MEMS-Based Piezoelectric Energy Harvesters: Major Design Considerations for Powering Remote Microsystems

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Abstract

MEMS devices are very attractive for standalone, remote devices, as their small size allows them to be integrated into most common application areas. In order to power MEMS devices in such applications, batteries with inherently limited lifetimes as well as chemical fuel sources may be considered; however, these solutions increase the size, complexity and cost of the devices substantially. While many alternative methods of providing energy to MEMS exist, piezoelectric vibration energy harvesters are generally considered the simplest approach while still allowing for potentially large power generation from the ambient environment. This quality makes them ideal for truly remote applications, such as those in wireless sensor nodes or in vivo BioMEMS. In this review, the most prominent MEMS-based piezoelectric energy harvesting devices are examined at depth, with a focus on their device structure and the best device output characteristics. To this end, the vibrational energy that may be feasibly acquired from ambient environments is analyzed and found to be within the region of 100Hz to 1000Hz. Simple cantilever devices have also been modelled by COMSOL to elucidate basic device operation. Finally, unimorph and bimorph cantilevers, as well as their variants and additional alternative device structures, have been studied in literature. A maximum power generation of 60µW at ~20m/s² input acceleration has been achieved for a single unimorph cantilever, showing great promise for this technology. In future thrusts of research, it is believed that new geometries and device structures will allow for significant improvements in energy harvesting efficiency, eventually granting the realization of truly autonomous MEMS devices.
1. MEMS Energy Harvesting Technology: A General Overview

With the rapid development of MEMS technologies, researchers have frequently touted the feasibility of miniature, autonomous sensors. However, the actual implementation and application of such technologies is limited by the ability to remotely power the devices. To this end, researchers have examined many different methods of micro power harvesting and generation [1], including simple combustion in micro-reactors [2-7], ambient vibration harvesting by electrostatic transducers [8, 9] as well as electromagnetic transducers [10-12], micro-direct methanol fuel cells (DMFCs) [13] and micro-solar cell arrays [14]. One of the most studied methods to date, and one of the most appealing due to its potential simplicity, involves the use of piezoelectric transducers in combination with ambient and human vibration [15-20]. This latter topic will be the focus of this review, with an emphasis on device design and the inherent limitations of piezoelectric energy harvesting technology.

As is the case with any energy harvesting system, one must consider two factors to efficiently produce electricity to power MEMS devices:

- The source of energy production
  - the most feasible and most commonly observed sources of energy with MEMS micro-power generators include: vibrational or mechanical movement, chemical combustion, other chemical reactions (such as with DMFCs) and solar power
- The method or means of transduction – to translate the energy provided in the previous sentiment into an electrical current or potential
  - these may include: the use of electrostatic/electromagnetic forces to induce electrical potential/current, the photovoltaic effect in semiconductors, the electrochemical effect in fuel cells and the piezoelectric effect in piezoelectric materials
Vibrational sources of energy production are especially attractive because the associated harvesters can be scaled to incredibly small sizes and do not require the constant addition of fuel, such as with combustion reactors and DMFCs. Furthermore, unlike solar energy harvesting technology, vibration-based energy harvesters may be packaged away from the ambient environment to increase their device lifetimes and they can be operated at all times throughout the day. In this regard, devices powered by vibrational energy are truly standalone and autonomous. Barring catastrophic failure of any individual components of the vibrational energy harvesting devices, they may therefore be operated indefinitely without any human interaction. Such a device property would be incredibly attractive for, for example, structural integrity sensors connected to RF-MEMS transmission antennas.

In any vibrational or kinetic motion energy harvesting system, one is concerned with maximizing mechanical motion of some device mass. This may be accomplished by increasing the device’s sensitivity to direct mechanical displacement or by increasing the device’s sensitivity to incident acoustic waves from the ambient environment. This mechanical motion is then translated into an electrical signal by one of three primary modes of transduction: electrostatic, electromagnetic or piezoelectric effects, as briefly noted above. The system can be understood most simply as a mass-spring system, with some damping coefficient related to any number of damping factors (for example, aerodynamic drag and friction damping), as illustrated in Figure 1. For this system, the equation of motion may be written simply as:
In a piezoelectric system, any external force is translated into acceleration and subsequent movement of the device mass. By clever placement of a piezoelectric film, the movement of the device mass will cause stress and, as such, strain in the piezoelectric material, which will yield an electrical signal that may be used to power a MEMS device.

The choice of a piezoelectric transducer follows from its absolute simplicity in implementation. The reader is encouraged to examine reference [19], where the authors provide an exceptionally detailed comparison of the three primary modes of transduction for kinetic energy harvesting. In brief, the principal benefit of piezoelectric-based transducers relates to the fact that additional components and complicated geometries are not required for basic operation. This point is further detailed below:

- In electromagnetic transducers, the output voltage is generally low – between 0.1 and 0.2V at most [19] – requiring additional circuitry, such as transformers, for practical MEMS applications. Furthermore, planar magnets and planar coils (which are limited in their number of turns due to the limited surface area) for current generation are generally weak, resulting in relatively low power output. More complicated 3-D structures are desired but are largely impractical for cost-effective fabrication.

