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Power Generation in Pipeline: Report

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Power Generation in Pipeline

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Executive Summary

This report is an exploration of the possibility of power generation in a natural gas pipeline due to the flow of the gas itself. It is shown that the flow of gas can produce vibration in the pipeline (i.e., pipe wall) that can be tapped as a source of energy. This vibration energy can be converted into electrical power (~ a few mW) for operating low power electronic devices. Modern electronic devices can operate at 10's -100's of μW of power. It should be possible to gradually build up electrical power and store in a capacitor till a threshold value is reached when the power is drawn from the electronics. In situations where it is not necessary to have continuous operation of a sensor or device, this type intermittent power at regular interval may suffice. A brief survey of commercial systems available for energy harvesting (i.e., converting vibration into electrical power) is also presented.

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Power Generation in Pipeline

BACKGROUND

Technology plays a significant role in assuring infrastructure integrity and reliability. While it is not the sole answer, it plays a major role in many critical areas. There are significant areas where relevant technology development can have a major role in providing public-sector benefits. Our national gas infrastructure is both vast and varied. Materials used in construction of pipeline, age, and location are major variables. The ability to inexpensively and efficiently monitor and assess pipeline integrity and status would provide improved means for service-life prediction and defect detection to ensure operational reliability. For any type of sensor required for monitoring, one invariably needs a power source, both for operating the sensor and also for transmitting the information to some central location. Currently, one relies on batteries to supply the required power. Unfortunately, batteries need to be replaced on a regular basis and this adds to the maintenance cost. The ability to operate sensors without using batteries would enhance pipeline surveillance significantly.

Modern sensors that can be attached to a pipeline for monitoring structural integrity, do not often use a lot of power for their operation. In addition, it is not necessary to operate these sensors continuously. Even once a day data gathering and transmission may be sufficient. In such situations, the power requirement is quite modest and it is possible to generate this power from the pipeline itself. This report addresses the technical merit for the development of a passive power generation approach that requires no maintenance (or periodic replacement) and is sufficient for operating modern sensors that meet future requirements.

INTRODUCTION

In an operating natural gas pipeline, gas flows through the pipeline under pressure. Flow of a gas through a pipe generates flow-induced vibration and there are several mechanisms for it. Essentially, some of the energy in the gas flow dissipates as mechanical vibration in the pipe. This energy is typically lost to the environment both as heat and also as vibration. It is possible to convert some of this lost vibration into usable electrical energy. So there are two main aspects to this issue: (1) generation of vibration in a small section of a pipe, and (2) conversion of this vibration into electrical power. Let's discuss each of these issues in the order mentioned.

Flow-induced vibration

This is a problem that has been studied extensively for decades because of its deleterious consequences in various industries. For example, structural failure due to flow-induced vibration is a common problem affecting the performance and reliability of heat exchangers. It is estimated that electric utility industries spend thousands of dollars every year in repair or replacement of tubes in steam generators and other heat exchangers damaged by vibrations. Under certain conditions fluid flow inside a pipe can initiate vibrations of the pipe. If the vibration intensity is large enough, pipes can strike against each other or against their supports causing structural fatigue or complete failure. Flow-induced vibration also occurs in transcontinental oil pipelines causing damage of support structure or cracks of the pipelines leading to costly shutdown. In marine applications, pipes can start to vibrate in the presence of external cross-flow of water caused by ocean current. Component failures due to excessive flow-induced vibrations continue to affect the performance of nuclear power plants. Such failures are very costly in terms of repairs and lost production. Generally, the problems caused by excessive vibration are fatigue cracks and fretting-wear damage. Considerable progress has been made in the area of flow-induced vibration since the early seventies. Vibration excitation mechanisms in single- phase (liquid or gas) flows are now reasonably well understood. In most industries, the flow-induced vibration is a nuisance and a lot of effort is made to dampen or counter such vibrations. The focus of this report is to take advantage of these vibrations and not as much to focus on the various mechanisms of vibration. Turbulent flow and acoustic resonance contribute to flow induced vibration in a pipeline to a large extent although the mechanisms are not limited to these two.

Vibration excitation may be induced by turbulence. Turbulence can be generated locally by the gas as it flows through the pipe. This is called near-field excitation. Alternatively, far-field excitation can be generated by upstream components such as inlet nozzles, elbows and other piping elements. Turbulence-induced excitation generates random pressure fluctuations around the inner surface of the pipe forcing it to vibrate.

