Micro-Engineered Devices for Motion Energy Harvesting

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Abstract

MEMS (micro-electro-mechanical systems) is being widely investigated for use in harvesting energy from motion, e.g. human body movement or machine vibration. MEMS harvesters are of interest for powering small electronic devices, particularly wireless sensor nodes. This paper summarises the general structures of these energy harvesters and their achievable power levels, and compares the different transduction mechanisms used. Some new device concepts are introduced, and likely future developments are discussed.

1. Introduction

Portable and wireless electronic devices are finding an increasing range of applications with reductions in cost and size, and increases in functional capability. However, the size and cost advantages are significantly limited by the need for provision and replacement or recharging of batteries, and therefore, devices that extract energy from their surroundings in some way (so called *energy scavenging* or *energy harvesting* devices) are attracting increasing attention [1, 2]. There are a number of potential energy sources to be harvested; this paper will consider only one of these, namely ambient motion. It will focus on micro-engineered devices, although larger scale devices are also an active topic of investigation.

Most motion energy harvesters are inertial: power is extracted from the motion of a proof mass suspended within the device, by use of a transduction mechanism which damps this internal motion (Fig. 1). A structure for converting motion into electrical power is inherently an electro-mechanical one, and therefore if it is engineered at a micro-scale, it would appear to fall clearly within the technology known as micro-electro-mechanical systems (MEMS). However, MEMS is often taken more narrowly to refer to devices engineered in silicon, or if in other materials, using processes and techniques adapted from silicon micro-electronics technology. Therefore we can consider two related issues: in which applications energy harvesting devices should be of a size appropriate to micro-engineering; and what benefits MEMS technology can offer to this application. For the first question, we will take micro-engineering to refer to feature sizes of a few microns or less, within device dimensions of about 1 cm or less.

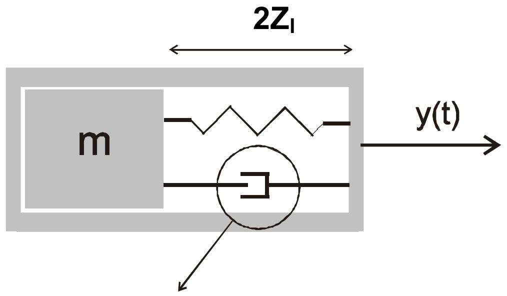

Figure 1: Schematic of linear inertial energy scavenger. A spring suspension supports a proof mass *m* within a frame, motion of the mass on its spring is excited by motion of the host structure y(t), and damping of this internal motion by the transducer generates electrical power.

The obvious motivation for micro-engineering is to satisfy a space or weight limitation, or to minimize the power source's impact on the total system size. Assuming there is only one motion energy harvester for each electronic device to be powered, and considering the strong dependence of power output on harvester size, a reasonable compromise is a harvester of about 10 – 30% of the overall device size. Therefore a micro-engineered energy harvester becomes attractive, or even necessary, if the total device is smaller than about 1 cc. The largest category of devices falling into this size range is wireless sensor nodes. These have the additional advantage of often having low power requirements, and there are many existing or proposed applications where large numbers of such devices are desirable, adding to the need to eliminate batteries from a cost and maintenance point of view.

For very small devices, i.e. of overall dimensions significantly below 1 mm, MEMS may offer the only practical fabrication approach. However, energy harvesters of such small size have not been reported to date. At intermediate size scales of several mm, MEMS may offer cost or performance advantages, both coming primarily from the possibility to monolithically integrate the power conditioning circuitry, and other electronic functions relating to the application, with the electro-mechanical parts. Such integration has been a key factor in the success of MEMS inertial sensors such as accelerometers, which are very similar in structure to inertial energy harvesters. However,

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successful low cost MEMS components with integrated electronics have generally used surface micromachining, where the mechanical parts are fabricated in relatively thin deposited layers, as this offers the best compatibility with standard integrated circuit processing [3]. Surface micromachined parts are necessarily of very low mass, and therefore unsuitable for use as proof masses in energy harvesters, despite performing the same role very successfully in accelerometers.

Consequently, although a variety of silicon micro-engineered inertial energy harvesters have been reported, all have used so called bulk micromachining methods such as deep reactive ion etching (DRIE), by which the proof mass can be formed in the whole thickness of the wafer. Partly for this reason, silicon energy harvesters have not yet been reported with integrated electronics. However, such circuit integration is possible with bulk micromachining, and offers performance as well as cost advantages, such as reduced electrical parasitics, which can be critical in achieving efficient power conversion.

