ENERGY HARVESTING WIRELESS PIEZOELECTRIC RESONANT FORCE SENSOR

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The piezoelectric energy harvester has become a new powering option for some low-power electronic devices such as MEMS (Micro Electrical Mechanical System) sensors. Piezoelectric materials can collect the ambient vibrations energy and convert it to electrical energy. This thesis is intended to demonstrate the behavior of a piezoelectric energy harvester system at elevated temperature from room temperature up to 82°C, and compares the system’s performance using different piezoelectric materials. The systems are structured with a Lead Magnesium Niobate-Lead Titanate (PMN-PT) single crystal patch bonded to an aluminum cantilever beam, Lead Indium Niobate-Lead Magnesium Niobate-Lead Titanate (PIN-PMN-PT) single crystal patch bonded to an aluminum cantilever beam and a bimorph cantilever beam which is made of Lead Zirconate Titanate (PZT). The results of this experimental study show the effects of the temperature on the operation frequency and output power of the piezoelectric energy harvesting system. The harvested electrical energy has been stored in storage circuits including a battery. Then, the stored energy has been used to power up the other part of the system, a wireless resonator force sensor, which uses frequency conversion techniques to convert the sensor’s ultrasonic signal to a microwave signal in order to transmit the signal wirelessly.
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CHAPTER 1
INTRODUCTION

Most of new small scale electronic devices need very low-power sources. Traditional batteries are normally used to power these devices; however, these batteries only provide a limited amount of electrical energy and have a limited lifetime especially at elevated temperatures which require frequently recharging or replacing batteries. Energy harvesting systems that can harvest energy from ambient vibrations and convert to the useful electrical energy would be a viable substitute to conventional batteries or it can work along with the battery to extend its lifetime [1]. Vibration-based energy harvesters have different sources such as biological sources [2-4], water current [5], wind [6-8], and structure systems [9-10].

The wide range of energy sources have led to the use of piezoelectric materials such as lead zirconate titanate (PZT) [11-17] and lead magnesium niobate-lead titanate (PMN-PT) [18-20] to many forms of application, including benders [4], [9], [10], stack actuators [21-22] and micro-electromechanical systems (MEMS) [23-24]. More references can be found in review articles [25-28] about piezoelectric vibrations energy harvesting.

Interest have been growing in development of high temperature energy harvesters to power devices such as near-engine sensors and remote sensors for geothermal explorations [29]. The performance of energy harvesters using single piezoelectric crystal materials in elevated temperatures conducted by other researchers was evaluated for some materials such as PZT. For example, Barker et al. 2010 showed the first high temperature PZT piezoelectric energy harvesting system, capable of operation up to 300° C. When the harvester is driven at 0.4 g it delivers 320μW at room temperature, falling to 80μW at 300° C. It also showed the peak output
voltage from the piezoelectric energy harvester and the resonance frequency of the device decrease at elevated temperatures.

In this study, I reveal a piezoelectric energy harvester system using PMN-PT, lead indium niobate-lead magnesium niobate-lead titanate (PIN-PMN-PT), and bimorph at higher temperature from room temperature up to 82° C for PZT bimorph, to 92 ºC for PMN-PT, and to 112 ºC for PIN-PMN-PT, and it shows the effects of temperature on the resonance frequency and power efficiency for each sample.

Furthermore, most communication systems and sensor networks use wires for connections, which make these systems expensive and bulky and limit the application of the sensor. bulk acoustic wave (BAW) quartz crystal resonators (QCRs) are frequently used as force or pressure sensors. The advantage of using this kind of sensor is based on its digital output, high resolution, high accuracy, good long-term stability, and low-power use [31].

This research also shows a wireless force sensor design using a BAW crystal resonator. In order to transmit the signal wirelessly, a frequency conversion technique comparable to that reported in a recent work [31-32] was used to convert the sensor’s ultrasonic signal to a higher frequency signal. The sensor was able to transmit the ultrasound signal by using passive components that modulate and transmit the signal [31]. For testing the performance of the sensor, a specially designed loading device was created to measure the frequency shifts of the resonator caused by a pair of diametric forces. The system used the resonator as its sensor [31]. Then wireless system data was compared with similar wired system data. The force-frequency effect is showed for both wired and wireless configurations. The wireless resonator force-sensing system has a wide diversity of applications, and the wireless transmission system has the potential to be used with other types of sensors as well [31].
2.1 Energy Harvesting

2.1.1 Energy Harvesting Using PMN-PT

Energy harvesting (EH) using PMN-PT materials has been studied both experimentally and analytically by many researchers (Ren et al.; Badel et al.; Hong and Moon,.) A typical vibrating energy harvesting system shown in Figure 1 consists of a PMN-PT patch, a metal beam, a tip mass and a fixture.

The mentioned researchers [18-20] conducted the EH system for high excitation level, but Song et al. investigated an EH utilizing single crystal PMN-PT patched to generate power for persistent excitation levels that are typically in the range of 0.05 – 0.2 g. The EH system in the research by Song et al. 2009 was composed of a cantilever beam having a single crystal PMN-PT patch, a tip mass, and a rectifier. The analysis and performance were validated experimentally for different excitation levels. The harvested DC power was measured for low acceleration levels of 0.05–0.2 g (where 1 g is 9.81 m/ s²) typical of rotating machinery. The maximum DC power generated was 19 mW for an excitation of 0.2 g. The measured power
density (i.e., maximum dc power over total device volume) was 0.73 mW/cm³. Then charging performance of the single crystal PMN-PT based EH was evaluated by recharging a battery [1].

Hong and Moon 2005 researched the effect of vibration amplitude on the performance of a PMN-PT single crystal film with interdigitated electrodes pattern. The prototype energy harvester was fabricated in $10 \times 1.2 \times 0.1 \text{ mm}^3$, converting the 50μm base displacement into 65μW power [20].

