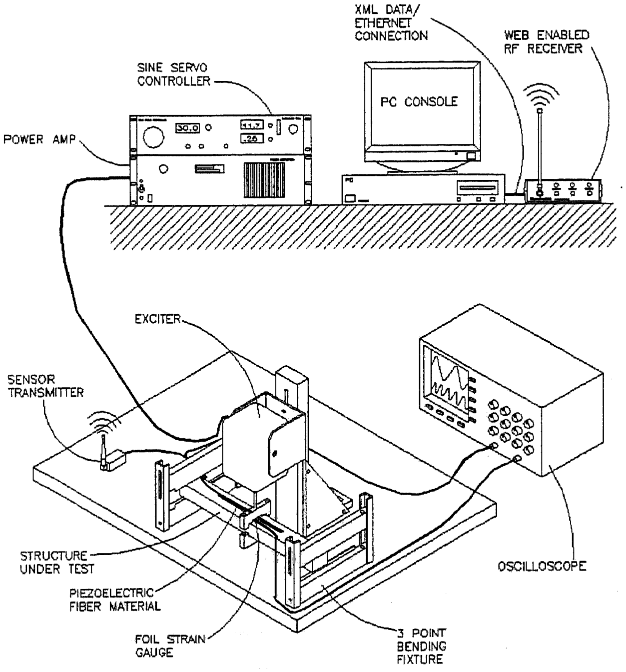
2. OBJECTIVES

Our goal was to design and construct a wireless sensing node capable of harvesting strain energy to provide power for the transmission of digital data to a remote receiver. The design criteria for the wireless sensing nodes were:

1) Capable of deployment of over 1000 nodes, using one RF transmission frequency to one receiver
2) Small size, easy to place in the field
3) Low production cost
4) Compatible with almost any sensor
5) Capable of automated Internet data delivery
6) Low power
7) Long transmission range

3. METHODOLOGY

A piezoelectric element consisting of unidirectionally aligned, 250 micron diameter PZT fibers embedded in a resin matrix was utilized (PZT5A, Advanced Cerametrics, Lambertville, NJ). It's overall dimensions were 0.38mm in thickness, and 130 x 13mm in length and width. This element was bonded to the surface of a composite beam test specimen (Fig 4). To record applied strains, a foil strain gauge (Micro-Measurements, Raleigh, NC) was bonded on top of the piezoelectric element at its center, and shunt calibrated.



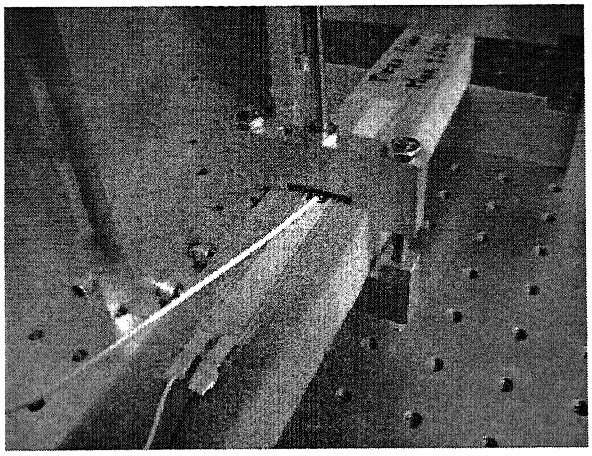


Figure 4. Schematic of strain energy harvesting system (left). Photograph of beam in three point bending with fiber PZT element bonded to surface (above).

The specimen was loaded in three point cyclic bending at 60,120, and 180 Hz using an electrodynamic actuator. The separation between the fixed loading points was 300mm. Due to the three point bending configuration, this exposed the PZT element to a non-uniform strain field with a maximum located at the center of the element, and diminishing linearly towards the ends. The strain at each end of the active area of the PZT element was 42% of the peak value at the center.

During cyclic bending, the PZT element converted the applied strain energy into electrical output. This output was connected to an energy harvesting and storage circuit consisting of a rectifier whose output was connected to a 47 µF storage capacitor (Fig 5). A critical concept in optimal system operation is to keep the electrical load (in this case a StrainLink Transmitter) in an "off" state until such time as there is adequate energy stored in the capacitor. In order to accomplish this, we used battery management circuits and adapted them for this purpose. An extremely low power "nano-amp" comparator (Linear Technology, Milpitas, CA, part number LTC1540) was employed as a voltage sensing switch to provide power management for the system. It draws only 350 nA quiescent current and can source 40mA at the output pin. This comparator also has a built-in reference supply of 1.182 volts which was used to drive a voltage divider to set the turn-on and turn-off thresholds.