- In electrostatic transducers, an initial input charge or voltage is required for kinetic energy harvesting, removing the truly autonomous benefit of using vibrational energy sources. The addition of a battery, for example, to supply this initial polarizing charge greatly complicates the energy harvesting devices and, in most cases, greatly increases its size. Furthermore, while the output voltage for electrostatic transducers is high (often >100V) [17], so is the output impedance, often resulting in low device current. In order to provide the current required for

\[
F_{external} = m \cdot \frac{d^2y}{dt^2} + q \cdot \frac{dy}{dt} + ky
\]
many MEMS applications, complicated external circuitry would also be required. In general, such devices offer less power per unit volume than piezoelectric devices [21].

2. Feasibility of Vibrational Power Sources for Efficient Energy Harvesting

Prior to continuing the analysis of piezoelectric-based energy harvesters, it is worthwhile to consider the amount of power that could feasibly be obtained via vibrational energy from the ambient environment. This provides information regarding the feasible input power available to MEMS-based devices and represents the ideal condition where the device may be operated while simply attached to an everyday object. Beyond this baseline value, one may consider any number of MEMS devices that can be carried on one’s person, where the motion of walking, for example, provides the necessary mechanical forces to generate electricity through the piezoelectric effect. For more information on this topic, the reader is encouraged to examine reference [18], where Anton et al. discuss implantable and wearable MEMS devices, among other sources of energy, for their feasibility in power generation.

Considering a simple mass-spring scenario, as illustrated in Figure 1, the maximum power of the system is at the resonant frequency, and may be written in terms of both the acceleration magnitude and the displacement magnitude, as shown below:

\[
P_{\text{max}} = \frac{m \xi_t A^2}{4 \omega_r (\xi_t + \xi_0)^2} = \frac{m \xi_t Y^2 \omega_r^2}{4 (\xi_t + \xi_0)^2} \tag{2}
\]

where \( m \) is the proof mass, \( \xi_t \) is the damping coefficient due to energy transfer to the transducer, \( A \) is the acceleration magnitude of the input vibration, \( Y \) is the displacement amplitude of the input
vibration, \( \omega_r \), is the resonant frequency of the system \((\omega_r = \sqrt{\frac{k}{m}})\) and \( \xi_0 \) is the damping coefficient due to unwanted effects (such as aerodynamic drag, squeeze/air-displacement forces, support losses and structural damping) [10]. Note that this is a heavily simplified form of this equation – for more information on this model, the reader is encouraged to examine reference [16], where the equation is derived and detailed in full. From equation (2), it is clear that in order to maximize the power of the spring-mass system, such that one can maximize the total power harvested, one should:

- Make use of a large proof mass, \( m \)
- Ensure large acceleration amplitude, \( A \) (although this is limited by the device application or the environment that the cantilever is placed in)
- Minimize losses to the ambient environment by unwanted effects \((\xi_0 > 0)\)
- Design the energy harvester to operate with a resonant frequency in the same frequency regime as intense ambient vibrational modes (or, if pertinent, with the same frequency as incident acoustic waves, although acoustic waves have very low power density [21])

Taking the latter point into consideration, one may identify the vibrational frequencies with the greatest intensity in a given ambient setting and use these frequency values to design the shape and structure of the piezoelectric energy harvester. This exercise ensures maximum harvested power from the system.

Consider vibrational information from an air conditioner duct, as illustrated in Figure 2 on the following page. First, it is important to note that it is incredibly difficult to fabricate MEMS structures with resonant frequencies less than \( \sim 100\text{Hz} \) [16]. Generally speaking, small dimensions imply large operating frequencies, whereas much larger dimensions can allow for very low resonant frequencies. This sets a lower cut-off value for the feasible input ambient frequencies and the operation of the devices. Also in Figure 2, the acceleration of a sample cantilever has been calculated both in vacuum
and in atmospheric conditions for a constant maximum power, with the power normalized to the power of the 170Hz maximum peak. This calculation was performed under the assumption that the damping coefficient is dominated by hydrodynamic drag (for atmospheric conditions) and that the cantilever is operated at its resonant frequency.

From the calculated constant-power plots in Figure 2, it is clear that the power is inversely proportional to frequency when the sample cantilever is operated in vacuum. In effect, a much smaller acceleration is required for equivalent power in vacuum because less energy is lost to non-idealities such as friction. In atmospheric operation, the acceleration is relatively constant because the drag term’s dependence on frequency cancels out the power dependence on frequency. Since most devices will be operated in atmosphere, one may note that there is no clear benefit to operate the piezoelectric energy harvesters at either higher or lower frequencies beyond the benefits implied by the vibrational data from the environment itself. In the case of the air conditioner and in the case of most ambient vibration sources, the ideal operating condition is at very low resonant frequencies.

From Figure 2, one may further refine and identify key regions of enhanced operation based on the vibrations of the air conditioner. Namely, in Figure 2, the ideal point of operation is at 53.8Hz. Since this is below the cut-off operating frequency for most MEMS devices, the next-best operational

Figure 2 - Representative Vibrational Frequency Data from an Air Conditioner Duct. Superimposed: Calculated Acceleration Data for a Cantilever under Constant Power Conditions – Normalized to f~170Hz (in Vacuum and in Atmospheric Conditions). Figure adapted from ref. [16].
frequency is at 170.6Hz. An alternative peak of operation is at 100.0Hz. However, one must be very careful in this method of ultra-fine analysis, as both the ambient peaks and the resonant frequency of the device itself are likely to shift with time and with variations in operating conditions. A more practical approach would be to design a small array of piezoelectric energy harvesters that collectively respond to a broad band of frequencies. While no single piezoelectric device will output its absolute maximum power, the array of devices will provide a relatively stable and constant power source. Such an array can be also be considered a mechanical band-pass filter, and has been studied and modeled at depth by Shahruz [22-24]. Regardless, it is possible to perform fine frequency analysis for all feasible application areas, as is shown in Table 1 below.