Badel et al. 2006 compared the performances of vibration-powered electrical generators using a piezoelectric single crystal and a piezoelectric ceramic of a same composition. Between both vibration-powered electrical generators having the same mechanical design, the one using a PMN-PT piezoelectric single crystal delivers greater than 20 times more power than the other one using a piezoelectric ceramic of a same composition [19].

Kailiang et al. 2006 investigated energy harvesting using composites of PMN-PT single crystals in a soft epoxy matrix. For comparison, composites with piezo-ceramic PZT are investigated in energy harvesting applications, and the results show that the high coupling factor of single crystal PMN-PT composites leads to much higher electric energy output for similar mechanical energy input. The research also shows the harvested energy density of the composite with single crystal (22.1 mW/cc) is about twice of that harvested with PZT ceramic composite (12 mW/cc). At a higher stress level, the harvested-energy density of PMN-PT single crystal composite can reach 96 mW/cm³ [18].

Mathers et al. 2009 [33] reported design, analysis, and experimental study of a vibration-based piezoelectric energy harvester. The energy harvester is made of a composite cantilever of a single crystal material (PMN-PT) and a base layer. A proof mass is constructed at the tip of the composite cantilever beam and is used as a means to tune the system natural frequency. This
study has demonstrated that a prototype of the harvester with a size of $7.4 \times 2 \times 110 \text{ mm}^3$ outputs a voltage of 10 V (0.3 mW of power) under a vibration excitation with a peak-to-peak amplitude of 1 mm at a frequency around 1.3 kHz [33].

Sun et al. 2009 studied piezoelectric energy harvesting device using single crystal PMN-PT. An analytical model for estimating the power-harvesting performance was derived for a cantilever mounted aluminum plate with a PMN-PT device bonded near the clamped end and a proof mass at the other free end. Considering the plate was subjected to both a steady-state sinusoidal vibration and a pulse impact excitation, static, and dynamic analyses were performed for device structure to achieve efficient energy harvesting. In dynamic analysis, transient response of the device was studied in the resonance frequency using a single degree of freedom system method [34].

Rakbamrung et al. 2010 [35] exposed the comparison of several energy harvesters both from the material and electronic aspects. From two different compositions of piezoelectric materials, it has been shown that the PMN–PT features higher coupling coefficient than the PZT based sample. The piezo-ceramics show a significant difference in power generation ability when using the classical energy harvesting technique [35].

Tang et al. 2012 [36] developed a piezoelectric MEMS vibration energy harvester with PMN-PT single material, which can convert low-level vibration energy into electrical energy. Compared with the conventional piezoelectric material (PZT), the PMN-PT single crystal has a higher coupling coefficient and electromechanical coefficient, which can improve the conversion efficiency of the power generating device [36].
2.1.2 High Temperature Energy Harvesting

All of the mentioned researchers performed the EH system in room temperature, with only a few works including the research of EH in elevated temperature. However, Barker et al. [30] reported the first demonstration of a high temperature piezoelectric energy harvester that was capable of operation up to 300°C. The system was comprised of a PZT piezoelectric energy harvesting system with a silicon carbide diode full wave rectifier, which can rectify the AC supplied by the piezoelectric harvester at higher temperatures than conventional silicon components. When the harvester was driven at 0.4 g into a matched load, the rectifier delivered 320 μW at room temperature, falling to 80 μW at 300°C. According to this work, it is caused by a combination of increased mechanical damping, decreased electromechanical coupling coefficient and an increase in the dielectric constant of the PZT [30].

Figure 2 shows frequency sweep change with temperature for a piezoelectric energy harvester. It is clear that the resonant frequency of the device decreases with temperature by the mechanical damping experienced by the cantilever [30].

![Figure 2: Frequency sweep change with temperature for a piezoelectric energy harvester [30]](image)
Besides the decrease in resonant frequency, the other notable change in Figure 2 is the change in the peak output voltage at resonance frequency. Given that most piezoelectric materials have a Curie point at which they change to a non-piezoelectric state, it would be expected that the output voltage would steadily decrease until this point [30].

2.1.3 Energy Harvesting Storage Circuitry

A vibration-based power generator converts the mechanical vibration energy into AC electrical power. Since micro-electronic devices and rechargeable batteries usually require a DC power source, a power conditioning circuitry is necessary to rectify and stable the AC power to the DC power [43]. A power conditioning circuit is important to the efficiency of electrical power production. Ottman et al. (2002, 2003) [37-38] derived the optimal DC voltage required to maximize the power extraction under the direct connection of the load to an AC-DC rectifier of a piezoelectric power generator [43]. The work also presented a solution using the DC-DC converter to achieve automated power optimization. Lefeuvre et al. (2007) [39] proposed using a boost converter running in discontinuous conduction mode to track the optimal working points of the generator. Badel et al. (2006), Guyomar et al. (2005), Richard et al. (1999), and Xu et al. (2005) developed several conditioning circuits to increase piezoelectric power generation that included electronic switches and inductors to shape the delivered voltage [43].

Ng and Liao [44-45] developed a power harvesting circuit to extract energy from a cantilever beam piezoelectric harvester [25]. It was found that the instantaneous power harvested by the piezoelectric device was too small to be used directly in most applications, so a power harvesting circuit was designed that releases the energy in a certain mode called burst mode. The energy generated by the piezoelectric material is first rectified with a diode and then stored in a
capacitor [25]. A voltage monitoring circuit is connected to the capacitor and releases energy from the capacitor in burst mode. The circuit reads the voltage across the capacitor and allows the capacitor to discharge through the load once a certain voltage level, release voltage, is detected. Additionally, the circuit stops allowing the capacitor to discharge once the voltage reaches a certain low level. The power harvesting circuit operating in burst mode was found to have an efficiency of 46% [25].