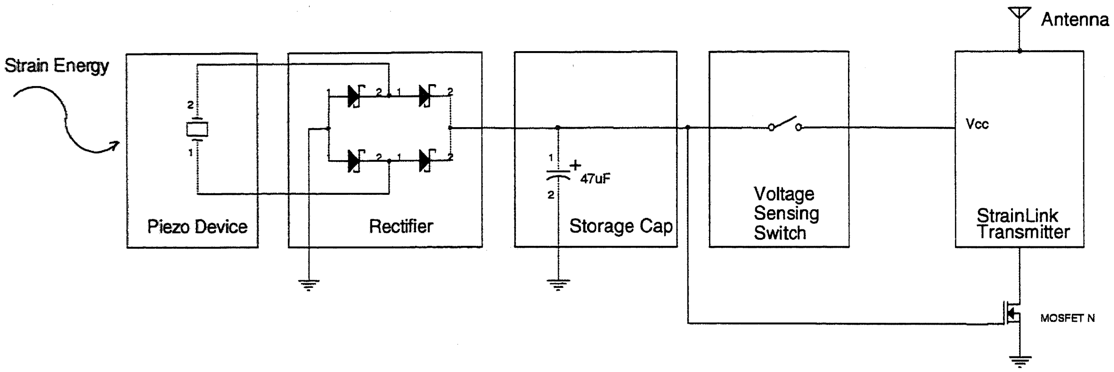


Figure 5 Electrical schematic of energy harvesting circuit powering StrainLink wireless sensor node.

This switch was normally in an open state while the storage capacitor was being charged. Once the capacitor voltage reached a preset threshold, the switch closed, allowing the stored energy to flow to the load. This technique insured that while electrical energy was being generated by the piezoelectric transducer and stored, the rest of the system did not attempt to draw power.

As soon as the storage capacitor voltage reached the turn-on threshold of 9.5V, the switch closed, and the charge was used to temporarily power an integrated, embeddable wireless sensor node (StrainLink, MicroStrain, Inc., Williston, VT). The StrainLink includes a 16 bit A/D converter w/ programmable gain and filter, 5 single ended or 3 differential sensor inputs, microcontroller w/16 bit address, on-board EEPROM, and 418 MHz FSK RF transmitter. Its transmission range is 1/3 mile (LOS, 1/4 wavelength antennas, 12 milliamps at +3 VDC). The corresponding RF receiver includes EEPROM, XML output, and Ethernet connectivity. Received data from network nodes are parsed according to their individual addresses so that multiple transmitters can be used with a single receiver base station.

Once supply voltage was provided to the StrainLink, its on-board regulator provided a high level signal to the reset controller, which in turn, powered up the micro controller (MicroChip Technologies, Chandler, AZ, PIC16C series). The micro controller powered up its sensor channels, read the signals from the on-board analog-to-digital converter (Analog Devices, Norwood, Mass, part number AD7714), and transmitted (by frequency shift keyed pulse code modulation of the narrowband radio frequency oscillator) these sensor data and/or alarm status, along with the unique 16 bit identification (ID) code, to the receiver. The transmitter remained powered-up until the voltage in the energy storage capacitor was drawn down to 2.5V, at which point the switch turned off again, de-powering the StrainLink.

Under conditions where the piezoelectric element is exposed to continuous cyclic strains, the action of the voltage sensing switch causes enough power to be periodically applied to the StrainLink transmitter to transmit sensor data. The time between transmissions, (i.e., the time required to charge the storage capacitor from 2.5 to 9.5 V) was used as the primary outcome measure in this work. This is essentially equivalent to the inverse of the rate at which energy is harvested by the system.

4. RESULTS

The time interval between transmissions is shown as a function of frequency and peak applied strain in Figure 6. For moderate strain levels of 150µε, the time to transmit was between 30 and 160 seconds (for 180 to 60 Hz tests). This implies that a sensor node in such a setup could report its sensed data to some central host at a time interval of as short as 30 seconds. Using higher strain levels reduced this to as little as 15 seconds. Still higher strain levels would be expected to further reduce the time, but could not be tested due to limitations of our electrodynamic shaker.