Acoustic resonance can also occur in axial flow, e.g. in the main flow line of natural gas pipeline. Acoustic pressure pulsations originating from the pumps or acoustic noise generated by piping elements such as valves can promote acoustic resonance in a receptive section of the piping system. If the acoustic resonance frequency is close to that of the structure, large vibration amplitudes may occur.

The amount of vibration that is induced in a pipeline depends of many parameters including flow rate, pressure, temperature, nature of the gas, the pipe geometry, presence of objects inside, etc. It is nontrivial to figure out how much energy is actually converted to vibration in a pipeline because of the number of factors that is involved. A reasonable estimate is a few mW per sensor of dimension 3 x 3 cm square surface area for a typical flow in a 6-inch diameter pipe. It will be assumed, based on the arguments presented above in terms of generation of flow-induced vibration, that there is sufficient energy available for harvesting for specialized applications. The primary focus of this report is to explore the possibility of such energy harvesting and how it can be done. The reason for such energy harvesting is to provide sufficient power for sensor electronics for monitoring purposes. As mentioned earlier, this monitoring need not be continuous thus reducing the power needs for electronics. The next section will describe the energy harvesting approaches.

Conversion of Vibration to Electrical Power

Energy harvesting is defined as the conversion of ambient energy into usable electrical energy. When compared with the energy stored in common storage elements, like batteries and the like, the environment (e.g., flow induced vibration in a natural gas pipeline) represents a relatively inexhaustible source of energy. Consequently, energy harvesting (i.e., scavenging) methods must be characterized by their power density, rather than energy density. An energy harvesting device generates electric energy from its surroundings (e.g., ambient vibration) using some method of what is called in the literature Direct Energy Conversion techniques. Therefore, the energy harvesting devices do not consume any fuel or substance, so that there is no associated maintenance problem. There are three main approached to converting vibration to electricity and these are Piezoelectric, Electrostatic, and Electromagnetic.

Vibration Energy: Energy extraction from vibrations is based on the movement of a "spring-mounted" mass relative to its support frame [1]. Mechanical acceleration is produced by vibrations that in turn cause the mass component to move and oscillate (kinetic energy). This relative displacement causes opposing frictional and damping forces to be exerted against the mass, thereby reducing and eventually extinguishing the oscillations. The damping forces literally absorb the kinetic energy of the initial vibration. This energy can be converted into electrical energy via an electric field (electrostatic), magnetic field (electromagnetic), or strain on a piezoelectric material. These energy-conversion schemes amount to harvesting energy from vibrations.

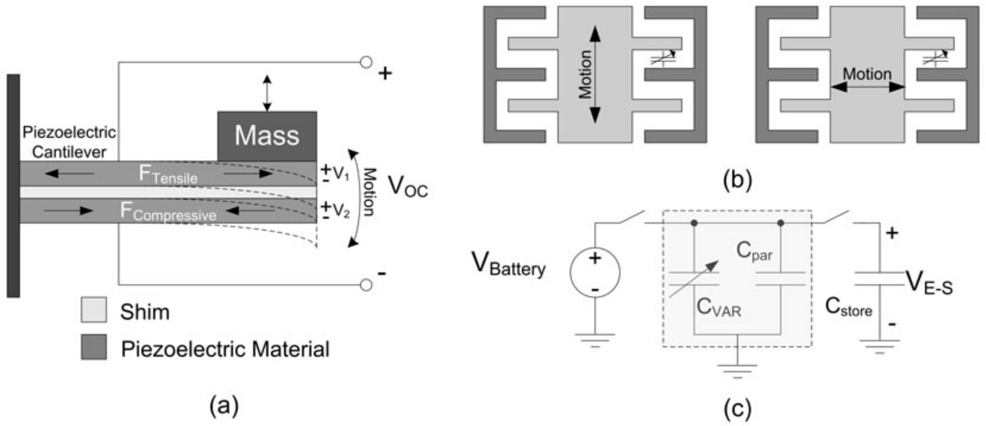


Figure 1. Piezoelectric and Electrostatic Energy Conversion

Piezoelectric energy harvesting converts mechanical energy to electrical by straining a piezoelectric material [1-3]. Strain, or deformation, in a piezoelectric material causes charge separation across the device, producing an electric field and consequently a voltage drop proportional to the stress applied. The oscillating system is typically a cantilever beam structure with a mass at the unattached end of the lever, since it provides higher strain for a given input force [1, 2] - see Figure 1a. The voltage produced varies with time and strain, effectively producing an irregular ac signal. Piezoelectric energy conversion produces relatively higher voltage and power density levels than the electromagnetic system.