<table>
<thead>
<tr>
<th>Vibrational Source</th>
<th>Primary Peak (Hz)</th>
<th>Secondary Peak (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Conditioner (side)</td>
<td>170.6</td>
<td>100.0</td>
</tr>
<tr>
<td>Computer Side Panel</td>
<td>276.3</td>
<td>120.0</td>
</tr>
<tr>
<td>Microwave Oven (top)</td>
<td>120.0</td>
<td>240.0</td>
</tr>
<tr>
<td>Microwave Oven (side)</td>
<td>148.1</td>
<td>120.0</td>
</tr>
<tr>
<td>Office Desk</td>
<td>120.0</td>
<td>546.3</td>
</tr>
<tr>
<td>Bridge Railing</td>
<td>171.3</td>
<td>136.3</td>
</tr>
<tr>
<td>Car Hood (3000RPM)</td>
<td>147.5</td>
<td>880.6</td>
</tr>
<tr>
<td>Medium-Size Tree</td>
<td>115.3</td>
<td>240.0</td>
</tr>
</tbody>
</table>

Note that in certain application areas, such as the car run at 3000RPM, more high frequency peaks exist. These particular application areas may prove to be rather troublesome for piezoelectric energy harvesting. Such vibrational sources can excite second and third resonance modes within the piezoelectric device, resulting in strain cancellation effects [16]. That is, with multiple modes excited within the beam, the beam will undergo non-uniform stress, whereby areas of high tensile stress due to the first mode may be counteracted by compressive stress following from the higher modes.
3. The Piezoelectric Effect and Simple Device Modelling

The piezoelectric effect occurs as a consequence of the electric dipole arrangement in a solid. Consider a molecular model with an overall neutral charge distribution, but with inherent asymmetry in its shape and structure, as shown in Figure 3.A) on the following page. When this molecular model experiences some form of stress – such as compressive stress, as illustrated in Figure 3.B) – the charges within the model redistribute, resulting in the formation of a dipole. Scaling the above sample up to a practical bulk piezoelectric material, asymmetry is generally provided by ion impurities or by asymmetry within the material’s crystal structure itself (any crystals based on non-centrosymmetric unit cells). Nearest-neighbour dipoles will preferentially align themselves to form domains, analogous to Weiss domains in ferromagnetic materials.

Now consider a solid composed of numerous domains of piezoelectric materials, where the domains are each composed of many species with aligned dipoles. Through regular film processing, without any special treatment, these domains will be randomly oriented such that the overall polarity of the crystal is neutral. However, by a process known as poling, where the material is subjected to a high electric field at elevated temperatures, the domains can be oriented in the same direction to create a strongly piezoelectric material. As a point of note, the axis parallel to the electric field during poling is generally referred to as axis 3. If poling is not performed, as not all piezoelectric materials can be poled, the axis perpendicular to the substrate during deposition is commonly referred to as axis 3.
In Figure 3.C, a solid piezoelectric film composed of many aligned domains is shown to be subjected to some external stress. This stress creates a strain within the film that leads to a deformation of the individual dipoles, resulting in a variation in the distribution of charge throughout the solid material. This redistribution of charge creates a potential difference across the film. By shorting the edges of the piezoelectric material, as illustrated in Figure 3.D), one may make use of the potential difference to generate and collect electrical current. This phenomenon is the basis behind piezoelectric transduction and subsequent power harvesting through vibrational energy.

The asymmetry of piezoelectric materials has been identified as a key driving force in the piezoelectric effect. Unfortunately, this asymmetry also complicates device operation and analysis, as the piezoelectric film exhibits anisotropy in both its electrical and mechanical characteristics, as well as in the piezoelectric effect itself. In order to make device analysis and testing simple, two piezoelectric coupling modes based on the direction of stress and current collection in the piezoelectric film with respect to axis 3 have been identified. These modes, referred to as the 33 and 31 coupling modes, are illustrated in Figure 3.E) and Figure 3.F) respectively.
While piezoelectric energy harvesters are a topic of interest in current MEMS, piezoelectric transducers for actuation and sensing purposes are historically some of the most intensively studied MEMS devices. These past applications offer strong insight into the expected behaviour of the currently studied energy harvesting devices. As such, to better understand the role of piezoelectric materials in energy harvesting devices, simple cantilever-based MEMS devices with piezoelectric transducers have been modelled in COMSOL based on historical designs, as shown in Figure 4.

The simple piezoelectric device shown in Figure 4 consists of a 1mmx50μmx20μm fixed-free single crystal silicon cantilever beam, which is clamped to the left side-wall. A 50μmx50μmx20μm Lead-Zirconate-Titanate (PZT) piezoelectric film has been placed at the base of the cantilever. In a more realistic simulation, metal electrodes would be placed across the PZT film in order to sense and harvest electrical current. For the purposes of this simulation, boundary conditions are used to ground the
bottom edge of the PZT film and to set the top edge of the PZT film to continuity. Since the silicon crystal subdomain has been set to inactive with regard to electrostatics, electric potential can be measured at the silicon-PZT interface. This choice in boundary conditions is analogous to placing very thin metal electrodes at the top and bottom edges of the PZT electrode respectively. The location of the PZT film has been chosen because stress is generally greatest at the point of clamping for fixed-free beams, as is clearly visible in Figure 4.B).