In a similar study, Tayahi et al. investigated piezoelectric power harvesting circuitry to be used in low-frequency applications such as walking and a circuit was developed that contained a rectifier, a capacitor, and a voltage regulator that supplied voltage to the load. Theoretically, the high efficiency of the converter should help improve the efficiency of the harvesting circuit; however, the circuit was only discussed in there and not tested [25].

Song et al. used an energy harvesting storage circuit module to store the harvested power of the EH and to regulate the output voltage. The module can regulate DC voltage ranging from 1.8 V to 3.6 V. Without using a battery, this energy harvesting storage module can store AC or DC input electrical energy from the EH and produce regulated DC output to a load. Moreover, he presented a charging circuit including the PMN-PT patch based EH, a rectifier circuit, and a polymer Li-ion battery.

2.2 Wireless Resonant Force Sensor

In the past, many types of QCR force/pressure sensors have been proposed [31]. EerNisse et al. [47-48] reviewed a number of works on all kinds of QCR sensors including force sensors. Muraoka et al. used the QCR to make a force sensor to detect forces applied to a robot finger [31]. Wang et al. [50-51] developed a high resolution QCR weight sensor and a temperature insensitive QCR force sensor. Yang et al. [52] performed a theoretical analysis for a highly
sensitive QCR pressure sensor [31]. In the situation of wireless sensors, BAW QCR force/pressure sensors are not often found in literature (a wireless passive QCR tire pressure sensor can be found in [53]) [31]. This situation may be due to fundamental incompatibilities between the high frequency of the resonator signal and the limited data throughput of existing wireless transceivers. Therefore, most commercial available QCR force/pressure sensors still rely on wired function, which is inconvenient and costly [31].
CHAPTER 3
EXPERIMENT

3.1 Energy Harvesting

3.1.1 Sample Preparation

Both PIN-PMN-PT and PMN-PT crystal samples obtained from H.C. Materials. PIN-PMN-PT crystal has superior depoling temperature and compulsive field [54], which is advantageous for energy harvesting purpose. <011> crystal was selected for its great transverse extensional coefficient d31. Crystal samples were prepared from <011> single crystals with dimension of 22 mm × 18 mm × 0.5 mm. Cr/Au electrodes were covered on 22 mm × 18 mm faces. Samples were poled and tested afterward. The third sample (beside PIN-PMN-PT and PMN-PT crystal samples) is a piezoelectric bimorph rectangular beam prepared at the APC International, Ltd, which is made from PZT ceramic and has the dimensions of 60 mm × 20 mm × 0.70 mm. Figure 3 shows the PIN-PMN-PT, PMN-PT and, bimorph plate, with details listed in Table 1.

![Bimorph](image_url)

**Figure 3:** PIN-PMN-PT and PMN-PT single crystal patches, and bimorph plate
<table>
<thead>
<tr>
<th>Sample</th>
<th>Length (mm) ±0.5</th>
<th>Width (mm) ±0.5</th>
<th>Thickness (mm) ±0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bimorph</td>
<td>60</td>
<td>20</td>
<td>0.7</td>
</tr>
<tr>
<td>PMN-PT</td>
<td>22</td>
<td>18</td>
<td>0.5</td>
</tr>
<tr>
<td>PIN-PMN-PT</td>
<td>22</td>
<td>18</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### 3.1.2 Experiment Setup

The piezoelectric devices used for PMN-PT and PIN-PMN-PT consisted of aluminum plates with the patches mounted to the plates via super-glue, and a bimorph plate which was used directly. The piezoelectric material is extremely brittle and it can easily be broken, so one cannot use the PMN-PT or PIN-PMN-PT patches directly. Therefore, using the aluminum plates and the super-glue was the best option to attach the patches to the aluminum plates. Figure 4 shows the aluminum plates with the PMN-PT and PIN-PMN-PT patches bounded to them and the bimorph plate.
Figure 4: PMN-PT and PIN-PMN-PT single crystal patch bounded to an aluminum plate and bimorph plate.

The thickness, width, and the length of the aluminum plates and the bimorph plate are listed in Table 2.

Table 2: Aluminum plates and bimorph plate geometry

<table>
<thead>
<tr>
<th>Sample</th>
<th>Geometry</th>
<th>Length (mm) ±0.5</th>
<th>Width (mm) ±0.5</th>
<th>Thickness (mm) ±0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bimorph</td>
<td></td>
<td>60</td>
<td>20</td>
<td>0.7</td>
</tr>
<tr>
<td>PMN-PT</td>
<td></td>
<td>137</td>
<td>30</td>
<td>1.5</td>
</tr>
<tr>
<td>PZN-PT</td>
<td></td>
<td>147</td>
<td>40</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Tip mass is used at the open end of the cantilever beam to tune the system resonance frequency.

Table 3 shows the tip mass and total mass of the energy harvesting systems.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tip Mass (g)</th>
<th>Total Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>±0.01</td>
<td>±0.01</td>
</tr>
<tr>
<td>Bimorph</td>
<td>1.32</td>
<td>4.49</td>
</tr>
<tr>
<td>PMN-PT</td>
<td>4.16</td>
<td>25.32</td>
</tr>
<tr>
<td>PZN-PT</td>
<td>2.62</td>
<td>33.97</td>
</tr>
</tbody>
</table>

In addition to the samples several devices are used in this experiment, which are shown in Fig. 5:

![Figure 5: EH experiment setup](image-url)
1) Power supply amplifier (Techron7541), shown in Figure 6, is used to power the shaker. By connecting to a function generator, the amplifier could drive the shaker at a preferred frequency.

2) Accelerometer (model PCB 355B04), shown in Figure 7, is used to measure the acceleration amplitude.