Electrostatic (capacitive) energy harvesting relies on the changing capacitance of vibration-dependant varactors [1, 4-5]. A varactor, or variable capacitor, is initially charged and, as its plates separate because of vibrations, mechanical energy is transformed into electrical energy (Figures 1b and 1c). The most attractive feature of this method is its IC-compatible nature, given that MEMS variable capacitors are fabricated through relatively mature silicon micro-machining techniques. This scheme produces higher and more practical output voltage levels than the electromagnetic method, with moderate power density.

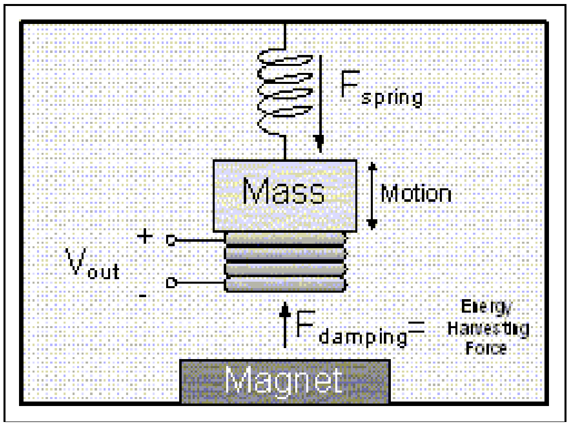


Figure 2. Electromagnetic vibration energy harvester

Electromagnetic energy harvesting uses a magnetic field to convert mechanical energy to electrical [6-7]. A coil attached to the oscillating mass traverses through a magnetic field that is established by a stationary magnet. The coil travels through a varying amount of magnetic flux, inducing a voltage according to Faraday's law (Fig. 2). The induced voltage is inherently small and must therefore be increased to viably source energy. Methods to increase the induced voltage include using a transformer, increasing the number of turns of the coil, and/or increasing the permanent magnetic field. However, each is limited by the size constraints of a microchip.

The power generation capacities is the highest for Piezoelectric (~ 200 μW/ cm^2), followed by Electrostatic (50-100 μW/ cm^2), and finally for Electromagnetic it is (<1 μW/ cm^3). Because of this, we had decided to focus primarily on the piezoelectric power conversion in our study.

We started with a novel approach for piezoelectric power conversion where instead of a cantilever as traditionally, we decided to use a hollow piezoelectric cylinder. The following is a picture of the experimental set up used in our studies.

