Energy Scavenging for Wireless Sensor Nodes

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Abstract

Most wireless sensor nodes are powered by primary or secondary (rechargeable) batteries. These take up a large proportion of the size and weight, and often the cost, of the nodes, and furthermore the need to replace or recharge them creates a significant maintenance burden. Maintenance free power provision would greatly increase the feasibility of networks with very large numbers of, or very widely distributed, nodes. Recently the scavenging of energy from the environment, in the form of heat, motion, light or other electromagnetic radiation, has been actively researched as a possible solution to this problem. In this paper the progress and ultimate potential of such power sources is reviewed, with an emphasis on motion and vibration scavenging. The power levels achievable are examined, and applications are considered in which such sources are attractive to substitute for or supplement batteries.

1. Introduction

A supply of electrical power is naturally a critical requirement for wireless sensor nodes, and because batteries have limited energy capacity, these frequently dominate the size and weight of such nodes. They also impose a maintenance burden of recharging or replacement if a long sensor lifetime is required. For this reason, devices that extract energy from their surroundings in some way (so called *energy scavenging* or *energy harvesting* devices) have attracted attention from many researchers [1, 2]. Ambient light, and temperature differences, are useful potential power sources in some applications, but there will be many instances where neither is sufficiently available. Mechanical motion is another energy source which has attracted considerable attention. Such motion sources generally fall into two clear classes – low frequency, high amplitude motion such as human body motion, and high frequency, low amplitude motion such as machine vibration. In the first category, the motion amplitudes are typically on the order of or greater than the desired device dimensions, while in the latter the reverse is generally true.

The extraction of energy from motion may be by direct application of force to the mechanism, such as foot strike in a shoe mounted device [3]. More common, and more universally applicable, are the inertial mechanisms. In these, the generator need only be attached to the moving host at a single point, as illustrated in Fig. 1. A proof mass is suspended within the generator such that internal motion is induced when the device frame moves along with the host; electrical power is then generated by a transduction mechanism which acts to damp this internal motion. Most devices described in the literature consider the case of linear internal motion driven by linear source motion, and this case has been extensively analysed in [4]. However, devices with rotating masses also exist, particularly for the generation of power in wrist watches.

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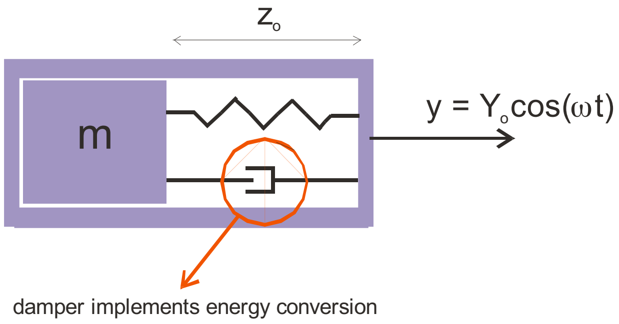

Figure 1: Schematic of linear inertial energy scavenger.

2. Ultimate Power Limits

The power levels theoretically achievable from linear inertial scavengers are limited by four parameters [5]: the proof mass and range of internal travel range of the device, m and Z_l, and the amplitude and frequency of the source motion, Y_o and ω (assuming harmonic source motion). The maximum frame acceleration for harmonic motion is simply $\omega^2 Y_o$; unless the damping force per unit mass is below this level, the proof mass will move together with the frame, so there will be no relative motion and thus no work done against the damper. This places an upper limit on the force of $m\omega^2 Y_o$, and thus on the energy per transit of :

$$U_{max} = m\omega^2 Y_o Z_l \qquad (1)$$

It is worth noting that this maximum requires use of the full internal travel range, whereas for high frequency sources this may be significantly greater than the excitation amplitude of the source. In these cases, resonant oscillation of the proof mass on its suspension is typically used to obtain the required internal amplitude. For low frequency, high amplitude sources, on the other hand, non-resonant devices can be exploited [6], and these have the significant advantage of operating effectively over a wide range of source frequency without requiring active tuning.

If energy is extracted in both directions of travel, then the maximum power is simply twice U_{max} divided by the period $2\pi/\omega$, giving:

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

Consequently, since mass is proportional to volume and maximum displacement to linear dimension, 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. Furthermore, the very strong dependence on frequency means that for the low frequency group of applications, such as body-mounted sensors, the power density is poor. For example, for a device of dimensions $s \times s \times 2s$, having a cubic mass of volume s^3 and a displacement range of s, and using frequency $f = \omega/2\pi$ and acceleration $a_o = \omega^2 Y_o$, the power density limit is:

$$P_{max}/Vol = 2\rho s a_o f \qquad (3)$$

with ρ the proof mass density. This is illustrated in Fig. 2, for a source acceleration of 1 g (10 m/s^2), and $\rho = 9$ g/cc (nickel), for several linear dimensions. As can be seen, in the frequency range 1 – 10 Hz and for devices below 1 cm^3, as might be the case for biomedical sensors, the power density is only a few mW/cm^3 (or equivalently, □W/mm^3). Note also that the approximation of proof mass volume s^3 and travel range s is unrealistic, as it leaves no space for the mechanism. On the other hand, some enhancement in energy density is possible, in principle, with use of a different aspect ratio, in order to extend the travel range for a given volume, but this possibility will be greatly limited by practical considerations.