After applying a downward force at the edge of the cantilever, the cantilever deforms such that its far edge reaches a maximum displacement of 3.4 µm. This is somewhat visible in Figure 4.B) and Figure 4.C), where the cantilever has shifted downward from its original position (denoted by a black outline). This deflection results in stress at the base of the silicon cantilever and within the PZT film, leading to an associated strain, as shown in Figure 4.C). The strain within the PZT film results in the creation of a potential, shown in Figure 4.D), with a maximum value of 3.8 V due to the piezoelectric effect described above. It is currently unknown if the -2.3 V reading at the far edge of the PZT film is realistic – it is feasible that this reading is due to local error in the finite element method as a consequence of the sharp corner at the PZT-silicon boundary.

It is also possible to do frequency analysis of the piezoelectric cantilever device shown in Figure 4 in order to determine its Eigenvalues. The first 3 Eigenfrequencies for the above structure were found to be: 81.1 KHz, 501 KHz and 1.38 MHz. As a point of note, these Eigenfrequencies have only been calculated for the undamped system – a complete analysis of damping factors is beyond the scope of this preliminary analysis. The true Eigenfrequencies for this structure would vary in a realistic environment where one is concerned with the ambient and structural damping losses discussed earlier. Regardless, it is clear that the dimensions and materials used in this preliminary example yield a device that operates at incredibly high frequencies, well above the 100 to 1000 Hz ambient vibration regime.
identified in Section 2. In piezoelectric energy harvesting devices, it is therefore desirable to make use of larger lateral dimensions, a sufficiently large proof mass, smaller thicknesses and more pliable materials (those with lower Young’s moduli). These alterations should allow for much smaller resonant frequencies to better utilize ambient vibrations.

4. Piezoelectric Energy Harvesters in Literature

The past decade has allowed for a great deal of ingenuity and creativity in the design of piezoelectric energy harvesting devices, with the realization of many different geometries, configurations and device types. In this section, these different structures for their application in MEMS will be examined at depth. In this regard, the most successful device configurations and experimental observations will be detailed to provide insight into the best methods to capture vibrational energy.

4.1. Unimorph Cantilever Structures

The simplest incarnation of a piezoelectric energy harvester is the unimorph structure. The term unimorph corresponds to the use of a single piezoelectric layer to act as the transducer. The full device structure, however, typically makes use of two or more layers, where the additional layers are structural or current carrying. Given its simplicity, this structure has enjoyed a great deal of research and has therefore seen the most promising results in power generation efficiency [25-28]. As a first point of analysis, consider the simple 31-unimorph PZT cantilever proposed by Johnson et al. [29], as illustrated in Figure 5.A). Johnson et al made two major observations during their device design:

- the simplest two-layer unimorph device structure should have equal layer thicknesses
  - This follows intuitively from the fact that we wish to maximize a single type of stress (either compressive or tensile) within the piezoelectric layer.
If the structural layer is too thick, the neutral axis will be present deep within the structural layer, and so the amount of stress felt by the piezoelectric will be inherently limited. For example, the structural layer may experience all of the cantilevers compressive stress and a portion of the tensile stress, while the piezoelectric layer only experiences a portion of the tensile stress.

If the structural layer is too thin, the neutral axis will be present within the piezoelectric layer. In this case, the presence of both compressive and tensile stresses serves to reduce the perceived piezoelectric effect.

- The ideal structural layer should be easily deformable (low Young’s modulus)
  - A lower Young’s modulus usually results in lower structural losses and, as a consequence, reduced damping effects
  - Further, a low Young’s modulus allows for much smaller resonant frequencies, thereby allowing the cantilever to harvest energy in the practical ambient vibration regime, as discussed previously in Section 2.

In this preliminary unimorph device structure, Johnson et al. made rather large, macro-size (25mm(L) x 3mm(W) x 254μm(t)) structures to allow for resonant frequencies on the order of 243 to 263 Hz. These beams granted upwards of 59.8mV open circuit voltages and a power generation of 0.058μW when subjected to a custom-made vibration system. The rather low powers and open circuit voltages were largely attributed to the fact that their custom vibration system had sharp vibration peaks at 240Hz, slightly away from the resonant frequencies of the studied cantilevers;
however, such situations are representative of realistic ambient test environments and so the data is still relevant.

Many authors have used the simple unimorph design structure as a starting point for further experimental variation – in this review these variants will still be considered as unimorphs, as they only have one truly active piezoelectric layer [25-28, 30, 31]. In one type of variant, Shen et al. as well as Fang et al. examined the effect of adding proof masses to the ends of unimorph cantilevers in order to decrease their resonant frequencies (thereby improving ambient vibration applications) [26, 27, 30]. This effect can be examined directly by revisiting the COMSOL model developed in Section 3. In this model, adding a (200µm)³ piece of crystalline silicon to the edge of the simple cantilever serves to decrease the device’s resonant frequency from 81.1KHz to 13.5KHz. Furthermore, following from the discussion in Section 2, an increased cantilever mass also serves to increase the maximum power of the cantilever due to an increased maximum displacement.