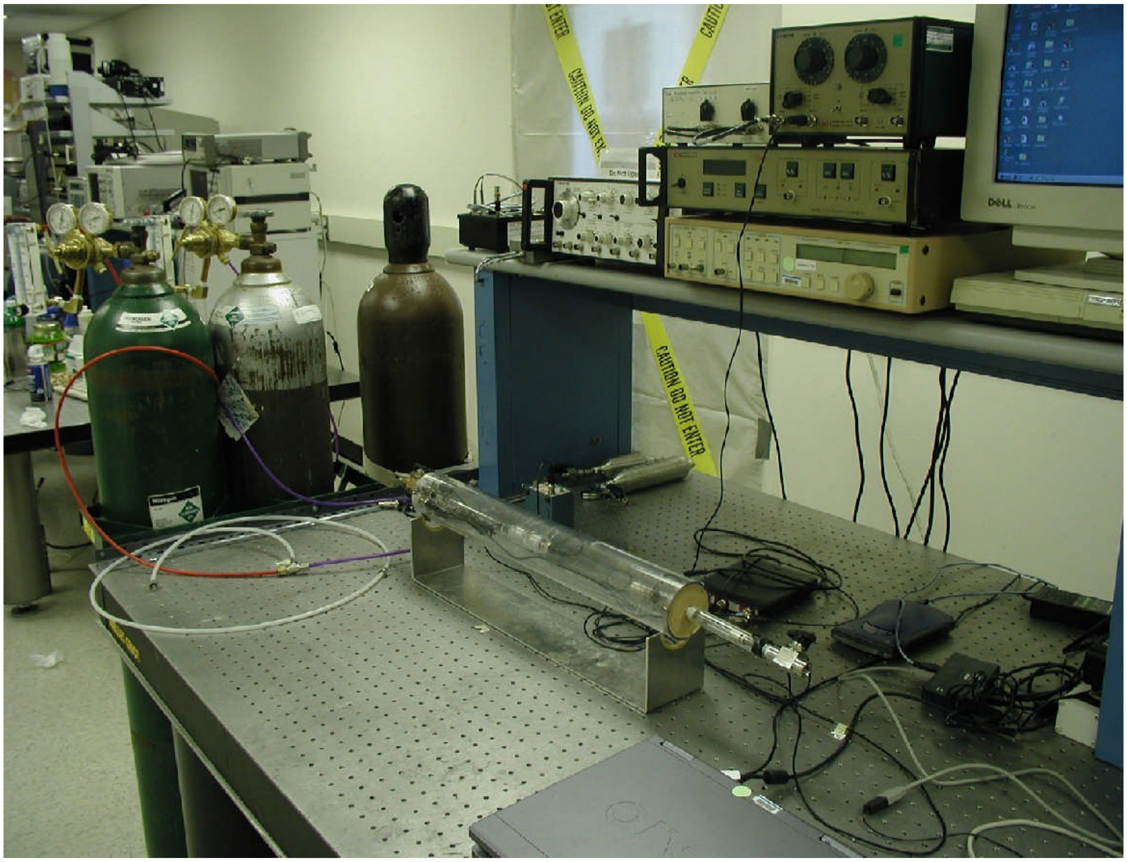


Figure 3. Experimental set up. Nitrogen gas was used to flow through a Plexiglas pipe (8 cm diameter), with various piezoelectric cylinders placed inside the pipe.

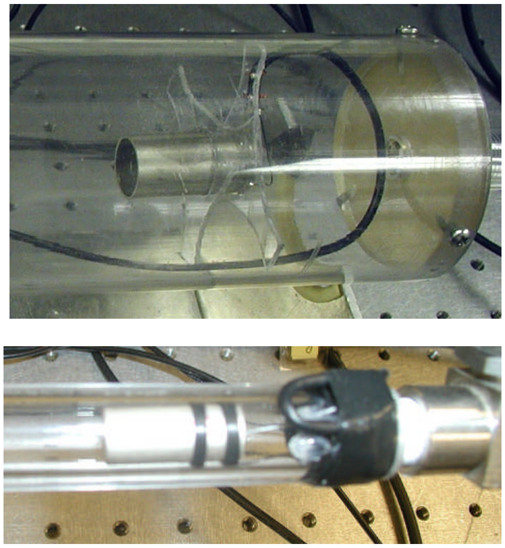


Figure 4. Two different piezoelectric cylinders are shown in the figures on the right. The top one is of 2-cm diameter and 4 cm in length while the bottom one is 1 cm in diameter and 2.5 cm in length.

The piezoelectric cylinders were off-the-shelf commercial items. We found that both types of cylinders, one made from PZT material and the other one from piezofilm worked quite efficiently and provided signal output of tens of mV even with modest flow levels.