2. Ultimate Power Limits of Inertial Harvesters

The power levels theoretically achievable from inertial scavengers with linear (as opposed to rotating) proof mass motion have been extensively analysed [4]. They are limited by four parameters: the proof mass and range of internal travel of the device, m and $2Z_l$, and the amplitude and frequency of the source motion, Y_o and ω (assuming harmonic source motion). The peak frame acceleration for harmonic motion is simply $\omega^2 Y_o$, from which we can define an equivalent force on the proof mass $m\omega^2 Y_o$. This, times the internal travel distance, gives the maximum energy per transit, from which we obtain the theoretical maximum for the harvested power:

$$P_{max} = 2m\omega^3 Y_o Z_l / \pi \qquad (1)$$

Since mass is proportional to volume and maximum displacement to linear dimension, this maximum power scales as linear dimension to the fourth power, or as volume$^{4/3}$. Thus power density reduces as device size decreases, obviously an undesirable feature for miniaturization. In addition, the very strong dependence on frequency means that for low frequency applications such as body-mounted sensors, the power density is poor.

For MEMS implementations, an important additional factor is the aspect ratio. MEMS structures, being based typically on silicon wafers and additional deposited layers, can be thought of as 2½ dimensional, having limited size and motion range in the out-of-plane direction. For a given volume, the power limit of (1) is maximized if the proof mass motion is along the longest dimension. Figure 2 illustrates the main geometries of inertial generators. The *block* has a proof mass with all three dimensions equal or similar. This is suitable for implementation in conventional engineering. The *pin shuttle* device is elongated in the direction of travel, which is optimum for power density; however, implementing a suspension for such a structure is difficult.

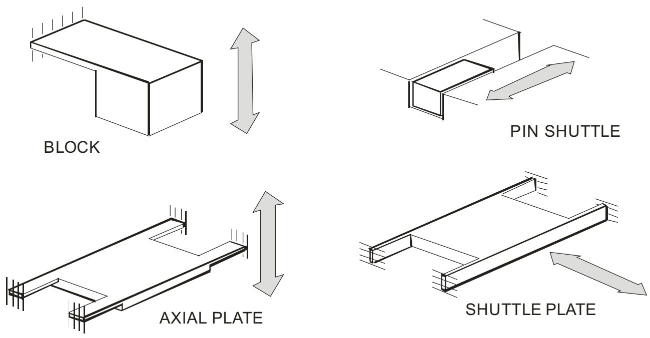

Figure 2: Principal proof mass and suspension geometries for inertial energy harvesters.

To quantify the advantage of the pin shuttle geometry, we compare a block device with proof mass dimensions $s \times s \times s$ with a pin proof mass dimensioned $a \times a \times \alpha a$, with the aspect ratio $\alpha > 1$. It is straightforward to show that for a given size constraint in the direction of motion, the proof mass should take up half this space, so that the device volume (neglecting the space taken up by the suspension, frame and other parts) will be twice the proof mass volume in every case. Then for devices of equal volume and density, it can be derived that the pin shuttle maximum power density is greater than that of the block device by a factor $\alpha^{2/3}$.

On the other hand, the lower two geometries in Fig. 2 are the ones typically reported for MEMS devices. Indeed, because of the constrained out-of-plane dimensions in MEMS as discussed above, these are the only practical forms. Motion of the mass may be either in-plane or out-of-plane as shown. We take the proof mass dimensions as being, again, $a \times a \times \alpha a$, but this time with $\alpha < 1$. Then the analysis for the *axial plate* geometry is the same as for the pin shuttle, i.e. this device has a power density *reduced* by a factor $\alpha^{2/3}$ compared to a block device of the same size. A typical aspect ratio for a MEMS bulk micromachined structure would be 0.1, giving $\alpha^{2/3} \approx 0.2$. For *shuttle plate* devices, which move in one of the long dimensions, the power density with respect to a block device is increased by a factor $\alpha^{-1/3}$., i.e. 2.2 for an aspect ratio of 0.1. However, this apparently large advantage of the shuttle plate motion is generally not fully realized, because of the difficulty of fabricating a suspension that allows the required long travel distance, while at the same time being of acceptable size and having reasonable stiffness for other motion axes.