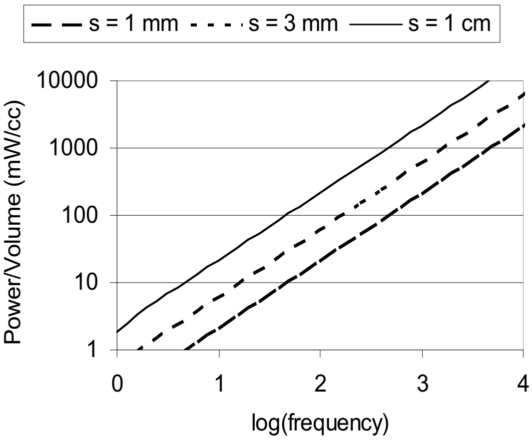

Figure 2: Maximum power density levels of linear inertial energy scavengers, for harmonic source motion of peak acceleration 1 g, and several linear dimensions as indicated.

Although (2) gives the level of maximum power for harmonic excitation, it is derived using the assumption that the damping force per unit mass can approach the maximum external acceleration throughout the motion cycle. This, however, also implies that the mass makes each internal transit in negligible time, since the peak external acceleration is by definition only present instantaneously. If we require the internal motion also to be harmonic, the maximum power is reduced by a factor of π/4 [4]:

$$P_{max} = m\omega^3 Y_o \, Z_l / 4 \qquad (4)$$

[Note also that in some references Z_l is defined as the maximum internal motion amplitude, rather than the range, in which case the factor "/4" in (4) is replaced by "/2"].

If we do not require harmonic internal motion, we can allow the proof mass to make each internal transit in less than half a cycle (resting at either end between transits). This allows a larger force closer to the maximum peak value $m\omega^2 Y_o$ to be employed, and brings the achievable power closer to that of (2). The possible improvement is greater for cases where $Y_o \gg Z_l$.

As stated above, 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 [7] 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:

$$P_{max} = 0.27 m\omega^3 Y_o R \qquad (5)$$

This is nearly identical to (4), 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 internal mass is likely to be based on practical considerations, such as ease of manufacture, cost or reliability, rather than ultimate power limit.

3. Power Limits of Reported Devices

Most reported inertial energy scavengers use one of three transduction mechanisms to convert motion to electrical power: piezoelectric, electrostatic, or electromagnetic. Recently we have reviewed reported progress in implementations of such devices [8]. It was found that the power levels are in general getting closer to the ultimate limits, but remain somewhat below them. In Fig. 3 historical progress is plotted for experimental reports in the literature, with normalized power P_n being defined as actual power divided by P_{max} as given in equation (4).

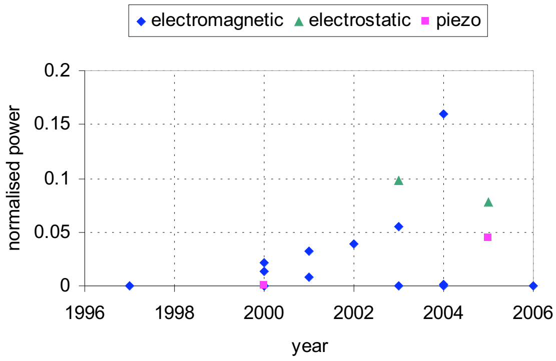

Figure 3 - Normalised measured power P_n vs. year of publication. From [8].

Also in [8] it was shown that higher normalized power levels are generally achieved for larger devices, and for lower operating frequencies. For the former, it is likely that practical constraints of integrated microengineered devices reduce the power extraction efficiency. For the latter factor, it is generally the case that high frequency sources have low excitation amplitudes, and thus require resonant enhancement within the extraction device to achieve optimum power. However, the higher the resonant enhancement (and thus the mechanical Q) needed, the greater is the impact of parasitic damping mechanisms such as viscous drag on the proof mass motion. In such cases the inherent Q (i.e. the quality factor excluding the effect of the transduction damping) becomes the limiting factor on achievable power. A final conclusion from [8] is that reported results do not show any clear differences between the three transducer types in terms of normalised power, and each has been investigated over a wide range of both device size and operating frequency.

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 in size. This device is reported to provide 2.4 mW at 1 g acceleration, for a drive frequency of 50 Hz. If we use the given dimensions to estimate the internal motion range and proof mass as 2.5 mm and 25 g respectively, then (2) gives a maximum theoretical power at 50 Hz and 1 g of about 60 mW. It should be noted that this device is not optimized for these specific operating conditions, and that (2) does not include any consideration of the efficiency of the power conditioning circuit. With these factors in mind, the device comes reasonably close to what is possible, while not precluding significant future improvement.