In the work by Shen et al., a Pt/PZT/ Pt/Ti/SiO₂/Si structure was fabricated, where platinum was used for electrodes, titanium was used as an adhesion layer, SiO₂ was used to provide electrical insulation, Si was used as a mechanical support as well as for the proof mass, and PZT was used as the active piezoelectric material. The device layers with their thicknesses and an SEM micrograph of the device are provided in Figure 6.A.1 and Figure 6.A.2 respectively. The cantilever dimensions were 3200µmX400µm, with the added 1360µmX940µm proof mass, allowing for a resonant frequency of 462.5Hz. In this particular example, the researchers were able to achieve 2.15µW and ~200mV output with a load resistance of ~6kΩ while using a 461.25Hz vibration source at 2g acceleration magnitude (where g=9.81m/s²).
In the work by Fang et al., a Ti:Pt/PZT/Ti:Pt/SiO$_2$/Si structure was fabricated, with a Ni proof mass added to the top of the device structure [26]. The roles of the individual layers are identical to the device described previously for Shen et al. In contrast to the device developed by Shen et al., the Ni proof mass was added to the top of the cantilever after the complete formation of the cantilever. This allowed Fang et al. to use a rather harsh KOH wet etch to remove the backside of the wafer instead of backside RIE. The downside to this approach, however, is the added difficulty of adding the Ni mass to the cantilever by glue without damaging the device. The finalized device exhibited a resonant frequency of 609Hz. With this device, Fang et al. were able to achieve 2.16µW and ~608mV output with a load resistance of 21.4kΩ while using a vibration source at 1g acceleration near the resonant frequency.

While the above results from Shen et al. and Fang et al. are impressive accomplishments, it should be noted that most ambient sources of vibration are much less than 1g acceleration and most MEMS applications require power in the hundreds of µW to few mW. Furthermore, Fang et al. note that the bandwidth of their devices is on the order of few Hz to tens of Hz, which quite small for ambient vibration applications [26]. In order to make use of this technology at its current state of development, one would have to implement arrays of hundreds to thousands of these cantilevers. Unfortunately, a mass array implementation would be incredibly difficult to wire and would cover too large of an area for practical use. Liu et al. (of the same laboratory as Fang) have recently examined the feasibility of making...
use of a smaller number of arrays, with initial work on an array of three cantilevers. The researchers have suggested AC-DC rectification circuitry to efficiently harvest energy from the multiple out-of-phase cantilevers [30].

Highlighting the importance of AC-DC rectification for piezoelectric energy harvesting, Elfrink et al. have very recently developed a unimorph cantilever based on an aluminum nitride (AlN) piezoelectric active layer, as shown below in Figure 7.A-C [25]. The use of an AlN active layer is not a novel idea – it had previously been examined with some success in one of the first MEMS-based piezoelectric energy harvesting devices in 2005 by Marzencki et al [32]. AlN films may be fabricated by a much simpler sputtering process (in contrast to the sol gel film formation and high temperature anneal usually used with PZT films), allowing for greater control in film quality and greater compatibility with standard microfabrication processes. Many researchers have since shifted toward PZT-based devices due to its enhanced $d_{31}$ piezoelectric coefficient [20, 25]. In contrast, Elfrink and coworkers note that the true power generation figure of merit relates to both the piezoelectric coefficient as well as the relative dielectric constant, as shown below. This is due to the fact that the $d_{31}^2/\varepsilon_r$ term appears in the time-averaged power of the cantilever when considering cantilever power loss by transfer of energy to the piezoelectric layer. With this in mind, PZT and AlN should have very similar ultimate power generation capabilities:

$$\chi = \frac{d_{31}^2}{\varepsilon_r}; \quad \chi_{PZT} \approx \frac{10^2}{800} = 0.125; \quad \chi_{AlN} \approx \frac{1.1^2}{10.5} = 0.12$$

Note that the values for PZT vary quite significantly depending on the quality and method of synthesis of the film, so average values have been taken based off of data provided by Elfrink et al. [25]. Units are not shown here because we are interested only in rough evaluations of the magnitudes of the figures of merit.

Elfrink et al. found that AlN devices exhibit their optimal power generation at much higher load resistances compared to PZT-based devices, owing to their greater relative dielectric constants. For the
same current output, this implies a larger voltage over the load (up to several volts for the devices examined currently and discussed below) that should allow for easier AC-DC rectification – for example, by a diode bridge.

In this research, Elfrink and coworkers developed Al/AlN/Pt/Ta/SiO₂/Si unimorph cantilevers with an Si proof mass, which were found to have resonant frequencies varying from 277Hz to 1100Hz depending on device dimensions [25]. The authors note that packaging the devices resulted in significantly greater damping losses due to squeeze forces/air displacement effects and the associated limitation in the maximum cantilever displacement. For a 2g-input acceleration, one such packaged cantilever experienced a decrease in output power from 60μW to 2.1μW. This effect is illustrated in Figure 7.D) above. Such data lends merit to the idea of packaging the devices in vacuum to greatly enhance power harvesting efficiency. The culmination of this study is an unpackaged device capable of 60μW and several-volt output with a load resistance of 0.1 to 1MΩ when using a vibration source at 2g acceleration near a resonant frequency of ~500-600Hz.
As a point of interest, Marzencki and coworkers have since continued their work on AlN-based devices for ultra low power wireless sensor node applications, with much of their work dedicated to the development of the power management circuitry [31, 33, 34]. In this regard, the researchers have developed custom circuitry (including low threshold voltage diodes for AC-DC rectification) to charge capacitors by low power energy harvesting with simple unimorph piezoelectric cantilevers. In one such example, Marzencki et al. were able to achieve a 1V output voltage by charging a 1μF capacitor using only 0.05g acceleration amplitudes at the cantilever resonant frequency of 1511Hz [33].