3) Multi-meter (HP33401A), shown in Figure 8, is used to measure the output voltage from the experiment. The multi-meter is connected to the oscilloscope and the oscilloscope is connected to the computer by GPIB cable.

4) Function Generator (HP33120A), shown in Figure 8, is used to generate a signal to the power supply amplifier of the shaker. The function generator is connected to both an oscilloscope and to the computer by GPIB cable.

5) Oscilloscope (TDS3054C), shown in Figure 8, is a measurement center between the computer and other devices.

6) Shaker (VG-100) is used to provide vibration for this experiment. Figure 9 shows how the shaker and the fixture are connected together.

7) Furnace (model ST-1200C), shown in Figure 9, is a programmable furnace used to control the experiment’s temperature.

8) LabVIEW software (National Instrument Inc.), shown in Figure 10, installed in the computer is the controlling center of the whole experiment. It is used to set the exciting frequency to the function generator, to assign the reading type of the multi-meter, and to record data from the oscilloscope.
Figure 6: Power supply amplifier of shaker

Figure 7: Accelerometer attached on the shaker
In order to excite the samples and simulate the vibration, the shaker (model VG-100) was used. One end of the cantilever beam (aluminum plates or bimorph plate) is fixed in a fixture attached on the shaker. A small mass can be attached on the other end of each cantilever beam. A pair of wire conducts the produced current through a resistor. Resistors used for different energy harvesting measurement are listed in Table 4.
Table 4: The resistors used for output power measurement

<table>
<thead>
<tr>
<th>Sample</th>
<th>Load (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>±0.05</td>
</tr>
<tr>
<td>Bimorph</td>
<td>19.75</td>
</tr>
<tr>
<td>PMN-PT</td>
<td>55.80</td>
</tr>
<tr>
<td>PZN-PT</td>
<td>55.80</td>
</tr>
</tbody>
</table>

The multi-meter, which was connected to the oscilloscope via GPIB cable, is used to measure the voltage across the resistor. The accelerometer attached to the shaker is also connected to the oscilloscope to measure the acceleration amplitude. The signal generator used to generate a signal with the frequency desired to excite the shaker along with the amplifier. All three (multi-meter, signal generator, and oscilloscope) are connected to the computer which has LabVIEW program installed on it. Moreover, from the LabVIEW program we control and monitor the whole experiment and collect the data. As shown in Figure 9 the furnace is used to control the temperature. The whole measurement system block diagram is shown in Figure 5.
3.1.3 Measurement Procedure

The measurements were started at room temperature. A program had been developed using LabVIEW, shown in Figure 10, for the control and signal processing of the energy harvester system.
By setting the starting and the ending frequency in the software, the function generator will provide a sweeping frequency and drive the mechanical shaker to vibrate at the preferred frequency range. The accelerometer which was connected to the oscilloscope measures the acceleration of the vibration. Our designed fixture was attached on the shaker and conveys the vibration to the connected sample. The output voltage to the connected resistance was recorded by the multi-meter. Both the function generator and the multi-meter were connected to the oscilloscope via GPIB cable. The oscilloscope was connected to the computer and the signals were processed by the software. As shown in Figure 9, a programmable furnace was used to control the temperature and repeat the experiment without changing the setup in different
temperature from room temperature to 82°C for PZT bimorph, to 92 °C for PMN-PT, and to 112 °C for PZN-PT with 10°C increments.

3.1.4 Store the Harvested Power

An energy harvesting storage circuit, module, (Advanced Linear Devices, Inc., EH301A) was used to store the harvested power of the EH and to regulate the output voltage. The module can regulate DC output voltage ranging from 3.1 V to 5.2 V. Without using a battery, this energy harvesting storage module, shown in Figure 11, can store AC or DC input electrical energy (in this case the input is AC from the EH) and makes regulated DC output to a load which is a battery in this experiment.

![Energy harvesting module](image)

**Figure 11: Energy harvesting module**

The LabVIEW program was set up to control the multi-meter and record the voltage across the battery continuously. In the room temperature, the beam of energy harvesting system using PMN-PT was connected to the module’s input. The output of module connected to the battery (polymer Li-ion battery, 3.7V, 120mAh) shows in Figure 12. The configuration of battery charging circuit using the module is shown in Figure 13.
Figure 12: configuration of battery charging circuit using the module

The signal generator was set to the system resonance frequency with the constant amplitude in order to vibrate the shaker in a constant acceleration of 0.4 g at the system resonance frequency.
Again discharged the battery by connecting a load across it and repeat charge it up, but this time instead of using the module to regulate the AC output of EH, charging the battery directly by using a full-bridge rectifier (Fairchild Corp., DF02M) and a capacitor (220µF) as shown in Figures 14 and 15.

Figure 13: Diagram of charging battery using the module EH301A

Figure 14: Direct charging the battery using full-bridge rectifier and a capacitor
Figure 15: Diagram of charging battery using the full-bridge rectifier

Figure 16 shows the charging characteristics of the battery for both using the full-bridge rectifier and using the module in 25 hours. With the same setup, the directly charging battery using full-bridge rectifier can charge the battery to near 3.5 V, and using the module can charge the battery to about 3.1 V, as shown in Figure 16.

The charged battery then was used to power up a Direct Digital Synthesizer (DDS) function generator, shown in Figure 17. This function generator (5MHz, UDB1005S) needs 5V
DC power supply to turn on. Since the battery has less than 5V of charge, a DC to DC converter, shown in Figure 17, is used to convert the battery voltage to a stable 5V DC. Figure 18 shows the block diagram of the connections. Figure 17 shows the sine wave signal on the oscilloscope generated by the function generator.

