Vibrational Energy Scavengers

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Abstract: *The field of vibrational energy scavengers is explored, focusing on three particular types of scavengers: electrostatic, electromagnetic, and piezoelectric. Piezoelectric scavengers are identified as the most suitable for biomedical implant applications, and their theoretical power output is examined. Finally, possible methods of improving power output from piezoelectric scavengers are discussed.*

1. Introduction

MEMS (micro-electro-mechanical-systems) are on their way to being implemented in many different kinds of applications. The technology has become more advanced and more attractive for embedded and remote systems. By using MEMS and VLSI technology, sensing and actuating functionalities can be added to almost everything that surrounds us. Such devices will be able to interact wirelessly with their environment and each other in applications such as medical implants and monitoring devices. But even though they are ultra-low-power systems, supplying power to these tiny devices can be a significant engineering problem. Usually, energy to power remote devices is supplied by batteries, but there are obvious problems with these (size, life span, etc.). And even though VLSI and MEMS devices have become much smaller, battery development has lagged behind, creating a need for alternative power supplies.

These days, there is a lot of research on making use of the energy in the environment of the system. Possible sources of ambient energy are: vibration, solar energy, and temperature difference. Because we are primarily interested in biomedical implant applications, only vibrational energy scavengers are viable. This paper explains the different kinds of vibrational scavengers and analyzes how power output can be improved for piezoelectric generators.

2. Vibrational energy

In order to be able to convert vibrational energy into electrical energy, there has to be a movement between the mechanical parts of the generator. The vibrations consist of traveling waves and it is often not possible to find a relative movement within the reach of a small generator.

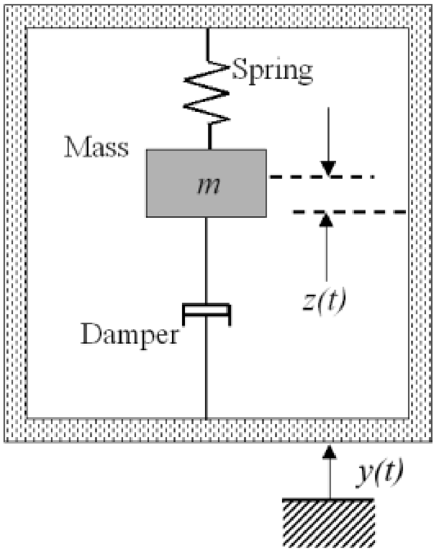


Fig. 1: Basic construction of a vibration scavenger [1]

The most common approach to couple the mechanical movement to the generator is to an inertial system, having a spring connected to the vibrating frame and a mass suspended by the spring (Fig 1). This way, the motion of the mass with respect to the frame can be converted to power by the electromechanical generator. The generated power will be delivered to an external load. There are three different kinds of generators that can be used: electrostatic, electromagnetic and piezoelectric. Below is an explanation of how the different generators work.

3. Vibration powered generators

a. Electrostatic

An electrostatic generator (Fig 2) consists of a variable capacitor with fin-type plates and an electret[1]. The fins of one side of the capacitor are attached to a suspended proof mass and move with vibrations while the other side of the capacitor is fixed to the glass wafer. The electret provides a polarization voltage, which is needed to initially charge the electrodes.

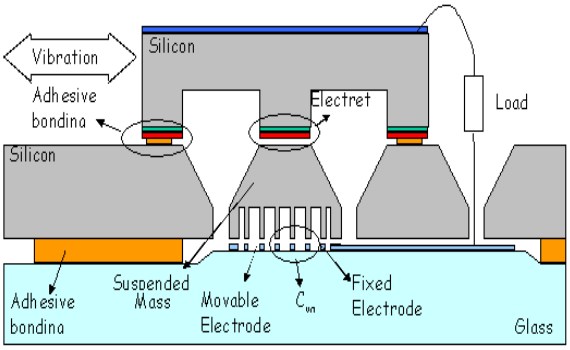


Fig 2b: schematic of an electrostatic scavenger with electret [1]

The capacitor has a value that changes as a function of displacement (Fig: 1). As the device resonates with the vibration, the total electrical energy stored in the capacitor increases. This redistribution of charge makes a current flow through the load, given by:

$$I = \frac{dQ}{dt} = \frac{d(C(z)V)}{dt}$$

As the plates move further apart, capacitance increases, causing an increase in current. This is harvested, stored, and as the plates contract again, the cycle is repeated [3].