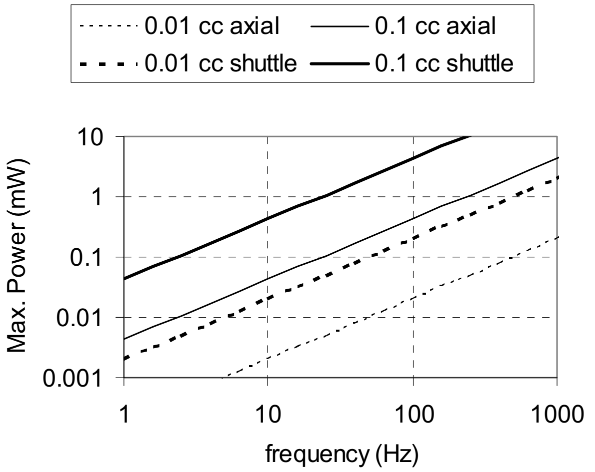

Figure 3: Maximum power levels for MEMS inertial energy harvesters of axial plate or shuttle plate geometries, for proof mass volumes as indicated.

Fig. 3 shows the maximum power levels for MEMS shuttle and axial plate devices having Si proof masses of aspect ratio 0.1, as a function of operating frequency, for proof mass volumes of 0.01 and 0.1 cm^3 and harmonic source acceleration of amplitude 10 m/s^2. As can be seen, in the frequency range 1 – 10 Hz, as might be the case for biomedical applications, power levels are likely to be at most 10's of μW for these harvester sizes. Typically the key challenge at these low frequencies is to achieve sufficient transduction forces to maximize output.

For higher frequency sources, such as machine vibration, mW power levels are achievable at MEMS size scales. However, the required internal motion amplitude is likely to be significantly greater than the source amplitude, and therefore resonant oscillation of the proof mass must be employed. This introduces two additional limitations. Firstly, the resonant enhancement (Q) will often be limited by parasitic damping forces such as viscous drag. MEMS offers two advantages in this regard: the low mechanical losses of single crystal Si suspensions, and the possibility of vacuum packaging to prevent air drag. The second limitation is the need to tune the device resonance to the source frequency, an increasing problem as Q rises. Realistic motion sources do not have well defined and unchanging frequencies, and therefore, although most reported motion harvesters have been fixed frequency resonators, active tuning or broadband response will almost certainly be required for real applications. With this important caveat in mind, a recent survey of inertial harvesters [5] indicated that power levels are in general getting closer to the ultimate limits, with the highest at about 20%.

Inertial scavengers may also use rotating masses. Typically these are unbalanced (e.g. semi-circular) so that they may be driven by linear motion. In [6] an analysis is presented which shows that the power limit of such a device, for a semi-circular proof mass m of radius R, is given by:

$$P_{max} = 0.27 m \omega^3 Y_o R \qquad (2)$$

This is nearly identical to (1), except with the proof mass radius taking the place of the internal travel range Z_l. Thus the choice between a linear and a rotating mass is likely to be based on practical considerations, such as ease of manufacture, cost or reliability.

3. Transduction Mechanisms

Most reported inertial energy scavengers use one of three transduction mechanisms to generate electrical power: piezoelectric, electrostatic, or electromagnetic. Each has advantages and drawbacks.

Electromagnetic devices are the most reported, with most being conventionally engineered but a few at MEMS scale. Most employ a coil on the proof mass moving through the magnetic flux from a permanent magnet, or a magnet moving through a coil. The latter is well suited to the pin shuttle geometry, this arrangement having been exploited for motion powered flashlights, although these are essentially a novelty product with very poor efficiency. MEMS electromagnetic harvesters generally use the shuttle plate design. Since the damping force between a coil and magnet depends on the relative velocity, sufficient forces are difficult to achieve for low frequency applications, where this velocity is low. Micro-engineered implementations are also limited in the number of coil turns that can be achieved, which tends to result in low output voltages, making rectification difficult.

Piezoelectric devices produce output effectively even at low frequencies, and generally at reasonably high voltage levels. Implementation requires a piezoelectric material, usually a ceramic such as PZT in monolith or thin film form. The latter can be incorporated into a MEMS device, typically in the block or axial plate geometry, with strain in the active material caused by flexure of the suspension to which it is attached. Damping forces tend to be small, so these devices are most suited to resonant devices. The output impedance of the piezo element is dominated by its capacitance, which due to its small size cannot be tuned out with a realistic inductance at the frequencies of interest. In practice a real load R is generally employed; in this case, power is maximized for an R that matches the magnitude of the capacitative impedance $1/\omega C$, which is far from a conjugate match, as required for theoretically optimum power.