![Figure 17: Function generator powered up with the battery](image)

![Figure 18: Function generator power-up block diagram](image)
3.1.5 Experiment Result

Tables 5 and 6 along with Figures 19-27 show typical results for the designed energy harvester systems. Figures 19, 20, and 21 clearly show the influence of temperature on resonance frequency and power for PMN-PT, PIN-PMN-PT, and bimorph respectively. In most cases piezoelectric materials show lower power generation at elevated temperatures. Only on PMN-PT did increasing the temperature initially cause the increase of the output power. It may be due to the pyroelectricity of the PMN-PT material and temperature gradient the furnace generated. The temperature eventually reduced the output power in all cases. In all three cases, the temperature reduced the resonance frequency of the energy harvesting devices as shown in Figures 22, 24, and 26. By comparing all three samples the PIN-PMN-PT showed the best performance of standing on higher temperature up to 112 ºC and lost about 20% of its maximum power output, while bimorph at 82ºC and PMN-PT at 92ºC lost their output power to about 50% of its maximum value. The uncertainty evaluation was carried out in accordance with [54].
Table 5: Resonance frequency of different energy harvesting system at elevated temperatures

<table>
<thead>
<tr>
<th>Temperature (°C) ±1</th>
<th>Resonance Frequency (Hz)±0.1 for PZN-PT</th>
<th>Resonance Frequency (Hz)±0.1 for PMN-PT</th>
<th>Resonance Frequency (Hz)±0.2 for bimorph</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>47.3</td>
<td>49.0</td>
<td>30.8</td>
</tr>
<tr>
<td>32</td>
<td>47.2</td>
<td>48.8</td>
<td>30.6</td>
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<td>47.1</td>
<td>48.2</td>
<td>30.2</td>
</tr>
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<td>48.1</td>
<td>30.0</td>
</tr>
<tr>
<td>72</td>
<td>46.8</td>
<td>47.7</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>112</td>
<td>45.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6: Maximum power output of different sample at elevated temperatures

<table>
<thead>
<tr>
<th>Temperature (°C) ±1</th>
<th>Max Power Output (mW) for PZN-PT ±0.01</th>
<th>Max Power Output (mW) for PMN-PT ±0.01</th>
<th>Max Power Output (mW) for bimprph ±0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>5.18</td>
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<td>1.38</td>
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<td>1.22</td>
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<td>2.57</td>
<td>1.08</td>
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<td>72</td>
<td>5.13</td>
<td>2.65</td>
<td>0.93</td>
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<td>92</td>
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</tr>
<tr>
<td>112</td>
<td>4.11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 19: The influence of temperature on resonance frequency and output power of PMN-PT energy harvester

Figure 20: The influence of temperature on resonance frequency and output power of PIN-PMN-PT energy harvester
Figure 21: The influence of temperature on resonance frequency and output power of bimorph energy harvester

Figure 22: Resonance frequency vs. temperature for PMN-PT energy harvester
Figure 23: Maximum power output vs. temperature for PMN-PT energy harvester

Figure 24: Resonance frequency vs. temperature for PZN-PT energy harvester
Figure 25: Maximum power output vs. temperature for PZN-PT energy harvester

Figure 26: Resonance frequency vs. temperature for bimorph energy harvester
3.2 Partially Wireless Resonant Force Sensor System

3.2.1 Design of the Resonator Force Sensor System

Figures 28 and 29 show how the energy harvesting system can be connected to the force sensor system to extend the battery life time. The fundamental mechanism for the force sensor is based on the force-frequency effect for resonators [31]. By establishing the relation between the applied force and change in the resonant frequency of the resonator, the applied force to the resonator can be determined. The resonant frequency of the crystal can be obtained by observing the frequency response of the crystal. The frequency response is found by applying an excitation signal to one side of the crystal and determining the gain of the crystal by comparing the crystal’s output signal to the excitation signal, while sweeping the excitation signal over a range of frequencies. In this part of the experiment, the crystal was excited with manually sweeping excitation signal with constant amplitude over a frequency range. The resonance frequency is indicated by a noticeable amplitude peak observation in the output signal.

Figure 27: Maximum power output vs. temperature for bimorph energy harvester
The core of the force sensor is a quartz crystal resonator (Crystek CY2A 2.000) with keyhole electrodes, shown in Figure 30. Figure 31 shows a picture of the loading device. The sensor is fixed on a resonator fixture mounted on a rotational stage (Thorlabs Inc.) The rotational stage is mounted on a square aluminum plate, shown in the Figure 32, fixed on an extension rod [31]. The extension rod is mounted on a XY translation stage (Newmark NLE-50-A), shown in Figure 31, mounted on an optical table (Thorlabs Inc) [31]. The XY translation stage has only been used as part of the fixture in this experiment; however, the XY translation stage can be connected through a controller (Newmark NSC-M2-E) to a computer with LabVIEW software. When programming using LabVIEW, the XY translation stage can move with a minimum distance of 0.1 μm [31].

Figure 28: Energy harvester connection to the force sensor system
Figure 29: Using battery to power up the circuit
Figure 30: Crystal resonator (Crystek CY2A 2.000) used as a force sensor
Figure 31: Loading device
Figure 32: Applying force on the resonator connected to a rotational stage

Figure 33: Partially wireless system diagram
Figure 33 presents the experimental system diagram. The resonator was excited with a signal (called excitation signal) using the DDS function generator with manually sweep frequency. Then the frequency sweep signal from the resonator (called sensor signal, the resonator response to the excitation signal) was transmitted wirelessly to the oscilloscope [31]. Wireless transmission of the sensor signal requires that the signal is up-converted to a high frequency, transmitted through the use of antenna, and then down-converted and filtered to deliver the sensor signal to the oscilloscope. This is done using the principle of frequency conversion by using of frequency mixers [31]. A frequency mixer is a nonlinear device that can convert a frequency into a suitable range. A frequency mixer has three main ports: the local oscillator port (LO), the radio frequency port (RF), and the intermediate frequency port (IF). Up-conversion using a frequency mixer is accomplished by applying signals to the LO port and the IF port, and outputting a signal at the RF port that is defined by eq. (1) [31].