One of the main advantages of electrostatic energy converters is that their technology is compatible with CMOS technology. However, the generators need an advanced control system in order to regulate the power switches. Also, high voltages can be generated which may harm the switches or the microelectronics.

b. Electromagnetic

The electromagnetic working principle is based on the relative motion of a magnetic mass and a coil (Fig: 3).

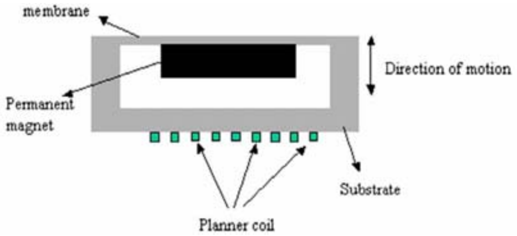


Fig 3: schematic of electromagnetic scavenger [2]

*[1] Electret (formed of electr- from "electricity" and -et from "magnet") is a dielectric material that has a quasi-permanent electric charge or dipole polarization. An electret generates internal and external electric fields, and is the electrostatic equivalent of a permanent magnet. [8]

An electro-motive force (e.m.f.) is induced across a coil if the magnetic flux coupled to the inductor changes as a function of time. The e.m.f. is proportional to the coil's total number of turns, the magnetic field density and the velocity of the motion. The relationship between the e.m.f. and the displacement of the mass depends on the design of the system.

Electromagnetic conversion has some advantages and disadvantages compared to electrostatic conversion. Its advantages are that it doesn't need an external voltage source or electret, nor does it need controlling or sensing electronics to manage the power switches. The only thing needed to regulate the e.m.f. is a diode bridge. Its disadvantages, on the other hand, are that its fabrication techniques are not compatible with CMOS technology and the converters generate relatively low e.m.f.

c. Piezoelectric

This type of scavenger makes use of the fact that a piezoelectric material generates an electric field when it is stressed mechanically. This electric field is related to stress by the materials "g" coefficients, whose units are [V/m]/[N/m^2]

$$g = \frac{\text{open circuit electric field}}{\text{applied mechanical stress}}$$

Output voltage is calculated by multiplying the electric field by the thickness of ceramic between electrodes [4].

The piezoelectric layer is polarized by applying a field through the electrodes after heating it up to 150°C. It is necessary to polarize both sides at once since heating one side will result in heating of the other side. It is not possible to connect the piezoceramic element directly between the mass and the frame because it is a stiff material and would result in having a generator with a very high resonance frequency. That's why the generator is often mounted on a long thin cantilever beam: as the beam/mass structure oscillates, the piezoelectric layer adhered to the surface of the beam deforms and causes a charge to be displaced across the capacitor electrodes positioned on the top and bottom surfaces of the piezoelectric elements (Fig: 4). A voltage then appears across the capacitor and a current will flow through the load. Roundy and colleagues have shown that piezoelectric scavengers produce highest level of practical power output [5].

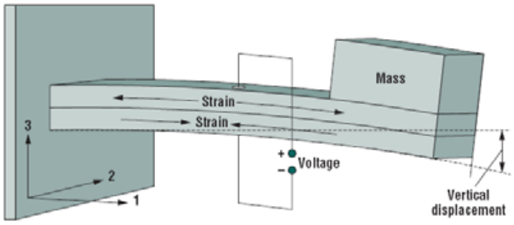
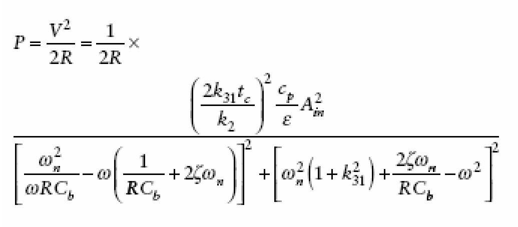