In more recent work, Marzencki et al. have demonstrated an adaptive device that can shift its resonant frequency up to 36% to best match the vibrations in a system of interest [34]. This is an important development because both the ambient vibrations as well as the resonant frequency of the cantilever are susceptible to shifting over time and during operation. By tuning the resonant frequency, one can match the cantilever device to the ambient vibrations in order to enhance power harvesting efficiency. Unfortunately, since this method relies on nonlinear resonance effects that require very large cantilever oscillation amplitudes, it is not immediately useful for application in ambient vibration energy harvesting where vibrations are typically less than 1g. The authors note a feasible application area of industrial machinery, where acceleration amplitudes can exceed 25g at frequencies of several KHz.

4.2. Bimorph Cantilever Structures

Based on their simple two-layer unimorph cantilever discussed previously, Johnson and coworkers suggested that increasing total piezoelectric volume by increasing the device area would enhance power harvesting efficiency [29]. Unfortunately, much like the arrays of cantilevers, such designs are too large for most practical MEMS applications and are therefore not relevant to the current review. In order to increase the amount of piezoelectric material used in energy harvesting devices
while maintaining small device sizes, one may consider bimorph structures, as illustrated in Figure 5.B) and Figure 5.C) above. Researchers have begun to model bimorph actuator piezoelectric devices for the purposes of energy harvesting [21, 35-40], some with the intent to use a bimorph piezoelectric sensing device to power itself [41, 42]. Two particular configurations of bimorph structures may be considered:

- series connection, where the resistive load is connected to each of the piezoelectric edges, across the piezoelectric and structural layers directly (Figure 5.B)
- parallel connection, where the two piezoelectric layers are shorted together and the resistive load is connected to the piezoelectric layers and to the conductive shim in between the piezoelectric layers (Figure 5.C)

At the current date, bimorph actuators for energy harvesting have largely remained theoretical constructs, with only a few practical applications at the macroscopic scale [35, 36, 39, 40]. In fact, to the best of this author’s knowledge, only one paper on a true MEMS bimorph piezoelectric cantilever has been developed for the purposes of energy harvesting [43]. In this work, Lee et al. make use of two PZT films to create the bimorph structure and then use a proof mass to adjust the resonant frequency, in the same manner as discussed above for unimorph cantilevers. The authors report an output power of 1.55µW and an open circuit voltage of 1.91V for the parallel bimorph configuration. Under the same 2g acceleration, Lee and coworkers note a maximum output power of 1.78µW and an open circuit voltage of 3.42V under the series bimorph configuration\(^1\).

While the aforementioned bimorph research articles do not specifically study MEMS devices, they still provide some insight into the operation of MEMS-based bimorph cantilevers. In fact, most of the early bimorph modelling articles provide the same conclusions that were reached in the earlier

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\(^1\) Note: This article was not yet available for UWaterloo online access, and the delay time on ordering the article directly was too long for it to be used in this paper. As such, information regarding device properties was derived exclusively from the abstract. For this reason, a complete analysis of this article was not possible.
analysis of unimorph cantilevers – such as the importance of matching the resonant frequency of the device to the ambient vibrations of the environment of interest, or the effect of the addition of a proof mass on device behaviour. In 2004, Roundy et al. fabricated a 1cm\(^3\) PZT-based bimorph cantilever with a tungsten proof mass, which allowed for a resonant frequency of 120Hz [39]. The device in this study generated \(\sim 190\mu\text{W}\) at 0.25g acceleration, allowing Roundy and coworkers to charge a 8.3-9.2nF capacitor.

In a more impressive feat, Roundy et al. were then able to use the capacitor from the above study to power a radio transmitter circuit [39]. Since the power required for the radio transmitter was larger than the power generated by the bimorph energy harvester, the transmission signal was limited to short bursts. Regardless, this application shows a great deal of promise for MEMS devices that may not need continuous operation. For example, an in vivo BioMEMS device may only need to communicate by RF once every few hours, providing the necessary time for a capacitor to adequately charge in order to power an RF-MEMS component.

In their modelling study of self-powered piezoelectric sensor/energy harvester bimorphs, Ng and Liao noted that each type of device – unimorphs, series-configured bimorphs and parallel-configured bimorphs – have an

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Figure 8 - Maximum Power Regions for Unimorph, Parallel-Configured Bimorph and Series-Configured Bimorph Piezoelectric Energy Harvesters. Image adapted from ref. [41].
optimal regime of operation with regard to resonant frequency and load resistance [41]. This behaviour is shown in Figure 8, where highlighted areas correspond to the device type and configuration with the maximum theoretical power harvesting capability. From this figure, one may note:

- **unimorph devices** perform best for devices with extremely low resonant frequencies and very small load resistances
  
  - Operational frequencies <100Hz are below the feasible fabrication limit of most MEMS devices, so it is unlikely that unimorphs will ever provide the optimal device behaviour.