\[ f_{RF} = f_{LO} \pm f_{IF} . \]  

Where \( f_{RF} \) is the signal out of the RF port, \( f_{IF} \) is the signal into the IF port, and \( f_{LO} \) is the signal into the LO port of the frequency mixer. This results in \( f_{RF} \) having a signal at two frequencies, \( f_{LO}+f_{IF} \) and \( f_{LO}−f_{IF}. \) Down-conversion using a frequency mixer is done using incoming signals at the LO and RF ports, and outputting a signal defined by eq. (2) at the IF port [31].

\[ f_{IF} = f_{RF} \pm f_{LO} . \]  

This means that the signal output from the IF port has two frequencies, \( f_{RF}−f_{LO} \) which is the desired signal, and \( f_{RF}+f_{LO} \) which is a very high frequency signal that is filtered out using a low-pass filter. Figure 34 shows the diagram of the sensor signal transmission system in more details. A voltage-controlled oscillator is tuned to oscillate at 2.4 GHz in order to generate a carrier signal that is used to transmit the sensor signal [31]. The 2.4 GHz signal is split using a
directional coupler where the coupled output is amplified and transmitted through the Sensor Signal Transmission System (SSTS)’s receiver transmission antenna [31]. In the (SSTS)’s transmitter part, a reception antenna receives the 2.4 GHz signal and then applies it to the LO port of the SSTS’s transmitter frequency mixer. The sensor’s signal, $f_x$, is sent to the IF port of the SSTS’s transmitter frequency mixer where it mixes with the 2.4 GHz signal to create a signal at the RF port with frequencies of $2.4 \text{ GHz} \pm f_x$ using eq. (1). This signal is then transmitted from the SSTS’s transmitter transmission antenna to the SSTS’s receiver reception antenna. The received signal is then passed through a band-pass filter in order to eliminate unwanted noise. The signal is then amplified, and sent to the RF port of the SSTS’s receiver’s frequency mixer where it is mixed with the 2.4 GHz signal coming from the output port of the directional coupler to the LO port of the frequency mixer [31]. Mixing these signals generates two output frequencies at the IF port. These frequencies are $f_x$ and $f_x + 4.8 \text{ GHz}$, using eq. (2). This new signal passes through a low-pass filter to eliminate the higher frequency signal, leaving only $f_x$. This signal is then amplified and sent to the input channel port of the oscilloscope. The loading device, shown in Figure 31, is used to apply the diametric force to the thin edge of the resonator, shown in the Figure 32. The frequency shift of the resonator would be detected wirelessly [31].
3.2.2 Sensor Signal Transmission System (SSTS)’s Transmitter

The resonator described in Sections 3.2.1, shown in Figure 30, was excited by the function generator, shown in Figure 17, and then connected to a frequency mixer (Mini-circuits, ZX05-73L-S+), shown in Figure 35 [31]. The SSTS’s transmission and reception antennas (Antenna Factor, ASY-EVAL-2.4-CHP), shown in Figure 35, were attached to the RF and LO ports of the frequency mixer [31].
3.2.3 Sensor Signal Transmission System (SSTS)’s Receiver

The SSTS’s receiver, shown in Figures 34 and 36, used a 2.4 GHz voltage controlled oscillator (Mini-Circuits, ZX95-2450C-S+) that delivered a 2.4 GHz signal to the input port of the directional coupler (Mini-Circuits, ZABDC20-322H-S+). The CPL-IN port of the directional coupler was terminated using a 50 Ω load (L-Com, BTS5M). The CPL-OUT port of the directional coupler was connected to the input of a low power amplifier (Mini-Circuits, ZX60-6013E-S+) [31]. The output of the low power amplifier was then sent through a second amplifier (Mini-Circuits, ZFL-2500VH+). The second amplifier was then connected to the SSTS’s receiver’s transmission antenna (L-Com, HG2458-08LP-NF), shown in Figure 37 [31]. The SSTS’s receiver’s reception antenna (L-Com, HG2458-08LP-NF), shown in Figure 37, was mounted perpendicular to the first antenna to eliminate crosstalk of the signals. This SSTS’s receiver antenna was connected to a band-pass filter (Mini-Circuits, VBFZ-2575+). This filter
was then connected to the input of a low noise amplifier (Mini-Circuits, ZRL-2400LN+) to boost the signal before mixing. The output of the low noise amplifier was then connected to the RF port of the SSTS’s receiver’s frequency mixer (Mini-Circuits, ZX05-73L-S+). The OUT port of the directional coupler was then connected to the LO port of the SSTS’s receiver’s frequency mixer [31]. A low pass filter (Mini-Circuits, VLF-1000+) was then attached to the IF port of the mixer. The low-pass filter was then connected to an ultra-low-noise voltage amplifier (Physical Acoustics Corporation) that was configured for a single input and a gain of 60 dB. The output of the ultra-low-noise voltage amplifier was connected to the oscilloscope. Figure 36 shows the implementation of the sensor signal transmission system [31].