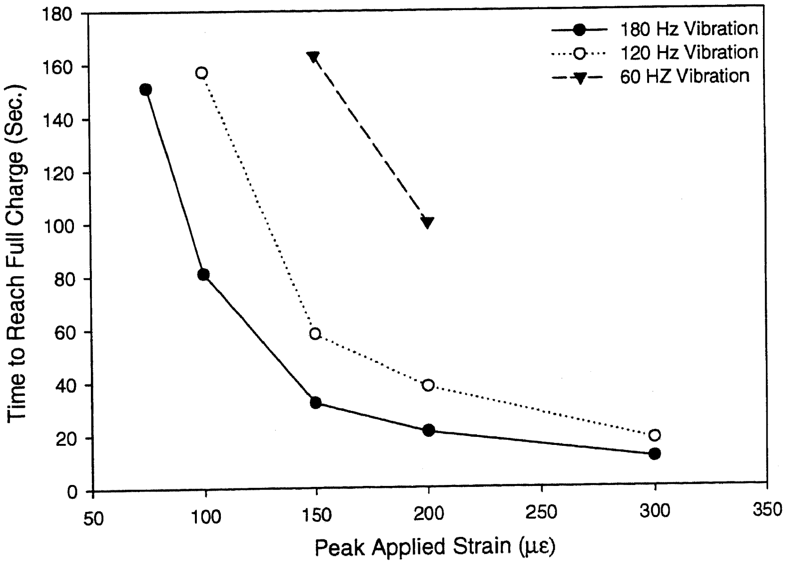


Figure 6 Experimentally measured charging times (time between transmissions) for strain energy harvesting demonstration. "Full Charge" was defined as the point at which enough energy was available to power a StrainLink transmitter and transmit valid data.

Once the storage capacitor was charged, it had sufficient energy to power the StrainLink transmitter for approximately 250msec. This is adequate to collect valid data from several sensors and transmit it with four to seven times redundancy.

At a vibration frequency of 180Hz, the system was able to repeatedly charge the storage capacitor using applied strains of between 75 and 300με. As the driving frequency was reduced, the minimum applied strain at which the system operated successfully increased (100με for 120Hz, and 150με for 60Hz). This implies that there is some leakage of energy even when the switch is in the off state. The leakage current of the capacitor is the primary contributor to this effect. Unless the energy is harvested at a rate higher than this leakage, the charge on the storage capacitor will not increase.

The data can also be expressed in terms of the power generating capability of the PZT element in combination with the energy harvesting circuit (Fig 7). Viewing the data in this form suggests that the rate of energy storage (i.e., output power) is approximately proportional to applied strain. In addition, uniform spacing between the individual traces suggests that the output power is approximately proportional to the applied frequency. Both of these findings are expected.

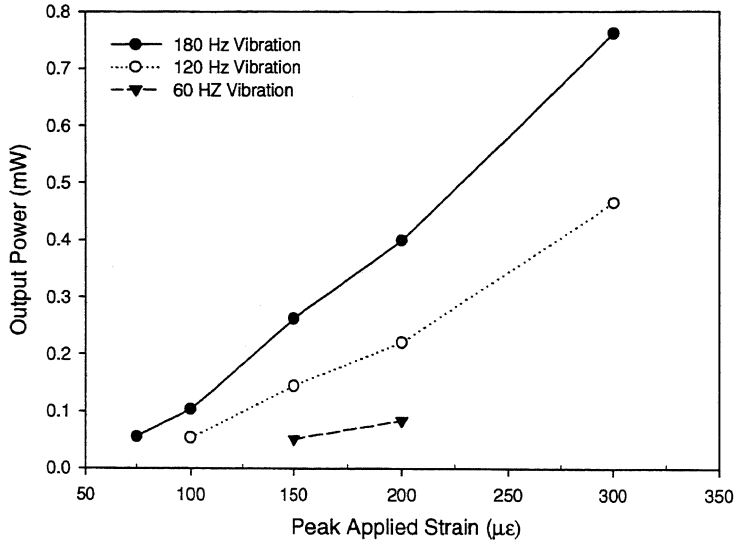


Figure 7. Output power of the PZT element in combination with the described energy harvesting circuit.

5. DISCUSSION

This work demonstrates the feasibility of a useful wireless sensor node whose power is derived solely from cyclic strain (vibration) in the local environment. The strain levels utilized (75 to 300με) are well within the range of what would be commonly expected in an industrial environment. Furthermore, the size of the required PZT element (less than 17 cm^2) should be quite acceptable in a majority of applications.

The size of the energy storage capacitor can be adjusted to provide different power levels to the load. For example, if a particular sensor requires a substantial startup time, then a larger capacitor could be used so that power could be applied for a sufficient interval. The trade-off would be that the charging time would be correspondingly longer. Alternatively, it may be possible to utilize a rechargeable battery in place of the capacitor.

These strain energy harvesting methods may be deployed with smart autonomous, self powered wireless sensor networks for monitoring of cyclically strained structures in aerospace, automotive, civil, and medical applications. We envision these systems, for example, applied to condition based maintenance and health monitoring of aircraft, helicopters, vibrating machines, and the next generation of smart tires.

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