- **series-configured bimorphs** perform well at higher frequencies and relatively large load resistances
  
  - As discussed in Section 2, most ambient noise sources are on the order of 100-1000Hz, which encompasses much of the operational region for series-configured bimorphs in Figure 8 when considering reasonably high load resistances.
  
  - For the same current, a higher load resistance corresponds to a larger operational voltage. Furthermore, the output voltage of the energy harvester must be greater than the threshold voltage of any AC-DC rectifier diodes in addition to the voltage across any storage capacitors. As such, a relatively large load resistance is good and desired for these applications.

- **parallel-configured bimorphs** sit in between the two regimes detailed above, with moderately small resonant frequencies and medium load resistances

  Taking the above data into consideration, it is reasonable to assume that the bimorph devices fabricated by Lee et al. and noted above are within the optimal power region for series bimorph structures, as shown in Figure 8. This follows from the fact that the series configuration showed greater
power harvesting capability and overall efficiency than the parallel configuration [43]. In choosing a series-configured bimorph, the researchers allow for large load resistances, granting potentially large open circuit voltages, at the cost of slightly higher resonant frequencies, feasibly reducing operational efficiency in a given ambient environment.

Beyond the basic operation of a bimorph cantilever, Wu et al. studied the notion of using a variable capacitive load to effectively tune the resonant frequency of the cantilever itself [44]. After tuning the resonant frequency of the cantilever to a desired value, Wu and coworkers were able to harvest energy optimally and specific to the ambient environment. Unlike the previous cantilever tuning discussed earlier, which relies on nonlinear mechanical effects, the current method does not require very large acceleration magnitudes. Unfortunately, for this preliminary work, the researchers could only demonstrate a frequency shift of 3Hz, from 91.5Hz to 94.5Hz, which is likely too small to account for any significant shifts in the ambient vibrational frequencies. Further, the microcontroller used to control the piezoelectric resonant frequency and effectively shift the gain of the device requires its own power source. As such, even assuming a low-power \( \mu \)W microcontroller, this approach is somewhat self-defeating unless the harvested power is in the range of several mW.

4.3. Additional Geometries and Modes of Operation

The above literature review is concentrated on simple rectangular 31-mode unimorph and bimorph cantilever structures, as these are the simplest and most studied structures to date. However, as noted previously, researchers have also examined numerous other geometries for their feasibility in energy harvesting. As with the bimorph structures, much of this data has yet to be realized at the micron-scale with MEMS devices. However, the understanding acquired from this research will undoubtedly be useful in further studies.
As a first area of consideration, one may make use of a 33-mode device instead of the more commonly examined 31-mode, as illustrated in Figure 9A.1/2). In order to realize such a device, several groups have employed interdigitated electrodes on the top-most layer of unimorph cantilevers [45-48]. Park and coworkers most recently demonstrated that such a device is capable of 1.1μW power generation with a very small acceleration magnitude of 0.39g [45]. Jeon et al. also previously noted that their 33-mode devices provide enhanced output voltages of up to 20-times higher than 31-mode when considering a Ti:Pt-PZT-ZrO$_2$-SiO$_2$-Si structure [47]. As discussed previously, an improvement in output voltage is useful for overcoming the threshold voltage of the diodes commonly used in AC-DC rectification, as well as the voltage of any capacitors that may be used to store the acquired charge.

A representative device structure for a 33-mode device is shown in Figure 9.B.1) and Figure 9.C), with the note that Figure 9.B.1) does not show the ZrO$_2$ layer mentioned previously. The ZrO$_2$ layer is commonly used as an additional diffusion-buffer layer to further prevent charge diffusion away from the piezoelectric layer. This is especially important for 33-mode devices, as variations in potential due to perceived strain can only be measured along the top-most interface of the piezoelectric layer. In their preliminary work, Jeon and coworkers developed a cantilever to operate at 13.9KHz resonant frequency, which is too large for simple ambient vibration energy harvesting. Regardless, their device was found to
be capable of a maximum power output of 1.0\(\mu\)W delivered to a 5.2M\(\Omega\) load resistance for an unreported acceleration intensity [47].

Lee et al. further noted that the output voltage for a 33-mode unimorph energy harvester can be manipulated simply by changing the spacing of the interdigitated electrodes [48]. In this work, the researchers were able to increase both the voltage and the output power by increasing the gap between the interdigitated electrodes from 20\(\mu\)m to 40\(\mu\)m. In later research, Lee and coworkers compared 31-mode to 33-mode unimorph devices and also observed an increase in maximum open circuit voltage from 2.4V to 4.1V when the devices were subjected to 2g acceleration [46]. For these devices, Lee et al. were able to achieve extremely low resonant frequencies of ~214-256Hz through the use of large proof masses. The output power, however, was higher for the 31-mode device, with 2.1\(\mu\)W generated compared to the 1.3\(\mu\)W generated for the 33-mode device at 2g acceleration.