Figure 36: Implementation of the SSTS’s receiver
3.2.4 Measurement Procedure

The function generator was used to generate the frequency sweep. In order to maintain comparable data, the experimental settings and connections were the same in all experimental measurements [31]. The start frequency sweep range was set to 1.999 MHz, and the stop frequency was 2.001 MHz since the resonance frequency of the resonator crystal was about 2 MHz. The resonance frequency was found by determining the frequency of the signal when the highest peak voltage value observed. After observing the resonance frequency in the first frequency sweep range, the frequency sweep range was narrowed down around the found resonance frequency one digit at a time (from thousands to hundreds, tens, and ones) and sweep the frequency again to find the resonance frequency of the resonator in higher resolution. The loading device applied loads from 0 to 20 N in 2.5 N increments. The distances between the antennas were about 1 m. The resonance frequency of the resonator was found for each load by connecting the oscilloscope to the crystal via either the wired or wireless system separately. Comparisons were then made between the wired and wireless results [31].
3.2.5 Experiment Result

A comparison between the wired and wireless system’s resonance frequencies from no-load to 20 N is shown in Table 7. The results for the force-frequency relation are shown in Figure 38. The data illustrates that the relationship between an applied force and the resonant frequency is linear. The data also shows that there is a frequency shift in resonant frequencies from the wired system to the wireless system [31]. The difference in frequency between the two systems is an almost constant value of 100 Hz. The force-frequency relationships as measured using the wired and wireless systems can be brought into a good agreement with a regular frequency shift correction [31]. The sensitivity of the sensor in average is 7 (Hz/N) for wired and 8 (Hz/N) for wireless configurations when the azimuth angle the resonator was fixed during the whole experiment.
Table 7: Resonance frequency at different load (wired and partially wireless)

<table>
<thead>
<tr>
<th>Force (N)</th>
<th>Resonance Freq. partially Wireless (Hz)±5</th>
<th>Resonance Freq. wired (Hz)±5</th>
</tr>
</thead>
<tbody>
<tr>
<td>±0.05</td>
<td>1999700</td>
<td>1999800</td>
</tr>
<tr>
<td>0.0</td>
<td>1999720</td>
<td>1999810</td>
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<tr>
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<tr>
<td>5.0</td>
<td>1999760</td>
<td>1999850</td>
</tr>
<tr>
<td>7.5</td>
<td>1999780</td>
<td>1999865</td>
</tr>
<tr>
<td>10.0</td>
<td>1999800</td>
<td>1999885</td>
</tr>
<tr>
<td>12.5</td>
<td>1999820</td>
<td>1999900</td>
</tr>
<tr>
<td>15.0</td>
<td>1999840</td>
<td>1999920</td>
</tr>
<tr>
<td>17.5</td>
<td>1999860</td>
<td>1999940</td>
</tr>
<tr>
<td>20.0</td>
<td>1999880</td>
<td>1999960</td>
</tr>
</tbody>
</table>

Figure 38: Force-frequency relation for the crystal (Crystek CY2A 2.000)
3.3 Completely Wireless Resonant Force Sensor System

3.3.1 Design of the Wirelessly Excitation the Crystal Resonator (Crystek CY2A 2.000)

In the previous section 3.2, the resonator was excited using the function generator connected with wires directly to the resonator crystal and the resonator’s response to the excitation signal was sent wirelessly to the oscilloscope. In order to have the sensor completely wirelessly, the excitation signal also has to be wirelessly transmitted to the resonator crystal. Figure 39 shows the block diagram of the completely wireless resonant force sensor system. The resonator was excited wirelessly using a Bode 100 Network Analyzer (OMICRON LAB), shown in Figure 40, and transmit the frequency sweep signal from the resonator wirelessly back to the network analyzer [31].

![Block diagram of the wireless resonant force sensor system](image)

Figure 39: Block diagram of the wireless resonant force sensor system
A technique similar to what has discussed in section 3.2.1 was used to transmit the excitation signal to the resonator crystal. Again, this was done using the principle of frequency conversion by using of frequency mixers. Figure 41 shows the excitation signal transmission system (ESTS) block diagram. As the diagram shows the ESTS has two parts, the transmitter and the receiver. A voltage controlled oscillator was tuned to oscillate at 869 MHz in order to generate a carrier signal that was used to convert the excitation signal. The 869 MHz signal was then split by using a directional coupler where the coupled output was amplified, and the non-coupled output was sent to a mixer’s LO port where it up-converts the excitation signal sent from the network analyzers output port that was input through the IF port of the frequency mixer. Then the output signal from the RF port of the mixer amplified. Both signals coming out of the amplifiers were then combined by using a two-way splitter. The signal output from the splitter was then sent to the ESTS’s transmission antenna. The ESTS’s receiver antennas received the 869 MHz signal along with the $869 \text{ MHz} \pm f_{IF}$ signal and then applied it to the LO and RF ports of the ESTS’s receiver frequency mixer. The IF port of the frequency mixer sent the signal through a low-pass filter to recover the excitation signal. The excitation signal was then applied to the crystal resonator. The crystal response signal (sensor signal) was then transmitter
wirelessly to the Network Analyzer with Sensor Signal Transmission System discussed in section 3.2.

![Diagram of the excitation signal transmission system (ESTS)](image)

Figure 41: Diagram of the excitation signal transmission system (ESTS)

3.3.2 Excitation Signal Transmission System (ESTS)’s Transmitter

The ESTS’s transmitter used a voltage controlled oscillator (Mini-Circuits, ZX95-1410-S+) that was tuned to delivered an 869 MHz signal to the input port of the ESTS’s directional coupler (Mini-Circuits, ZNDC-13-2G-S+). The output port of the directional coupler was connected to the LO port of the ESTS’s transmitter’s frequency mixer (Mini-Circuits, ZX05-10L-S+). The output of the Bode 100 Network Analyzer was connected to the IF port of the ESTS’s transmitter’s frequency mixer. The RF port of the frequency mixer was attached to the
input of an amplifier (Mini-Circuits, ZX60-14012L-S+). The output of that amplifier was then connected to the input of a second amplifier (Mini-Circuits, ZHL-2010+). The output of the second amplifier was then connected to one of the two inputs on a two-way splitter (L-Com, SCW02). The coupled output of the directional coupler was then connected to the input of an amplifier (Mini-Circuits, ZHL-1010+). The output of this amplifier was then attached to the second input of the two-way splitter. The output of the two-way splitter was then connected to the ESTS’s transmitter antenna (Air802, ANBB8002500), shown in Figure 42 along with SSTS antennas. The Excitation signal transmission system’s transmitter is shown in Figure 43.