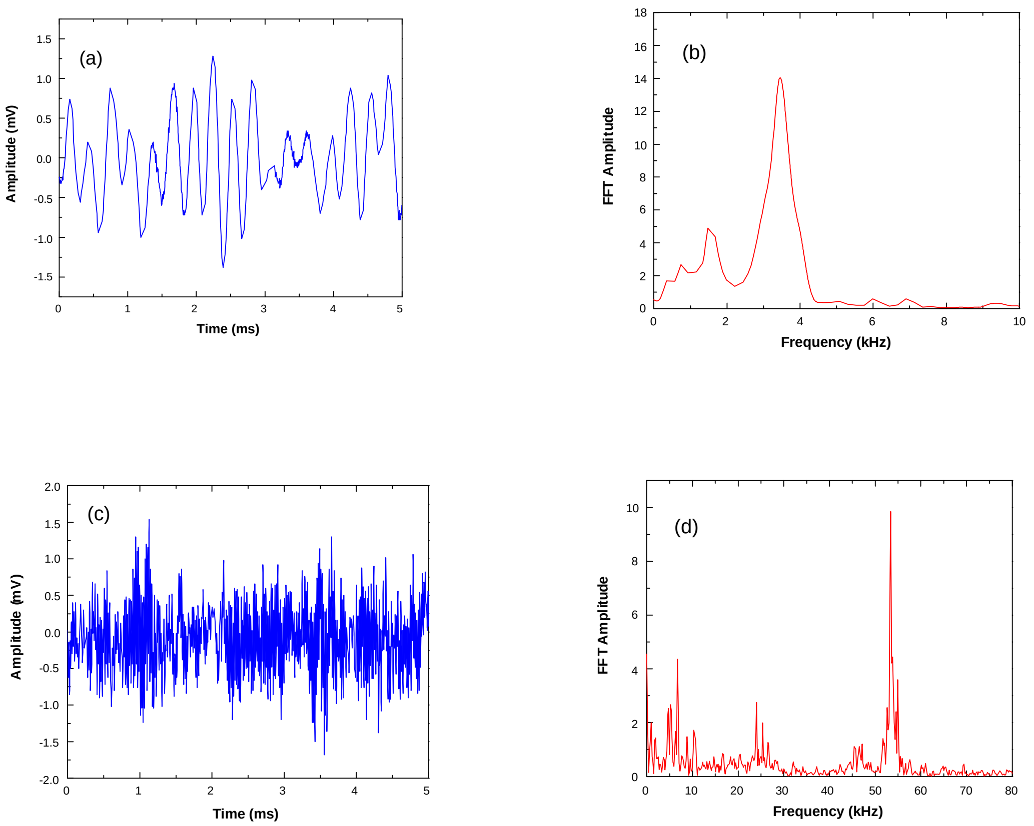


Figure 5. Flow-induced vibration in the piezoelectric cylinders mentioned in Fig. 3. Figure 5(a) shows the electrical signal produced due to flow through the 2-cm diameter tube and Fig. 5(b) shows the Fourier transform of the data. Figures 5(c) and 5(d) are similar data for the smaller cylinder made from piezofilm.

The flow-induced vibrations and its frequency characteristics are shown in Fig.5 for the two piezoelectric tubes mentioned in Fig. 4. The large peaks in Figs. 5(b) and (d) represent the resonant frequencies of the tubes. These data are obtained from a Fourier transform of the time data. The voltage signal produced from each tube is recorded directly on a digital oscilloscope without any amplification. The rms value of the voltage output increase as the flow increases almost linearly. At higher flow rates one obtains a broader spectrum with many vibration modes participating. It should be pointed out that the voltage signal generated is an alternating voltage and it cannot be used directly for any useful purpose without first converting it to a DC signal. This will be discussed later.

The next step was to detect the vibration from outside the Plexiglas pipe and convert that to electrical power (not shown in Fig. 3 above). We tested various types of piezomaterials and shapes and sizes that were attached to the outside surface of the pipe and not in direct flow. We tested peiezofilms wrapped around the pipe surface where small pieces of flat piezo materials were attached to the surface and also curved piezo pieces. Again, we found the highest voltage outputs were obtained from curved surfaces, which were essentially a small curved section cut from a piezo-cylinder. It is not necessary for the curved piezo to match the curvature of the Plexiglas pipe. Thicker piezomaterials produced larger signal as can be expected. It was possible to obtain voltage output of the order of 10 mV from even a small piece (3 cm x 3 cm) of a curved piezo sensor for flows with pressure difference even less than 30 psi. It should be pointed out that a properly designed piezo system can produce many times this signal level from the vibration present in a pipe. The values mentioned here are not optimized at all and these experiments were only for exploratory purposes. It is worth pointing out the factors involved in the efficiency of such piezoelectric power conversion. A vibrating or resonating system has a certain Q (quality factor). It is seen as the sharpness of the resonance peak in a spectrum (see Fig. 5). The other factor is the electromechanical coupling factor k. This factor relates to the amount of mechanical energy that can be transformed into electrical energy for the piezoelectric device. Different piezoelectric materials have different coupling factors. Following Richards *et a* [8], one can express this efficiency in terms of only the Q value and the k-factor exactly as

$$\eta = \frac{1}{2}\frac{k^2}{1-k^2} \Big/ \left(\frac{1}{Q} + \frac{1}{2}\frac{k^2}{1-k^2}\right)$$

Examination of the above equation shows that the efficiency vanishes when the electromechanical coupling factor approaches zero. The exact value of efficiency achieved by a given device depends upon the relative magnitudes of the electromechanical coupling and the quality factors. This is shown graphically in Fig. 6.