Since the piezoelectric effect is directly proportional to the strain felt in a piezoelectric material, one may also vary the geometry of the cantilever beam in order to maximize the average strain felt within the piezoelectric layer. Roundy et al. suggested a trapezoidal cantilever structure instead of the standard rectangular structure [49], as illustrated in Figure 10.A). This structure allows for more even strain across the entire structure, which should enhance the structure’s power generation capabilities. This notion was supported by Mateu and Moll, who modelled triangular versus rectangular piezoelectric beams for applications in shoe inserts [50]. In this work, they note that the total strain of a rectangular cantilever is, analytically, 75% of the total strain of a triangular cantilever for the same device length, thickness and applied force.
Choi et al. proposed a serpentine structure, as illustrated in Figure 10.B), to allow for greater beam lengths while minimizing the total area occupied by the device structure. As shown in the left image of Figure 10.B), one may connect the centre of the structure to a proof mass in order to vary the cantilever’s resonant frequency. A second beam may be further added to the proof mass, as illustrated in the right image of Figure 10.B), in order to suppress horizontal and twisting (non-vertical) vibration modes, which are not as efficient for power generation applications and may cause strain cancellation effects (discussed briefly in Section 2).

One may also consider straying more significantly from the cantilever design and instead use entirely different device structures. Kuehne et al. suggested the use of a MEMS diaphragm instead of a cantilever for power generation [51]. The authors demonstrate the capability to harvest direct mechanical energy by dropping a 20mg ball onto the diaphragm, thereby allowing the device to output 185mV and ~1μW of power. The mechanical robustness of such a system may make it well-suited to an application where the diaphragm is repeatedly struck by some other larger actuating component. In this manner, some of the energy lost through actuation of the other component can be recovered.

Kim et al. further suggested a cymbal-like piezoelectric energy harvester [52, 53], as illustrated in Figure 10.C). The inner ‘empty’ areas of the cymbal may be vacuum if the device is sealed, or simply

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air if there are through-holes in the metallic shell. While Kim and coworkers’ cymbal device was fabricated with dimensions on the order of several centimetres, one may consider clever anisotropic etch and MEMS processing techniques to scale down such a structure for the current application. In this device, a downward force on the outer metallic frame causes tensile stress/strain on the piezoelectric film in order to generate energy. Similar to the diaphragm example above, such a device is mechanically robust. As such, it is suited to applications where the device is in direct contact with some driving force or where the ambient acceleration amplitudes may be too large for the previously examined cantilever devices. In this regard, cymbal-type devices may be perfectly suited to harvest energy from car vibrations or industrial machinery.
5. Conclusions and Future Areas of Investigation

MEMS-based piezoelectric energy harvesters have seen significant improvements in a very small period of time. In fact, from the detailed literature search performed in this review paper, the vast majority of piezoelectric energy harvesting research done at the micron-scale has been performed only within the past 5 years. To date, most of the critical milestones in piezoelectric energy harvesting research have been set by 31-mode rectangular unimorph cantilevers, which are the simplest designs comprising of a single active piezoelectric material and any number of structural materials placed between two electrodes. With this simple device structure, researchers have demonstrated single cantilevers capable of 60μW and several-volt output with a 2g input acceleration. The properties of these cantilevers have been varied to allow for resonant frequencies on the order of 100-1000Hz, which is in the ideal range for ambient vibration energy harvesting.

Furthermore, researchers have noted the importance of a proof mass to be added to cantilevers in order to reduce their resonant frequencies and to enhance their amplitudes of deflection. Researchers have also shown the feasibility of multiple cantilever arrays, including arrays of varying dimensions to allow for a larger energy harvesting bandwidth. In other thrusts of research, tunable cantilevers with variable resonant frequencies have been examined to better match the cantilever’s frequency to the ambient environment for more efficient energy harvesting. 31-mode and AlN-based unimorph devices have also been investigated for their improved voltage output characteristics, which should be useful to overcome the threshold voltages of the diodes required for AC-DC rectification.

Perhaps the most frustrating aspect of this review has been the lack of a set of standards in device characterization and device output behaviour. The research focus in piezoelectric energy harvesters has grown rapidly and is now at a critical point. Organic Solar Cell technology recently...
enjoyed a similar level of success, and, while it took several years, researchers eventually decided upon a specific solar intensity and solar spectrum for device characterization. In a similar manner, researchers in this field must agree upon adequate and repeatable test conditions. In this manner, it will be possible to prevent researchers from wasting time by investigating repeat data and to ensure results across different groups are comparable. The following conditions seem to be relatively common in literature and are suggested as a starting point for standard test conditions:

- Vibration source measured in fractions of g, where g=9.81m/s², with specific device measurements at: 0.25g, 1g and 2g
- Vibration measurements performed at the resonant frequency of the device, and if desired, for frequencies away from the resonant frequency
- Maximum power output values always reported along with the following data: resonant frequency of device, frequency of vibration source, acceleration magnitude of vibration source, open circuit output voltage and load resistance at maximum power

With much of the preliminary work on basic energy harvesting completed for unimorph devices, researchers are now free to examine more complicated structures and geometries. As noted throughout this review, much of this work has been previously completed for much larger, macro-scale structures. These previous reports should serve as good starting points for the micron-scale equivalent devices. Based on the above review, researchers are encouraged to examine numerous device configurations, including: trapezoidal unimorph devices with large proof masses based on the AlN piezoelectric material, the same devices with interdigitated electrodes in a 33-mode configuration, trapezoidal series-configured bimorph devices with large proof masses, and any other unique geometries that have been discussed but not yet tested, such as the serpentine-shape cantilever.
Works Cited