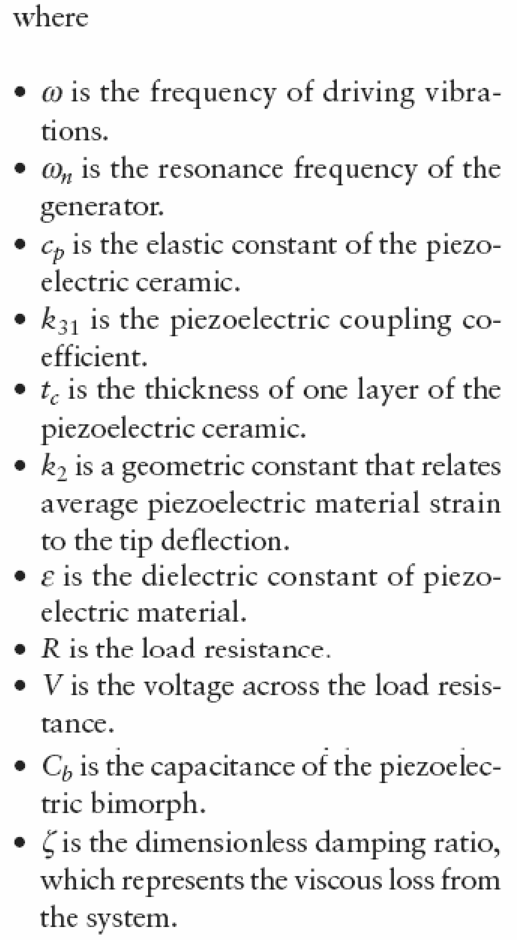
Fig 4: schematic of a piezoelectric scavenger [5]

4. Piezoelectric Generator Power

When a resistor is connected across the device electrodes, the relationship for power output as a function of input vibration amplitude and frequency is:



$$P = \frac{V^2}{2R} = \frac{1}{2R} \times \frac{\left(\frac{2k_{31}t_c}{k_2}\right)^2 \frac{c_p}{\varepsilon} A_{in}^2}{\left[\frac{\omega_n^2}{\omega R C_b} - \omega\left(\frac{1}{RC_b} + 2\zeta\omega_n\right)\right]^2 + \left[\omega_n^2\left(1+k_{31}^2\right) + \frac{2\zeta\omega_n}{RC_b} - \omega^2\right]^2}$$



where

- ω is the frequency of driving vibrations.
- ω_n is the resonance frequency of the generator.
- c_p is the elastic constant of the piezoelectric ceramic.
- k_{31} is the piezoelectric coupling coefficient.
- t_c is the thickness of one layer of the piezoelectric ceramic.
- k_2 is a geometric constant that relates average piezoelectric material strain to the tip deflection.
- ε is the dielectric constant of piezoelectric material.
- R is the load resistance.
- V is the voltage across the load resistance.
- C_b is the capacitance of the piezoelectric bimorph.
- ζ is the dimensionless damping ratio, which represents the viscous loss from the system.

[5]

Power output is maximized when the driving frequency is operating at the resonance frequency of the generator. That frequency depends on the stiffness and the mass of the beam according to:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m_{eff}}}$$

5. Improving Power Output

There are three basic approaches to improving power output from a piezoelectric cantilever scavenger. The first is to modify the cantilever geometry to produce more strain. This can be accomplished by making a cantilever beam which is longer and narrower or by increasing the proof mass. But because of the brittle nature of piezoelectric ceramics, too much strain will damage them. Another approach is to increase the width/thickness of the piezoelectric material, but this stiffens the beam, reducing overall strain and increasing resonant frequency. Most biomedical applications target frequencies in the 10s of Hz, so a low resonant frequency is essential.

The third approach seems to be the most viable: tuning the resonant frequency of the device to match the frequency of excitation. In cases where the excitation frequency changes (which is true in most practical applications—particularly biomedical), this calls for either wide-bandwidth designs which are optimized for a wider range of frequencies or adaptive self-tuning mechanisms which can detect excitation frequencies and adjust the cantilever's resonant frequency to match. The only practical wide-bandwidth design approach involves multiple cantilevers with different resonant frequencies. The obvious problem with this approach is that it increases size and decreases the power-to-volume ratio. Since size is of utmost importance in a biomedical application, we are left with adaptive self-tuning.

There are two methods of self-tuning, which Roundy calls “active” and “passive” [5]. Active tuning mechanisms run continuously to match the cantilever’s resonant frequency to the excitation frequency. Electronic springs are an example. Passive tuning mechanisms tune the cantilever and then turn off. In other words, no power is required to maintain the desired resonant frequency once it has been set. An example would be a variable/moveable proof mass or a mechanism that adjusts the length of the beam. It has been mathematically shown that active tuning mechanisms will never be practical because the power gains they provide will never be enough to offset the power they require to operate [9]. Therefore, passive tuning is the only viable approach, and it is the one we explore in our research proposal.

References:

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