Electrostatic devices generate power by doing work against the mechanical force between capacitor plates. Both the axial plate and shuttle plate geometries have been reported. An example of the former is illustrated in Fig. 4. This device uses a non-resonant proof mass suspension, with a non-linear and discontinuous internal motion [7]. The mass is pre-charged in one position, where it is held in place until the external acceleration is enough to overcome the electrostatic force. At that point the mass accelerates across to the other side of the frame, where it discharges its energy. Thus it can operate equally effectively for a wide range of input motions. Since the pre-charge voltage sets the holding force, this parameter can in principle be used to dynamically optimize the power for different motion amplitudes. Shuttle plate harvesters typically use comb drive electrodes for the transduction.

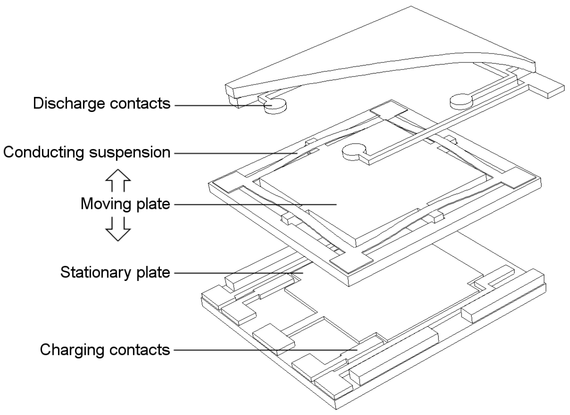

Figure 4 MEMS Electrostatic energy scavenger for low frequency applications (from [7]), using a Si proof mass on a polyimide suspension.

For electrostatic devices, high output power and efficiency requires high device capacitances, partly to overcome parasitics. Unfortunately, this is a major challenge because of the difficulty in both comb drives and parallel plate devices of combining small gaps with long travel ranges. Furthermore, the need for a pre-charge or priming voltage is a disadvantage, although this can be avoided by use of an electret.

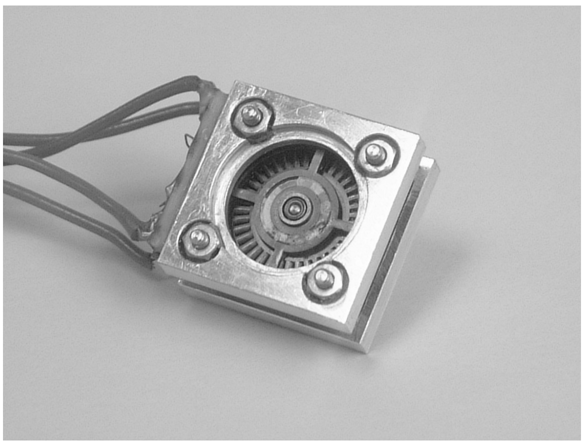

Figure 5 MEMS axial flow turbine generator (approximate size 15 x 15 mm).

In addition to inertial devices, there is the possibility of extracting power from fluid flow. MEMS axial flow turbines have been demonstrated (Fig. 5) which can generate milliwatts in a modest air stream such as in a ventilation duct [8]. This can also be considered motion energy harvesting.

4. Conclusions and Future Prospects

Recently, commercial inertial energy scavenging devices have begun to appear. These have mostly been based on piezoelectric cantilever designs, with device size in the cm range. For example, the Midé Technology Corp. advertises a piezo scavenger [9] of about 40 cm^3 and 50 g. This device is reported to provide 2.4 mW at 1 g acceleration, for a drive frequency of 50 Hz. Vibration powered energy harvesters have also been used to demonstrate fully autonomous self-powered sensor nodes. In [10], a wireless temperature sensor is reported powered by piezoelectric transduction from vibration on a staircase to which the device was attached.

Two new forms of harvesting device are under development in our laboratory. One is an electrostatic device in which the electrodes and other ancillary features are surface micromachined for maximum integration potential, but the proof mass is a rolling metal cylinder, which allows its mass to be maximized. The other is an electromagnetic harvester powered by continuous rotation, e.g. for use in a tire-mounted sensor. Here, gravitational torque on an offset mass provides the counter-force to create relative rotation within the generator, allowing it to be attached at a single point on a rotating structure.

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