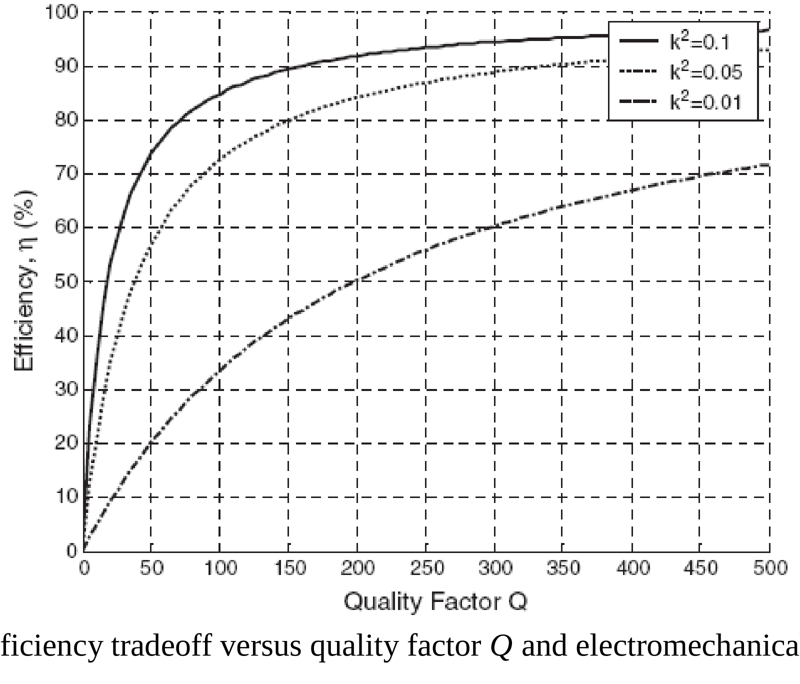


Figure 6. Efficiency tradeoff versus quality factor *Q* and electromechanical coupling factor *k*2.

According to Fig. 6, higher efficiency can be obtained by a design that incorporates material with higher coupling factor and higher Q. The cylindrical tube used in our study can be designed in a manner that maximizes this conversion efficiency. It is worth pointing out the kind of efficiency one can obtain from various types of piezoelectric device design. Funasaka *et al* [9] has recently demonstrated that for a cantilever made from lithium niobate that has k^2 value of 0.08 and a Q of 229 and a resonance frequency of 4.75 kHz, the efficiency can be as high as 91%. For a cantilever made from a simple PZT, they obtained efficiency of 82%. Umeda *et al* [10] were able top obtain 80% efficiency with a diaphragm design made from PZT material.

The above discussion only focused on conversion of energy from a single piezoelectric device. Of course, one can increase the amount of power generation by using several such piezo converter elements together and not just a single one. When several piezoelectric elements are present in the structure, they can be connected either in parallel or in series. In a parallel connection, the charge generated by the piezoelectrics is added whereas in a series connection, the charge generated corresponds to the strain of one of the piezoelectric elements connected, and the voltage of the piezoelectric elements is added. In order to adequately connect the piezoelectric elements in series or parallel, the orientation of the poling axis has to be taken into account.

As mentioned earlier, one needs to convert the ac signal to dc for this energy to be useful for practical purposes. The following is a straightforward scheme that can be used for this purpose as shown in Fig. 7 below.

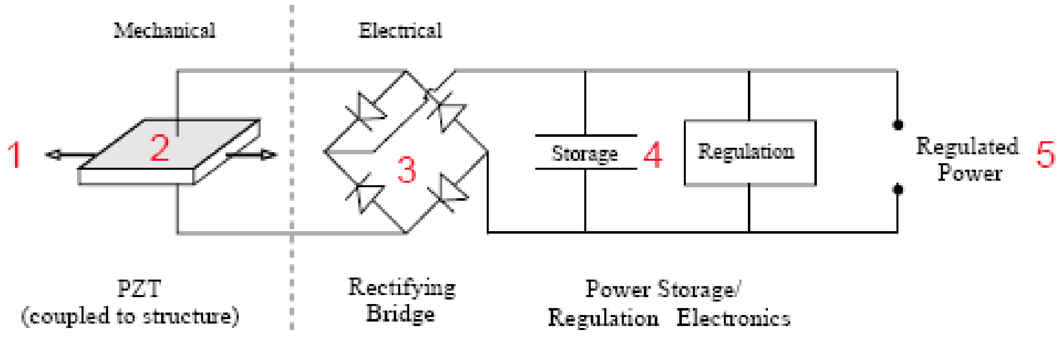


Figure 7. Power generation main technology components.