One possible area for improvement is in transducer damping strength. High frequency devices, requiring high mechanical Q, do not require strong damping by the transduction mechanism, but at lower frequencies the damping force needed to maximize power may well be more than can be practically achieved. This is for different reasons in each of the transduction cases. In piezoelectric devices, the output impedance of the piezo element is dominated by its capacitance, which is too large be tuned out with inductance at the frequencies of interest. This means that the optimum load is the one that matches the magnitude of the capacitative impedance $1/\omega C$, which is far from matching the real component of the output impedance, as would be optimum if the capacitance were not present or could be compensated. Consequently, a number of groups are looking at improved circuits to get higher power extraction (and stronger damping) from piezoelectric scavengers, e.g [10].

For electromagnetic devices, strong damping forces require a high time rate of change of linked flux. This is inevitably more difficult at low frequencies and small device size, since the slow relative movement of the proof mass demands a very high spatial flux gradient, and a large number of coil turns. The latter is difficult to achieve in micro-engineered form, and leads to undesirably high coil resistance owing to the high length to diameter ratio of the coil windings. For electrostatic devices, the holding force (and thus the damping strength) depends on the applied voltage and on the spatial rate of change of capacitance. Unfortunately, high absolute capacitance, and thus high capacitance variation, is difficult to achieve in a mechanically variable capacitor compared to a fixed device of similar size. Furthermore, dealing with high voltages is undesirable in a micro-engineered device, and the need for a pre-charge or priming voltage in these devices is already a disadvantage, which is exacerbated if this voltage is high.

4. A Non-Resonant Electrostatic Energy Scavenger

Most reported inertial linear energy scavengers have used a resonant mechanical mounting for the inertial proof mass. This is necessary for high frequency devices, where the internal motion range is likely to be greater than the excitation amplitude. However, it necessarily limits effective operation to a narrow range of source frequencies. For low frequency operation, such as for body motion excitation, the internal motion enhancement is not required, and operation across a wide range of excitation frequencies and waveforms is essential for a practical application. For that reason we pioneered an electrostatic device which has a non-resonant proof mass mounting, whose internal motion is non-linear and discontinuous [11]. This is illustrated in Fig. 4. 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.

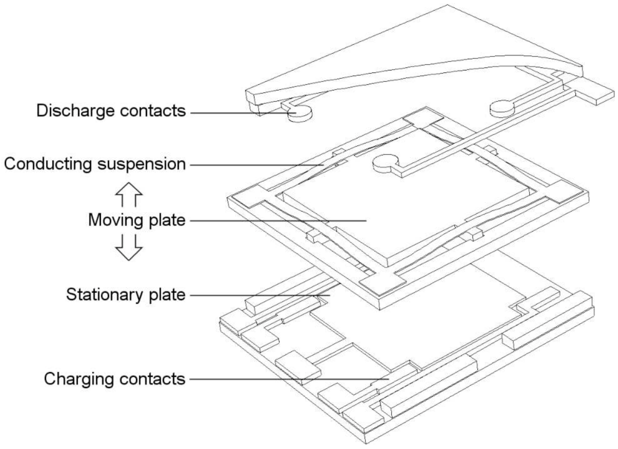

Figure 4 Electrostatic energy scavenger for low frequency applications (from [11]).

This device also illustrates some of the issues discussed in section 3. The moving plate dimensions are ≈ 11 × 11 × 1 mm, and the maximum capacitance is about 150 pF. This required a pre-charge voltage of 30 V to generate 120 nJ/cycle. Increasing the starting capacitance would allow reduction of the pre-charge voltage without loss of output power, and would lessen the effects of parasitic capacitances. The output is in the form of high voltage pulses, which creates considerable demands on the power conditioning circuitry [12].

5. Sensor Node Power Requirements

Crucial to the practical exploitation of energy scavenging devices is the identification of applications whose power requirements are within the range such scavengers can achieve in the environment determined by the application. Solar power has been the most successful scavenging technology to date, benefiting from a well developed technology, strong compatibility with electronic integration, and reasonable cost. However, solar cells are dependent on a strong and reliable source of light, and must be correctly oriented and free of obstructions. In [13], solar cells were used to power wireless senor nodes only 16 mm^3 in size, with on-board (passive) optical data communication, two sensors, and some processing and control circuitry. However, the light source for powering was a remote laser rather than ambient light.

Vibration –powered energy harvesters have also been used to demonstrate fully autonomous self-powered sensor nodes. In [14], a wireless temperature sensor is reported which was powered by piezoelectric transduction from vibration present on a staircase to which the device was attached. The scavenger provided 30 μW under continuous stairway traffic, enough to power the sensor electronics and short range data transmission.

Wireless sensor arrays are attracting great interest in many application domains, and appear to be the most attractive application for energy scavenging, as they often have low power requirements, combined with a need for low cost and size, and ease of maintenance. The three main power requirements in such devices are the sensors themselves, the signal conditioning circuitry, and the wireless data communication. For sensor types generating modest amounts of data and requiring low sampling and transmission rates, total power requirements in the micro-watt level range are realistic [15], and are becoming increasingly so with advances in low power analogue and digital circuitry.

6. Conclusions

Motion or vibration energy scavenging is an attractive approach to powering wireless electronic devices, particularly sensor nodes. While achievable power levels are modest, they are sufficient for many applications, and reported devices continue to advance towards realizing power output near the ultimate limits.

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