![Figure 42: ESTS’s transmitter antenna along with SSTS antennas](image-url)
3.3.3 Excitation Signal Transmission System (ESTS)’s Receiver

The ESTS receiver antennas receives the 869 MHz signal along with the 869 MHz ± f_{IF} signal and then applies it to the LO and RF ports of the ESTS’s receiver frequency mixer. The IF port of the frequency mixer outputs a signal that is sent through a low pass filter to recover the excitation signal. The excitation signal is then applied to the crystal resonator. The excitation signal transmission system’s receiver is shown in Figure 44.
3.3.4 Measurement Procedure

The Bode 100 Network Analyzer was used to generate the frequency sweep. In order to maintain comparable data, the experimental settings in the Bode Analyzer were the same in every experimental measurement. The start frequency was set to 1.997 MHz, and the stop frequency was set to 2.002 MHz with a span of 5 KHz [31]. The sweep mode was set to linear, with 801 data points. The level of the output signal from the Bode 100 network analyzer was set to a level of 0 dBm. The attenuator for CH1 was set to 20 dB, and the attenuator for CH2 was set to 0 dB [31]. The reference resistance was set to 50.00 Ω. The network analyzer was set up to measure the gain. The loading device applied loads from 0 to 20 N in 2.5 N increments. The distances between the antennas were about 1 m. Once the loading device began to apply a load, the Bode 100 started to take measurements. The frequency spectrum of the resonator was found
for each load by connecting the Bode Analyzer to the resonator via either the wired or wireless system separately. The resonant frequency was found by determining the peak of the frequency spectrum. Comparisons were then made between the wired and wireless results [31].

3.3.5 Experiment Result

A comparison between the wired and wireless resonance frequencies from no-load to 20 N is shown in Table 8. Similarly a comparison between the wired and wireless frequency spectrum of the resonator at no-load is shown in Figure 45. The result for the force-frequency relation is shown in Figure 46. The data shows that the relationship between an applied force and the resonant frequency is linear as expected [31]. The data also shows that there is a shift in resonant frequencies from the completely wired system to the completely wireless system. The difference in frequency between the two systems is an almost constant value of 85 Hz. The force-frequency relationships as measured using the wired and wireless systems can be brought into a good agreement with a constant frequency shift correction. The sensitivity of the sensor in average is 7.2 (Hz/N) for both wired and wireless configurations when the azimuth angle of the resonator was kept fixed during the whole experiment [31].

In the last section of this experiment a new piezoelectric crystal called AT-cut quartz resonator was used as a force censor. AT-cut has superior behavior such as having a stable frequency-temperature behavior and high electrical-mechanical coupling coefficient [31]. The result of experimenting AT-cut as a force sensor is similar to the result of the first crystal (Crystek CY2A 2.000). The force-frequency relation of the AT-cut resonator from no-load to 22.5 N is shown in Figure 47. The sensitivity of the AT-cut sensor in average is 40 (Hz/N) for both wired and wireless configurations when the azimuth angle of the resonator was zero during the whole experiment.
Table 8: Resonance frequency at different load (wire and wireless)

<table>
<thead>
<tr>
<th>Force(N)</th>
<th>Resonance Freq. Wireless (Hz)±0.5</th>
<th>Resonance Freq. Wired (Hz)±0.5</th>
</tr>
</thead>
<tbody>
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</tr>
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<td>0.0</td>
<td>1999600</td>
<td>1999681</td>
</tr>
<tr>
<td>2.5</td>
<td>1999613</td>
<td>1999700</td>
</tr>
<tr>
<td>5.0</td>
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<td>1999719</td>
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<tr>
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<td>17.5</td>
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<td>1999806</td>
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<tr>
<td>20.0</td>
<td>1999741</td>
<td>1999825</td>
</tr>
</tbody>
</table>
Figure 45: Comparison between (a) wired and (b) wireless frequency spectrum at zero load for the crystal (Crystek CY2A 2.000)
Figure 46: Force-frequency relation for the crystal (Crystek CY2A 2.000)

Figure 47: Force-frequency relation for the crystal (AT-cut quartz)
In this experimental research, the prototypes of a self-powered and a powered-less quartz crystal resonator force sensor was built. The thesis research divided into three main parts. In the first part we have experimentally demonstrated a prototype of a vibration piezoelectric energy harvesting system operating in higher temperature than room temperature, and also storing the produced electrical energy. From the experimental observation, the elevated temperature affected the operation frequency and power density. Increasing temperature finally caused the power output decrease and also shifts the resonance frequencies to the lower values. The influence of temperature gradient which may cause to generate a voltage needs to be investigated in future work to explain the unusual behavior that the PMN-PT energy harvester exhibited. The results suggest that we can predict our energy harvester resonance frequency at different temperatures to match the source frequency with it for the maximum power output. Moreover, in the future research by mathematical modeling the energy harvesting system we may be able to increase the generated electricity and also with the improved circuitry designed, transfer more power to the load.

In the second and the third parts, the prototype partially and completely wireless resonator force sensor was demonstrated experimentally using frequency conversion techniques. It has been demonstrated that the energy harvester can be used to power a portion of the wireless sensor circuit. The wireless transmission system used in this research potentially can be used in many other applications. An agreement between the measurements in this part can be achieved using a frequency offset shift. In the future by miniaturization of the components and the design
we can improve the system power efficiency. Furthermore, using of a crystal with known properties as our force sensor is in our future research efforts to find the largest sensor sensitivity azimuth angle.
REFERENCES