First, one needs a way to convert the available mechanical vibration energy into electrical energy and it is done using a piezoelectric element (or system). This electrical energy is in the form of AC and so it needs to be converted into a DC signal using a rectifying bridge. A lot of research is being done in this area of efficient rectifying bridge. A capacitive storage system is used to even out any fluctuation in the vibration level and the consequent electrical power generation. Finally, one needs a proper regulating system to maintain a sustained power level to power any microelectronics circuits. There is a lot of development work going on in this area and some of the components are available commercially. Therefore, it is not very worthwhile discussing the electronic circuitry behind power regulation because there is new development of integrated circuit available on a regular basis.

It may seem that the amount of power obtained from vibration of a pipeline is small. Fortunately, advances in “low power” DSPs (Digital Signal Processors) and trends in VLSI (Very Large Scale Integration) system design have reduced power requirements to 10’s-100’s of μW. These power levels are obtainable through piezoelectric harvesting of pipeline vibration energy. The reminder of this report will point out commercial systems that are available today that are based on such vibration harvesting.

Today’s vibration energy harvesters are so sensitive and efficient; they can generate electricity from vibrations that are barely noticeable to the human touch. Input vibrations are measured in *g*’s, where 1 g is equal to the acceleration of gravity. (Tapping on a table creates ~0.02 g, or 20 mg vibrations that are detectable by a hand.) One example is the Energy Harvester made by Ferro Solutions [11]. In an environment with vibrations at 28 Hz and 100 mg, this harvester produces a power output of 9.3 mW from a cylinder measuring ~1.8 in. diameter by ~1.8 in. high. Doubling the volume of the harvester will double the useful energy produced. The power output scales linearly with increased vibration frequency and exponentially with increased g-force. When the electricity thus generated is not used immediately, it can be stored in a super capacitor.

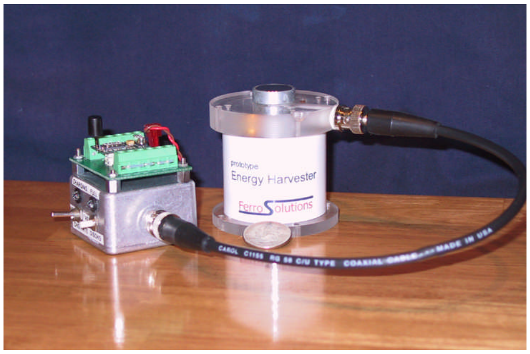
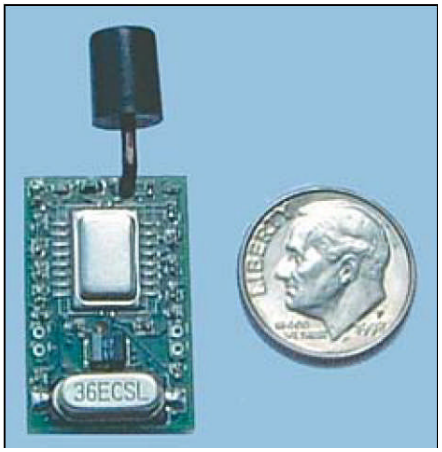


Figure 8. Demonstration unit powering Millennial Net's [12] *i-Bean* wireless transceiver (see on right).



Another example is Continuum Control Corp.’s [13] iPower energy harvesters. These devices, about the size of a pack of gum (see Fig. 9), extract electric energy from mechanical vibrations, motion, or impact, and store it for use by wireless sensors or other electronic devices. The technology couples proprietary transducers and circuits to a mechanical system, creating a solution that maximizes power flow from the mechanical to the electrical storage and is specifically targeted at converting micromotion into usable power.

Both technologies provide enough energy to power a wireless sensor node and its attached sensors, and both are viable alternatives to line or battery power for the appropriate sensor network application.

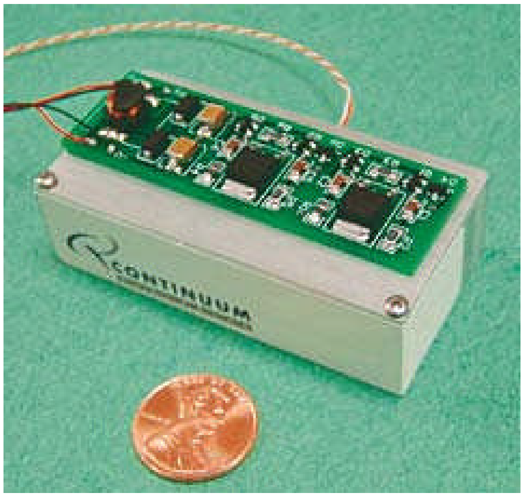


Figure 9. Continuum Control Corp.'s harvester package, featuring an integrated transducer and harvesting electronics including power conditioning up to 3 V, offers tunable coupling and frequency.

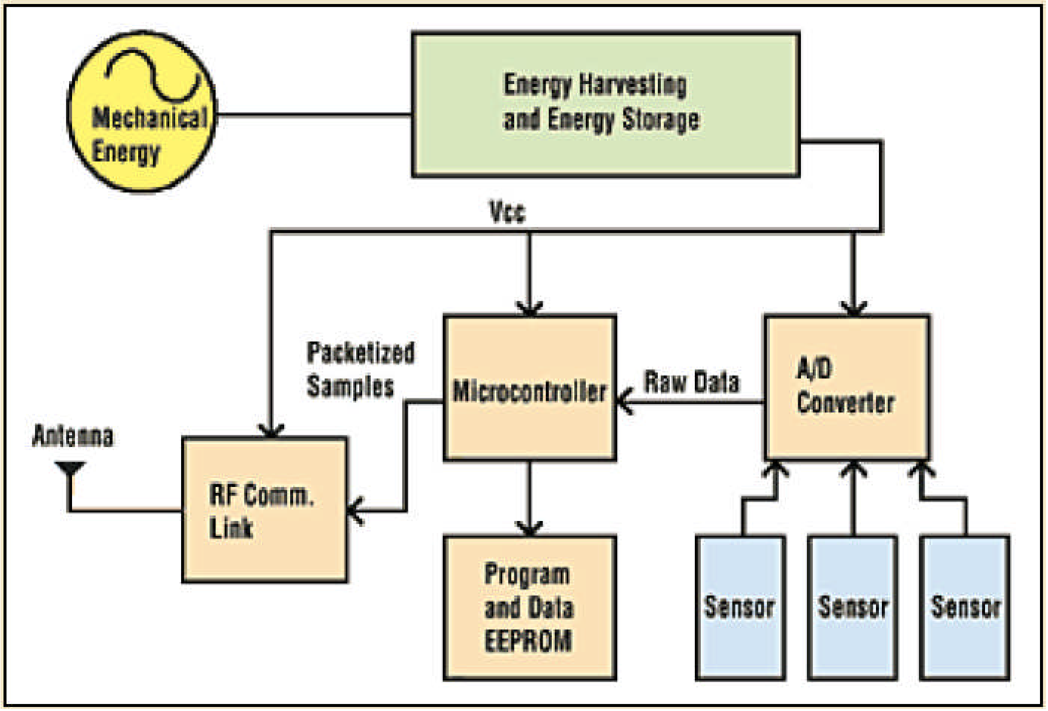


Figure 10. MicroStrain's goal is to combine energy harvesting with low-power sensors and networks to create a completely wireless sensor network that can deployed easily in the field and operate unattended for long periods.

Microstrain [14] is developing complete wireless sensor networking solution that takes advantage of vibration as its power source (see Fig. 10). The field of energy harvesting has become very popular and one expects to see real improvement in the area of extremely low power electronics and sensor integration.

In summary, It appears feasible to extract power from natural gas flow in pipelines and use this power to operate sensors, at least in discontinuous mode where the power builds up over a period of time and triggers a measurement when some threshold is reached.

Various types of sensors can be integrated with such a system and form a network of sensors with each module behaving as anode in that network. The connection among the nodes can be done through wireless communication and powered through energy harvesting from the pipeline itself. In the near future, the technology is expected to improve sufficiently that even continuous surveillance of a pipeline (e.g., structural integrity monitoring) may be possible. It will also be important to develop appropriate sensors that can work with very low power.

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